Geology and Soils

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Abstract

The subject geology and soils is fundamental for tropical forest management. This chapter is divided into three logical parts: The first describes soil-forming factors and processes. The second provides the exhaustive description of definition, properties of different soil types, and their use for forest purposes. The following soil groups are dealt with: Mature Soils of the Humid and Subhumid Tropics, Representative Soils of the Semiarid and Arid Tropics, Soils Mainly Conditioned by Parent Material and Topography, Temporarily or Permanently Hydromorphic Soils, Soils of the Steppes, and finally Tropical Soils Conditioned by Human Influence. The third part deals with the organization and management of soil surveys; this allows the forest manager to project necessary soil surveys.

Keywords

Soil formation factors • Soil formation processes • Mature soils • Soils of humid and subhumid tropics • Semiarid tropical soils • Arid tropical soils • Hydromorphic soils • Steppe soils • Soil Survey

List of Abbreviations

a	year
AEC	Anion exchange capacity
BD	Bulk density
BS_{pot}	Potential base saturation, calculated according to [(Ca + Mg + Na + K)/CEC_{pot}] × 100 (exchangeable Ca, Mg, Na and K by 1 M NH_4OAc, pH 7)
BS_{eff}	Effective base saturation, calculated according to [(Ca + Mg + Na + K)/CEC_{eff}] × 100 (exchangeable Ca, Mg, Na and K by 1 M NH_4OAc, pH 7)
cal ka BP	Calibrated kiloyears before present
CEC_{eff}	Cation exchange capacity, sum of exchangeable base cations (by 1 M NH_4OAc, pH 7) plus exchangeable Al (by 1 M KCl, unpuffered)

CEC_{pot}	Cation exchange capacity by 1 M NH_4OAc, pH 7
cmol	centimol
C_{org}	Organic carbon
d	Extractable with dithionate-citrate (e.g., Fe_d, Al_d)
$\delta^{13}C$	$[R_{sample}/R_{standard}) - 1] \times 1000$, where = $^{13}C/^{12}C$; carbon reference standard = VPDP (Vienna Pee Dee belemnite)
$\delta^{15}N$	s. $\delta^{13}C$, where R = $^{15}N/^{14}N$; nitrogen reference standard = AIR N_2
$\delta^{18}O$	s. $\delta^{13}C$, where R = $^{18}O/^{16}O$; oxygen reference standard = VSMOW (Vienna Standard Mean Ocean Water)
δD	s. $\delta^{13}C$, where R = D/H (Deuterium/Hydrogen)
DOM	Dissolved organic matter
EC_e	Electrical conductivity in the saturation extract
ESP	Exchangeable sodium percentage
ET	Evapotranspiration
FE	Fine earth fraction <2 mm
HACs	High activity clays
LAC_S	Low activity clays (clay minerals min low CEC; mostly two-layer clay minerals)
LGM	Last glacial maximum (last maximum glaciation, before approximately 25–18 ka BP)
o	Oxalate soluble (e.g., Fe_o, Al_o)
Pg	Pentagram
PV	Pore volume
py	Soluble in pyrophosphate (e.g., Al_{py})
rH	The negative logarithm of the hydrogen partial pressure
RSG	Reference Soil Group
SAR	Sodium adsorption ration: $Na^+/0.5\ (Ca^{2+} + Mg^{2+})^{0,5}$, ions in cmol (+)/liter of soil solution
SOC	Soil organic carbon
SOM	Soil organic matter
TOR	Terms of reference
*	Annex 4
**	Annexes 1, 2, and 3

Introduction

Soils are the result of transformation processes in the uppermost part of the lithosphere; These processes are influenced by fluctuations of temperature, by organisms, and by inputs from the atmosphere, including precipitation (H_2O), gases (CO_2, SO_x, $NO_{x,}$ O_2), inorganic and organic particles, aerosols, and radiation. The transformation zone is called pedosphere (Fig. 1). It covers the lithosphere to different degrees and thicknesses. According to Laatsch and Schlichting (1959) soils are three-dimensional sectors of the pedosphere, limited above by the litter

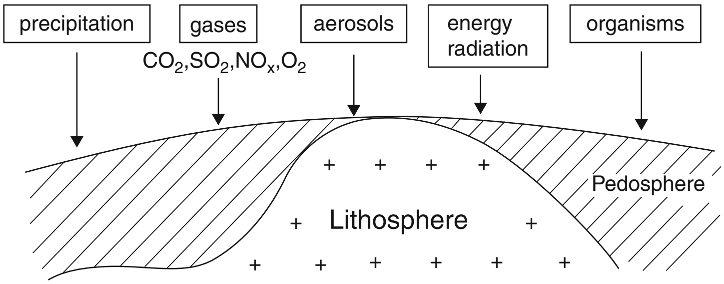


Fig. 1 The pedosphere is, or has developed by, in situ alteration of the upper part of the lithosphere under the influence of precipitation, carbon dioxide, sulfur dioxide, nitrous gases, aerosols, radiation, and organisms

Photo 1 In the tropics the pedosphere is sometimes very thick, consisting of different layers (Rwanda)

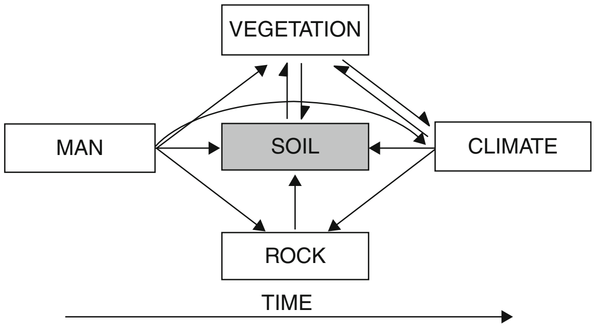
layer and below by the parent rock. This definition holds true for the middle latitudes, where the pedosphere has a thickness of about 1–2 m in general. In the tropics the transformation zone may be as thick as 50–100 m or even more (Photo 1). In this case, the concept "soil" encompasses only the upper, biologically active part of the pedosphere, which contains plant roots and organisms. The deeper part, almost empty of life, and not containing roots, is called weathered mantle or saprolite if it still shows the structure of the parent material (Photo 2). If erosion

Photo 2 If the lower part of the transformation zone still reveals the structure of the lithosphere it is called saprolite (southern Thailand)

causes the weathered mantle to come to the surface, it will in time be transformed into soil, after it has been invaded and settled by plants, animals, and microbes.

Soils consist of an inorganic solid phase, which is formed during the weathering of the parent rock. In addition, there is an organic solid phase, which is based on biota but mainly on dead and decomposed plant and animal parts. Besides, soils contain gaseous (e.g., air, CH_4) and liquid (e.g., water, dissolved organic matter) phases. Fertile soils are characterized by an optimal relationship between these solid, liquid, and gaseous compounds. This is obvious, since soils are the substrates in which plants are growing and rooted and which have to supply them with nutrients (e.g., N and S from the organic phase, K and Ca from the mineral solid phase), water, and oxygen (for root respiration) to produce biomass. However, the requirements of plants may be highly variable, and the soils themselves may change over time with respect to nutrient availability, and air and water budgets. These facts explain why evaluating the quality of a soil in relation to its suitability for growing plants may be a highly complex task. It requires not only competent knowledge of soil and plant sciences but in addition, geomorphological and climatological information. Such concepts as "site" and "site science" are therefore more

Fig. 2 Soil-forming factors and their interactions (Schroeder 1984)



encompassing than "soil" and "soil science" alone. While soil science includes mainly the chemical, physical, and biological properties of soils, the objective of "site science" is to demonstrate the interactions between vegetation and site, whereby site properties are the result of combined effects of soil, climate, and relief. Sustainable yields, without doubt, are additionally based on sound management practices in forestry and agriculture.

Soils and sites are not static entities. They change as a function of the environment. That is why in the pedosphere a multitude of processes are constantly at work. In general, these processes cause a differentiation of the pedosphere into **soil horizons**. They are typical soil characteristics resulting from the changes occurring in the pedosphere and can be recognized in a soil pit or soil cut. Usually, soil horizons differ in color, texture, structure and root penetration, etc. The intensity and direction of the soil horizon forming processes and thereby the genetic and ecological properties of a soil are determined mainly by the **soil-forming factors**. These include the **parent material (PM),** the **climate (CI),** the **relief (Re),** the **biological factor including man (Biol. Fac.),** and **time (Ti).**

According to Jenny (1941) the soils or soil properties obey the following expression:

$$\text{Soils or soil properties} = f(\text{PM, Cl, Re, Biol. Fac., Ti})$$

The factor time, of course, does not have a direct influence; however, the other factors affect the soil with the passage of time. Interactions may also occur (Fig. 2). In modern publications also **gravitation** and **water** are included in the soil-forming factors.

In section "The Tropical Environment and the Soil-Forming Factors" these soil-forming factors are introduced. In section "Processes of Soil Formation" there is a description of the processes of soil formation, and in section "Soil Horizons (After FAO 2006; WRB 2014)" the soil horizons, which represent the most important soil characteristics, are introduced, and in section "Reference Soil Groups and their Use in Forestry" individual soils, their properties, and suitability (including risks) for forest utilization are discussed. Finally a few recommendations regarding forest management are presented.

The Tropical Environment and the Soil-Forming Factors

Parent Material

Rocks, consolidated and unconsolidated, represent typical associations of minerals. They are, with the exception of organic soils (Histosols) and some man-made soils (s. Anthrosols and Technosols in sections "Anthrosols (AT)" and "Technosols (TC)") the inorganic parent material of soil formation. Their structural fabric, the mineralogical composition, and graininess influence to a large extent particle size distribution, the chemical properties of soils, as well as the intensity and effectiveness of other soil-forming processes. In the humid tropics, soil formation is often far advanced and soils may be many meters thick, especially on peneplains. Under these circumstances, the relationship between parent rock and soil properties is no longer clearly distinguishable, and the soil minerals mainly consist of highly stabile ones formed secondarily from weathering products. Young soils, which often are represented in mountainous areas, are generally clearly defined by the parent rock, and their minerals are strongly related with those of the parent material. Metamorphic rocks are generally more rapidly weathered than compact plutonites. Also highly stratified sediments are more rapidly altered than thick-bedded ones. From compact limestone, for instance, primarily shallow soils with high pH values derive, and breakdown of silicates occurs only after leaching of carbonates, whereas quartz-rich, loose sands are transformed into soils of low pH. Sandy soils are usually easily penetrated by roots. Because of the importance of the parent rocks and their mineral contents, their properties will be described in more detail. A distinction is made between igneous or magmatic rocks, sedimentary rocks, and metamorphic rocks. They consist of minerals, the solid, inorganic, homogeneous, and natural parts of the lithosphere. One further distinguishes between **primary minerals**, which originate during magma crystallization, and **secondary minerals**, which are weathering products. The most important group of the primary minerals is called silicates. They form the building blocks of the igneous rocks.

Igneous Rocks and Their Minerals

Chemically, the silicates are salts of silicic acids. They consist of two building blocks:

- The SiO_4 tetrahedra (Si^{4+} is in the center of the tetrahedron, surrounded by four O-ions)
- The Al(OH) octahedra (Al^{3+} is in the octahedron center, surrounded by six OH-ions)

Depending on the degree of interlinkages between the tetrahedra, one distinguishes between silicates that have island, chain, band, layer, or scaffold structures. Silicates with island structure consist of a loose arrangement of SiO_4 tetrahedra, connected via divalent cations (example: olivine $(Mg, Fe)_2SiO_4$). Silicates with a chain structure are derived from metasilicic acid $[(H_2SiO_3)_n]$ formed from SiO_4 tetrahedra by elimination of water and formation of oxygen bridges. An example is augite (pyroxene) with the formula $Ca(Mg, Fe)Si_2O_6$. The cohesion of the $(SiO_3)_n$ chains is due to Ca, Mg, and Fe ions.

Silicates with a band structure are formed when chains undergo the same reaction schemes, i.e., with the elimination of water and the formation of oxygen bridges. The silicic acid on which they are based on has the formula $H_6Si_4O_{11}$. Hornblende has a band structure [amphibole, e.g., $Ca_2(MgFe)_5Si_8O_{22}(OH)_2$]. The cohesion of the bands is again due to divalent cations.

If further condensation reactions occur (by H_2O elimination), silicates with layer structures are formed. They are based on a more condensed silicic acid with the formula $H_2Si_2O_5$. Typical representatives of these layered silicates are mica, biotite, and muscovite. Their crystal lattice consists, schematically seen, of layers, which themselves contain each two SiO_4tetrahedral sheets and one sandwiching Al $(OH)_6$-octahedral sheet. These three-sheet layers are held together by potassium ions arranged in the interlayer space. Since the K-ions can be released into the soil solution during weathering, mica-rich soils generally provide sufficient K for plant growth. Simultaneously, secondary minerals can also be formed from the weathering products. Under tropical conditions this is preferentially kaolinite, whereas in the middle latitudes it is illite. These examples demonstrate that both mineralogical as well as site-specific soil properties derive ultimately from the parent material.

SiO_4-tetrahedra can also form three-dimensional networks, which lead to silicates with a scaffold structure. Quartz (SiO_2) and feldspars are typical examples:

$$\left.\begin{array}{ll} Na(Al\,Si_3O_8) & \text{albite} \\ Ca(Al_2Si_2O_8) & \text{anorthite} \\ K(Al\,Si_3O_8) & \text{orthoclase} \end{array}\right\} \text{plagioclases}$$

Orthoclases as well as mica are the dominant sources of potassium.

Besides the silicates, other minerals like apatite, e.g., $Ca_3(PO_4)_2\,Ca(OH, F)_2$ and pyrit (FeS_2), are important because they represent the most significant mineral sources of phosphorus and sulfur. But strongly weathered tropical soils are often poor in apatite and thus P deficient, whereas stable minerals like zircon ($ZrSiO_4$) may accumulate.

After this short presentation of mainly primary silicates, the respective parent rock material will be considered. Depending on the site of magma solidification, the magmatic rocks are subdivided further into

- Plutonites (solidified slowly in deep geological strata, with coarse granitic structure; examples: granite, diorite, and gabbro)
- Volcanites (solidified rapidly after eruption on the earth surface, with porphyric or basaltic structure; examples: rhyolite, andesite, porphyrite, basalt, diabase)
- Intrusive or dyke rocks

The chemical and morphological properties of the plutonites vary considerably, as is seen in Table 1. Granite and rhyolite are Si-rich acid rocks, while gabbro and basalt belong to the calcium-and magnesium-rich basic rocks. Soils formed from gabbro and basalt contain therefore as a rule more Ca and Mg than those formed from granites or rhyolites. Igneous rocks are widely distributed in the tropics (Photo 3); they predominate in the Precambrian shields, the cratons, which form major morphostructural units of eastern South America, equatorial Africa, and central and southern India. These shields belong to the oldest cores of the continents which experienced periods of mountain building more than 600 million years ago, besides erosion and sedimentation. At present their topography is mainly undulating. Examples are the granites of the African basements and the basalts of Central America, Ethiopia, and the Indian Highlands.

Sedimentary Rocks and Their Minerals

Sediments arise through weathering of magmatic and metamorphic rocks and transportation and deposition of the weathering products. They may contain primary as well as secondary minerals. Typical secondary minerals are the carbonates, clay minerals, and sesquioxides. Based on the different mechanisms during genesis they are subdivided into classic, chemical, and biogenetic sediments (Table 2). Young sediments are the parent materials of soils in tropical alluvial plains comprising fluvial sedimentary basins (e.g., Congo basin, Amazon basin, the inundation zones of Nile, Ganges, Indus) and coastal plains (mangrove). Besides in alluvial plains sediments also occur on the Precambrian shields and frequently along the foot slopes of mountain areas (e.g., Kilimanjaro, young alpine fold belts). Especially fertile soils are derived from nutrient-enriched sediments. A lack of water limits the fertility of sandy soils developed from aeolian sediments in desert surroundings (e.g., Sahara). Tertiary sediments (e.g. limestone, gypsum, sandstone) are the parent material of soils, for instance, in Central Somalia or Yucatán (Photo 4).

Metamorphic Rocks and Their Minerals

When, in connection with tectonic processes, igneous rocks and sediments are transformed under high-pressure and high-temperature conditions metamorphic rocks are formed. Their structure is schistous and foliated, while sedimentary rocks are stratified. In the course of metamorphosis ortho-metamorphic rocks are formed from magmatites and para-metamorphic rocks from sediments. Typical minerals of metamorphic rocks are chlorite, serpentine, and disthen. Depending on the intensity of the metamorphosis, there is a subdivision into slate, phyllite, mica schists, and gneiss; also quartzite and marble are metamorphic rocks.

In the tropics metamorphic rocks are broadly distributed, for example, in the area of the Precambrian shields (e.g., African basement) and along the young alpine fold belts. Together with igneous rocks, they contribute about 25 % to the earth's surface, while sediments contribute about 75 % (Photo 5).

This short description of the petrographic/mineralogical principles clarifies the basic significance of the parent rock as the inorganic parent material for both the genetic and ecological properties of soils. Ca- and Mg- enriched rocks of similar

Table 1 Survey and composition of igneous rocks (Schroeder 1984)

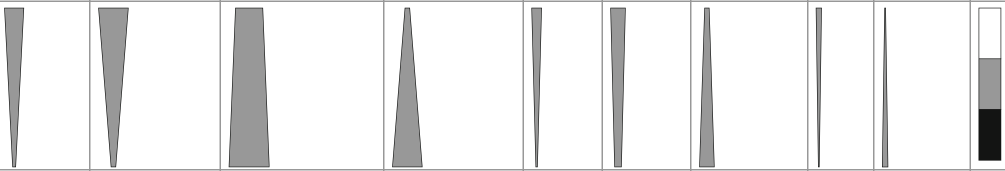
Plutonites	Vulcanites	Quartz	Orthoclase	Plagioclase + Anorthite	Augite + Hornblende	Mica	Si	Ca + Mg	K.	Spec. gravity	Color	Character
		%	%	%	%	%	%	%	%	%	%	%
Granite	Rhyolite	20–30	30–50	30–40	<1	5–8	30–35	2–8	4–6	~2.7	light	“acid”Si rich
Diorite	Andesite Porphyrite											
Gabbro	Basalt Diabase	<1	<1	50–60	45–60	<1	20–25	10–15	<1	~3.0	dark	“basic” Ca + Mg rich

Photo 3 The Siringiya Inselberg in Sri Lanka consists of igneous rock

granularity under comparable relief and water regimes weather in general more slowly than Si-enriched but Ca- and Mg- poor substrates. This is because the speed of soil formation is directly correlated to the buffer capacity against hydrogen ions. When H^+ activity is high, rock and mineral structures are quickly destroyed. High Ca and Mg contents, however, buffer the H-ions, thereby slowing the rate of soil development. At the same time they counter through antagonistic reactions. Al toxicity in many tropical soils influences negatively the vitality and productivity of economically important plant species. Even in the case where the surface soil horizons are already acidified, if there are Ca- and Mg-enriched layers in the subsoil, litter from deep-rooting woody plants may ensure the accumulation of basic cations such as Ca^{2+}, Mg^{2+}, K^+ and Na^+, in the topsoil. This phenomenon is called "cation pump effect." It comprises the accumulation of base ions in the subsoil by plant roots, their transportation and accumulation in the leaves, and after leaf fall their accumulation on the soil surface. This is one reason why forest destruction on such sites by stopping the "cation pump effect" has especially negative consequences on soil properties. On the other hand, there are many examples, specifically from the tropics, where afforestation of degraded sites has resulted in soil regeneration via the "cation pump effect."

The degree and intensity of soil development depend not only on the chemistry of the parent rock minerals but also on grain size and structural properties. Compact rocks weather more slowly than less compact rocks, even if they are of similar

Table 2 Properties of the main sediments (Schroeder 1984)

	Origin							
	Marine or limnetic		Fluvial or fluvioglacial		Landslide and solifluction		Glacial	Aeolian
	Unconsolidated	Consolidated	Unconsolidated	Consolidated	Unconsolidated	Consolidated		
Clastic	Clay Loam Marl Silt Sand	Clay shale Silty shale Sandstone	Loam Sand Gravel Pebbles stones	Sandstone conglomerate	Grit Rock fragments	Breccia	Boulder clay Boulder marl Boulder sand	Loess Sandy loess Dune sand Volcanicash Tuff
Chemical	$CaCO_3$ $CaMg(CO)_3$	Limestone Dolomite						
Biogenic	Calcareous shells and skeletons	Limestone	Marine and lake sediments regularly, river and glacial sediments irregularly stratified, glacial sediments unstratified and unsorted; aeolian sediments unstratified but sorted					
	Siliceous shells and skeletons Muds peats	Flint chert siliceous schist	Transformation of unconsolidated to consolidated sediment is called diagenesis (through dehydration, mechanical pressure, cementation by carbonates, Si, Fe, Al oxides and hydroxides, and clay minerals; followed by hardening)					

Photo 4 Tertiary limestone as parent material of soils. The soil on the surface of the limestone has already been eroded. The red soil pocket within the limestone documents karstphenomena (Yucatan)

mineralogical composition. Porosity is of critical importance. Rocks with a coarse structure are preferentially weathered by physical action, while compact rocks with tight structures inhibit water penetration, and enhance surface runoff and erosion, which is contrary to soil development.

In the tropics old and strongly weathered soils are widely distributed. Because of this, the direct influence of the parent rock on soil formation and on ecological soil properties is not as distinctively visible as in the younger soils of the middle latitudes. In tropical soils, only the contents of heavy weatherable minerals point to a relationship with the parent material, while in young soils the mineral spectrum is similar to, or strongly resembles, that of the parent rock. Such young soils are present in tropical mountain areas or in river inundation zones. Old, deeply weathered soils dominate on geomorphologically rather stable peneplains. They do not, or only mildly, exhibit "**petrovariance**" but, in contrast, "**climate variance,**" if they are located in different climatic zones.

Detailed studies in many tropical regions have shown that tropical soils often are not derived from the rocks underlying them but instead from deposited soil sediments, sand accumulations, or sheets of slope debris. They therefore exhibit

Photo 5 Metamorphic rocks are besides igneous rocks and sediments important parent materials for soil formation. For instance, the Precambrian Basement of the African Continent mainly consists of metamorphic rocks like gneiss and schists

stratification (Photo 6). This is explicitly demonstrated by the so-called **stonelines** that may be formed by termite action or by accelerated erosion (Photo 7).

Radiocarbon analyses of buried organic matter indicate the latter to be the dominant process and furthermore that stonelines can be related to young Quaternary variations in climate. At about 30,000–25,000 years BP, increased droughts led to a significant thinning of the forest vegetation in many parts of Africa, South America, and Asia. Due to interspersed strong rain showers of high intensity water erosion increased causing high soil losses, which, it is now believed, has contributed to the formation of stone lines. Today there are **cover layers** on the stonelines consisting of fine-textured materials called hillwash, which are the parent materials of the recent soils. If these upper layers contain large amounts of material from the deeper layers, because of bioturbation (termites), the differences between the recent soils and the deeper-lying substrate are small. Often, however, the upper layers contain drifted or washed-in foreign material, and in such situations recent soils are significantly different from the underlying subsoils. It may then be difficult to prove the relationships between the genetic and ecological properties of the soils and those of the parent rock. In summary, tropical soils derived from old and morphologically stable landscapes often no longer clearly reveal the relationship to the parent rock, because of their own advanced age. Only in young soils in regions that are morphologically highly active are such connections between the lithogenic and

Photo 6 Cover sediments over saprolite (Manaus, Brazil)

Photo 7 Stonelines (watershed Nile/Congo, Rwanda)

pedogenic/ecological properties unambiguous. Since the parent material is only one factor that determinates pedogenesis and soil fertility, the following sections discuss the influence of climate, gravitation and relief, biotic factors, water, and time on soil properties.

Climate

In the preceding section it was indicated that the influence of climate on soil development may often be greater than that of the parent material, or that of other factors. This becomes especially significant if one considers the zonal distribution of definite soil groups and their dependence on climatic factors.

The most important factors are **temperature** (heat energy), **precipitation** (water), and **wind.** Their influence may be either direct on the parent material and soils or indirect, by way of the vegetation. It is well known that the higher temperatures of the tropics speed up numerous chemical, physical, and biological processes, such as litter breakdown or chemical weathering. Via the vegetation, temperature also influences litter production; but despite higher biomass production in the humid tropics, their soils have generally lower SOM stocks than soils of cooler climates where litter decomposition is less advanced. The deep weathering of rocks and soils in the humid tropics is, however, not only a consequence of higher temperatures but is also a function of time, if periods of morphological stability last long enough to make possible intensive pedogenesis. The balance between incoming and outgoing radiation influences the extent and intensity of temperature-dependent pedogenic processes directly as well as indirectly through **evapotranspiration. Frost** and frost-related soil-forming processes like cryoturbation are only of relevance in tropical high mountain ecosystems (e.g., Kilimanjaro, Andes).

Pedogenesis as well as soil fertility strongly depend on the amount of **precipitation** arriving at the soil surface and percolating into the soil profile or causing erosion due to runoff. Parts of the water penetrating into the solum will be stored in pores with diameters of 0.2–10 μm, available for plants. In coarser pores water will percolate into deeper layers accelerating pedogenesis e.g., by removing soluble compounds by leaching. If the saturation deficit of the air is high, as occurs often in the arid and semiarid regions, soil water no longer percolates through the soil by gravitation but begins to ascend. The result is that weathering products can no longer be leached out of the soil profile but will accumulate in its upper parts due to a**scendance**, where they may form crusts and salt deposits. In humid regions, **descendence** dominates soil water movement, because of frequent precipitation. The leaching of weathering products depends on their solubility. This explains why highly weathered soils of the humid tropics are enriched, for instance, with hardly soluble Fe and Al compounds. If this enrichment occurs because of the preferred removal of more soluble substances (e.g., silicates) a **relative or residual enrichment** takes place. If iron and aluminum are additionally enriched by laterally moving or ascending water, this is called **absolute enrichment** (see section "Ferralization and Plinthization", page 62).

Besides temperature and precipitation, **wind** influences many soil properties. Of importance are both deflation and accumulation, the latter one, e.g., by the formation of cover sediments. The effects of wind depend to a great extent on the roughness of the vegetation cover, as well as on the intensity by which soils are formed. A typical example of wind-dependent soil accumulation is represented by the West African Harmattan. According to Mc Tainish and Walker (1982) and Wilke et al. (1984), the deposition rates of Harmattan winds reach up to about 1.8 $Mgha^{-1}$ during one season in Northern West Africa and Nigeria. Since this wind-borne dust is relatively rich in phosphorus, potassium, calcium, and magnesium, the traditional meaning that a strong Harmattan means a good harvest finds its explanation. Dust from the Sahara is even transported to the Amazon forests (up to 40 million tons annually according to Koren et al. 2006) and the Caribbean islands (Muhs and Budhan 2009), significantly influencing soil fertility.

At present much discussion focuses on the effects of **actual climate change,** for instance, on biodiversity, global food supply, and sustainability (IPCC 2014). Most likely, mean annual temperature in regions near the equator might increase up to more than 3 °C till 2100 (in comparison to 1980–1999), drastically reducing biodiversity, influencing atmospheric circulation systems, etc. At the same time sea level is assumed to increase up to ca. 50–100 cm, strongly destroying the mangrove belt. There is no doubt that land use practices in tropical regions like fire clearing of forests significantly contribute to the global CO_2 increase (up to 10–20 % according to IPCC 2014). FAO (2007) reports that per year about 120 000 km^2 of tropical rainforests are destroyed and in Africa more than 1 % of the forests (Achard et al. 2002), mainly by direct human activities but in addition by climate change. Such events also influence soils and their fertility. For Africa the prognosis is that till 2080 desertification will increase by 5–8 % destroying 60–90 million ha of arable soils (WBGU 2008). We come back to this item when describing the processes of soil formation (section “Processes of Soil Formation”).

Climate as a major soil-forming factor was already fluctuating during former geological times. Well documented are periods of aridity during the Quaternary, strongly changing the vegetation cover, soil-forming processes, and the morphological stability (Tricart 1974). Suitable archives for the reconstruction of such paleoclimatic fluctuations are cover sediments often revealing paleosols (Faust 1991; Emmerich 1997).

Various equations have been developed to quantify the influence of climate on soil development. Seen in the light of soil genesis and ecology, the humidity of the soil is crucial. It can be calculated in a simplified manner as follows:

$$\text{Soil humidity} = (\text{precipitation} - \text{surface runoff}) - \text{actual evapotranspiration}$$

According to Lang (1915), the rain factor is developed from the mean annual precipitation divided by the mean temperature of the frost-free period. Also Thornwaite (1931) and Fränzle (1965) tried to correlate climatic factors with soil properties. Such calculations allow usually only for rough approximations and give less information on seasonal or periodic fluctuations.

In summary, temperature and precipitation considerably influence the soil processes, because of their direct effect on soil temperature and soil water regimes. At the same time they also influence plant growth. Temperature and precipitation allow the distinction between different climatic zones. From the standpoint of soil science, a first approximation as to the boundaries of the different climatic zones on the basis of mean monthly temperatures is sufficient. In the **tropics**, mean monthly temperatures always exceed 18 °C. Areas with a period of mean monthly temperatures of less than 18 °C but with the mean temperature of all the months being greater than 5 °C are designated as the **subtropics**. They can be further subdivided into subtropics with winter rainfall, and arid subtropics, humid subtropics with rainfall maxima during the summertime, and arid subtropics.

In this contribution the tropical climates are divided into

Arid and semiarid tropics with

– 0–180 plant growing days/year
– Up to 800 mm mean annual precipitation
– Less than 6 humid months

Subhumid tropics with

– 180–270 plant growing days/year
– Between ca. 800 and 1,500 mm mean annual precipitation
– 6–9.5 humid months

Humid tropics with

– More than 270 plant growing days/year
– More than 1,500 mm mean annual precipitation
– 10 or more humid months

Detailed information on the climatological characteristics of the tropics is found in chapter "► Climate Aspects of the Tropics" of this Handbook. The distribution of arid to humid environments in sub-Saharan Africa is shown in Fig. 3.

Gravitation and Relief

Besides the macroclimate, the so-called microclimate very often plays a significant role in genetic and ecological soil processes. It depends mainly on topographic features like **altitude, exposure**, and **inclination**.

In mountain regions, the typical parameters for tropical climates (namely, the 18 °C mean monthly temperatures, as defined in section "Climate") no longer are relevant above 1,500 m a.s.l. Despite this fact, these highlands are defined as tropical, because they have, like the tropical lowlands, high radiation intensities

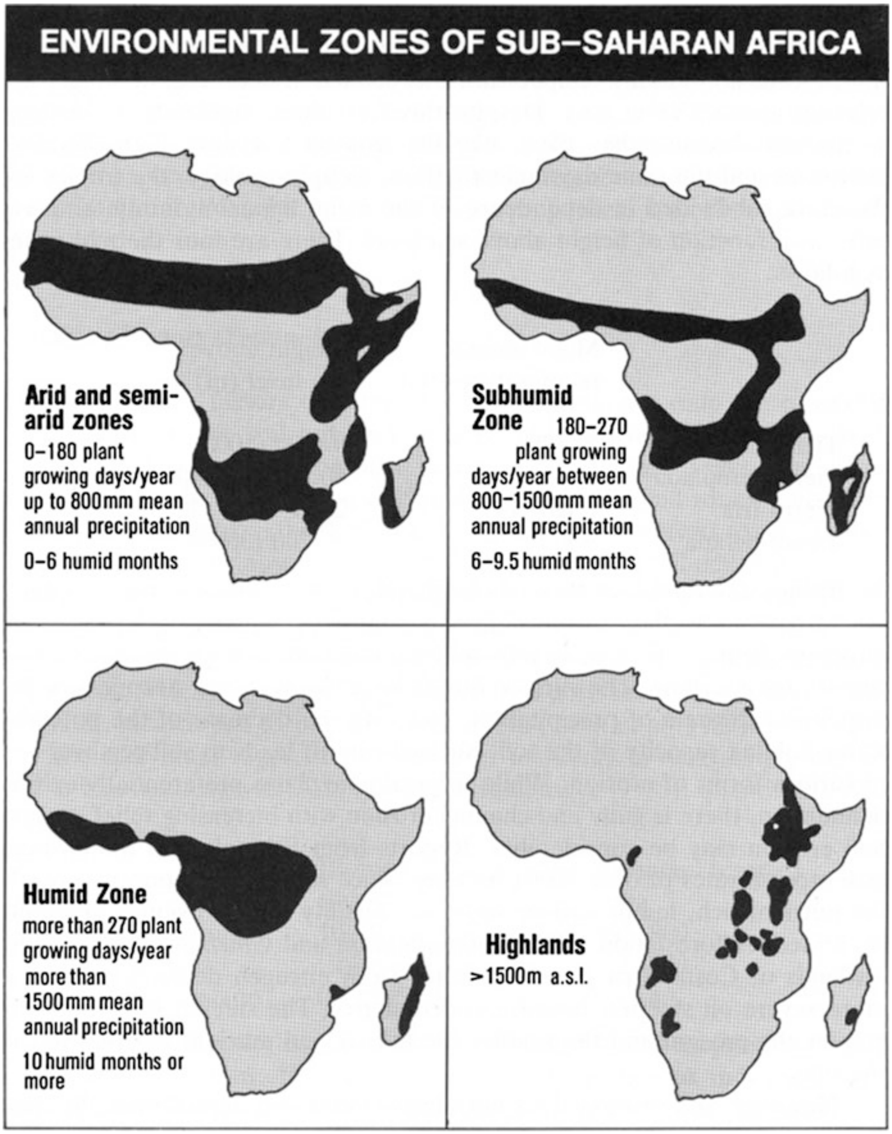


Fig. 3 Environmental zones of sub-Saharan Africa (Zech 1993)

and the same day/night rhythms. In agroecology, the tropics are therefore subdivided in dependence of the mean annual/monthly temperatures as a function of height above sea level. Along the east exposed slopes of the Andes, e.g., in Ecuador, five thermal zones can be distinguished as follows (see Fig. 4):

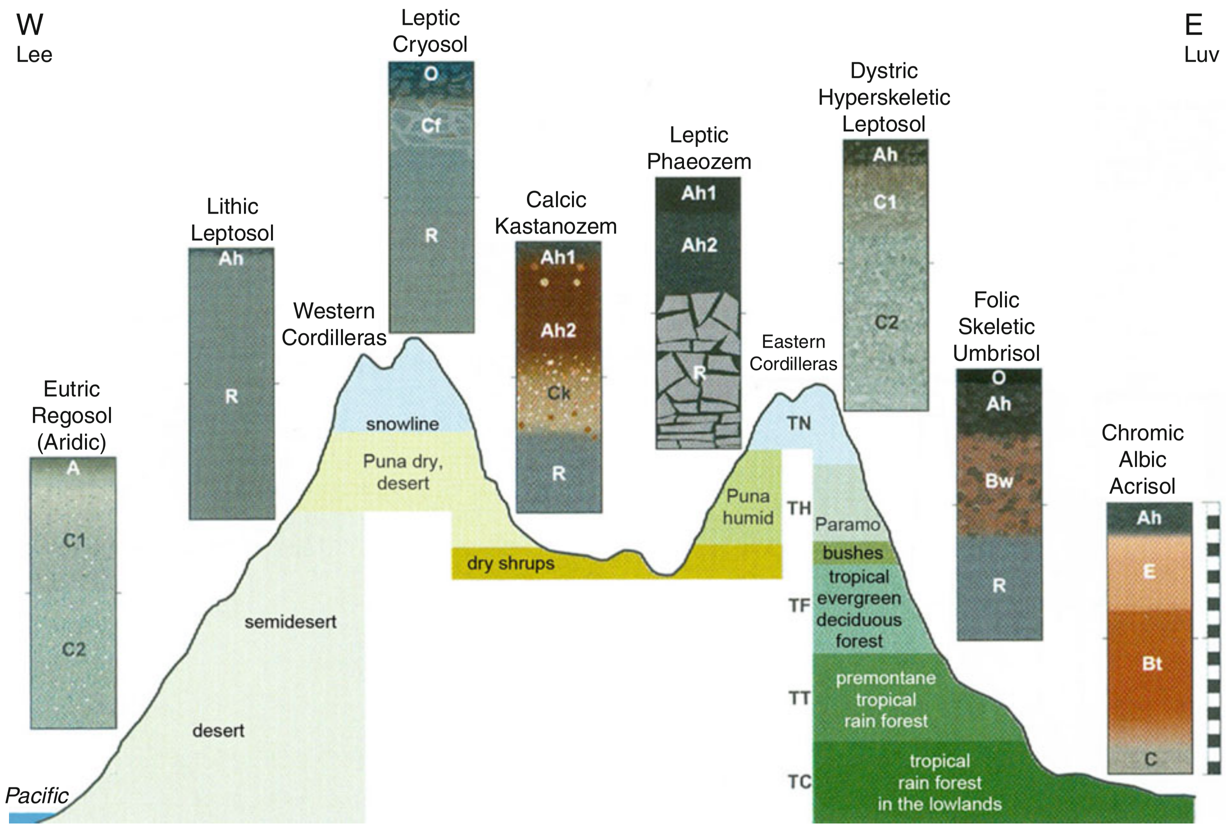


Fig. 4 West–east transect through the Andes in Ecuador demonstrating the dependence of soils and vegetation as a function of altitude and exposition (Zech et al. 2014)

	Mean annual temperature (°C)	Height above sea level (m)	Representative vegetation
Tierra nevada	~0	>4,400–4,500	Pioneer vegetation
Tierra helada	<7	3,200–4,400 (4,500)	Páramo, puna, dwarf shrubs
Tierra fria	7(10)–14	2,100–3,200 (3,600)	Evergreen deciduous forest, cloud forest (Ceja), *Polylepis*, *Erica* sp., timberline
Tierra templada	14–22	800–2,100 (2,400)	Premontane tropical rainforest (Yungas)
Tierra caliente	22–28	0–800 (1,000)	Tropical rainforest

In contrast to flat areas, where water and dissolved substances move preferentially in a vertical direction through the coarse soil pores, in hilly and mountainous terrain there is **surface runoff** and **interflow**, all partly controlled by **gravitation**. Surface runoff increases with the steepness of the slopes and the rate of precipitation and with the decrease of the potential water-holding capacity of the soil. Surface runoff leads to soil removal and to various forms of **erosion** along the upper and middle slopes and to colluvial deposits locally with buried soils in lower slope and concave positions; in valleys alluvial sediments are deposited. While tropical peneplains preferentially exhibit **denudation**, there is gully and channel erosion with increasing relief energy. Soil erosion may be considerable. Reports from Ethiopia and Madagascar give erosion rates of over 1,000 Mg ha^{-1} $year^{-1}$ mainly induced by deforestation, overgrazing, and cropping. Since soil erosion concerns mostly the nutrient-rich, humic surface soils, soil fertility after erosion is generally decreased. Plantations with *Cordia alliodora* and *Gmelina arborea* in the hilly lowlands of Costa Rica often suffer from nitrogen deficiency which is more severe on steeper, heavily eroded slopes. The steeper the slope, the greater the erosion and the smaller the humus and nutrient reserves left in the soils.

However, soil erosion does not always mean soil degradation, because erosion may induce soil **rejuvenation**. Soils of the humid tropics are often weathered very intensively, and are therefore poor in nutrient-rich, primary minerals, for example, apatite. If, in connection with soil removal, mineral-rich layers become exposed, trees planted on respective sites may be better supplied with nutrients. In contrast to altitude and inclination, differences in exposition have less impact in the tropics, because of the generally high position of the sun. Many soils, however, testify to the influence that topography has on soil properties. Concave sites generally have higher humus and nutrient reserves, as well as a higher content of plant available water, than do convex ridges or hilltops. It is well known that in depressions and along rivers surplus water can give rise to hydromorphic soils. Their use in forestry is often difficult, and only adapted tree species are able to survive.

Reports from regions in semiarid East Africa describe soil associations that are directly dependent on relief: in the depressions, black, clay-enriched substrates occur with deep dry fissures during the dry periods, but on slopes and hilltops, red loamy clays dominate. Such neighboring soils on identical parent material, but with relief-dependent properties, are called **soil catena** (Milne 1936; Birkeland 1999). Figure 5 informs about a soil catena in southern Ethiopia comprising lowland savanna, the subhumid afromontane forest, the ericaceous belt, and the alpine meadows.

Water

Soils may be influenced by **rain water**, **ground water,** or **stagnant water** existing only during rainy periods in upper parts of the soil profiles. In valleys alluvial soils will be influenced by **running river waters**, partly eroding soils, partly accumulating fresh mineral material, and thus affecting soil formation. Subhydrical soils in lakes are influenced by mostly calm **lake waters**, and in the mangrove belts soils are in contact with **coastal waters** rich in sodium chloride and magnesium salts. A high water table strongly influences the vegetation cover and litter decomposition. Long-lasting periods with anaerobic conditions in surface soil layers or under subhydrical site conditions impede the microbial decomposition of organic matter, thus promoting moor formation. Soluble substances in ground and stagnant water may precipitate and accumulate if they come in contact with oxygen. An example from the humid tropics and savannas is the enrichment of sesquoxides in Plinthosols (see page 71, section "Plinthosols (PT)"). Soils of arid zones are frequently enriched in carbonates, sodium chloride, and gypsum due to capillary rise (see section page 93, "Representative Soils of the Semi-Arid and Arid Tropics").

Biotic Factors (Fauna, Flora)

The soil-forming factors described so far influence not only the processes taking place in the soil but, importantly, also the fauna and flora; their living amount in a soil is called **edaphon**. Well known are the interrelationships between climate and vegetation, as is manifested by the overlapping of climate and vegetational zones. The latter vary in the tropics from the dense, species-enriched rainforests to the deserts, characterized by the absence of vegetation. Critical for soil development are the quantities and the biochemical composition (e.g., lignin, sugars, proteins) of both aboveground and belowground (roots) litter, varying according to the plant community, climate, and also soil properties. Litter can be considered as the main source of the soil organic matter. As time passes, litter is transformed under the influence of animals and microbes into humic substances, which are comparatively poorer in polysaccharides but richer in aromatic, recalcitrant carboxylated structures than the organic parent material (Zech et al. 1989).

The individual vegetation zones differ markedly in biomass production and in biomass reserves. According to Straβburger (1983), quantities are as follows:

	Biomass production (Mg/ha/year)	Biomass reserves (Mg/ha)
Tropical rainforest	10–35	60–800
Grass savanna	2–20	2–150
Sahelian grassland	0.1–2.5	1–40

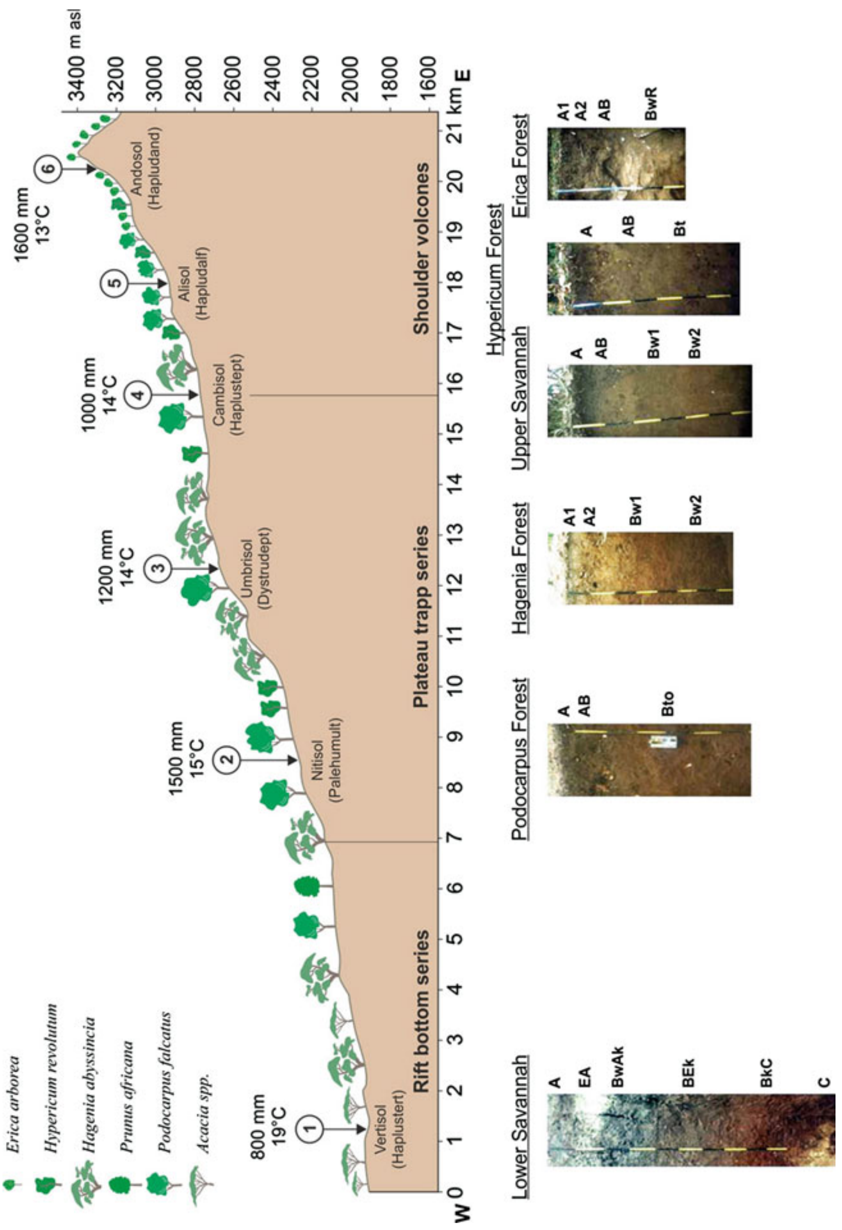


Fig. 5 Relief-dependent geoecological features along a catena in southern Ethiopia (Fritzsche et al. 2007, modified)

The rate of transformation of litter into humus can be assessed according to the **type of humus**. Big organic deposits of **raw humus** or **peat** indicate a slow decomposition of litter, while **mull** points to a quick transformation. For deep, strongly weathered tropical soils with a dominance of sorption-weak clays, the humus body is critically important to site quality. Under these conditions the nutrients are preferentially stored in the humus. Its destruction, as it may occur in connection with forest clearing, leads relatively fast to impoverishment and acidification of the soil. Vegetation, especially deep-rooting trees, serves not only as a "nutrient pump" due to the enrichment of surface soil layers with litter bond nutrients but also as a "water pump," because transpiration as well as interception lessen the quantity of percolating water and the concomitant displacement processes in the soil. Segregation of organic acids by roots and microorganisms is known to contribute to chemical weathering. In addition, the vegetation cover may significantly reduce wind and water erosion. The soil fauna acts in comparable fashion. Soil animals like **earthworms** generally produce more stable aggregates (especially the big ones which may be up to 3 m long) thus counteracting erosion (Guggenberger et al. 2001; Lavelle and Martin 1992; Photo 8 and 9).

The establishment of improved pastures with deep-rooting grasses (*Brachiaria decumbens*) and legumes (*Pueraria phaseoloides*) in combination with the application of phosphorus fertilizer and lime has drastically increased the earthworm biomass (up to 510 kg ha^{-1}) of savanna soils in the llanos of Colombia (Guggenberger et al. 1995). Simultaneously biological activity and nutrient availability increased. Earthworm cast may contain twice more SOM than the surrounding soil. Through the bioturbative action of earthworms, termites, and ants, significant amounts of fine earth are transported to the soil surface and into the soil, degrading the differentiation of soil horizons; at the same time SOM can be incorporated into the solum. To sum up, **humification, bioturbation,** and **formation of stable aggregates** are main soil-forming processes affected by soil fauna and flora.

Photo 8 Earthworm cast on the surface of Acrisols documenting increased bioturbation after application of phosphorus fertilizer and lime (Llanos, Colombia)

Photo 9 Mangrove soils frequently exhibit high bioturbation (Sri Lanka)

Human Activity

High population growth rates, together with increased human demands, have had, and are currently having, highly negative consequences on tropical soils. This will be illustrated on hand of several examples. The first is a consideration of the phenomenon of **deforestation**. Tropical forests grow in large part on kaolinitic, deeply weathered soils with very low contents of weatherable, primary minerals. Clearing, either in connection with wood exploitation or for agriculture (field, grassland, plantation), goes hand in hand with the loss of humus and increased mineralization of the organic fractions of C, N, S, and P. According to Popp et al. (2014) about 1/10 of the anthropogenic greeenhouse gas emissions are generated due to the conversion of tropical forests into agricultural land. Simultaneously cations like K^+, Mg^{2+}, Ca^{2+}, and NH_4^+ are leached. This was clearly demonstrated by an experiment of Parker (1985) studying the electrical conductivity, an index of ionic concentration in soil water, in a premontane rainforest of Costa Rica before and after tree cutting. Electrical conductivity was highest after cutting 2,500 m^2 in comparison to cuts of 500 m^2. Single tree gaps, often used for enrichment planting with valuable tree species, did not differ from the undisturbed control plots (Fig. 6). Figure 7 informs in more detail about the effects of tree cutting and burning on the leaching of nutrients in the Amazon lowlands of Venezuela. Frequently deforestation of tropical soils also leads to the deterioration of the soil structure and to a significant decline of the microbial biomass and microbial activity (Sahani and Behera 2001; Basu and Behera 1993).

In addition, forest burning contributes to the increase of CO_2 in the atmosphere, promoting climate change. Heavy rains result in the loss of the topsoil in slope position after deforestation and from ploughed lands through **accelerated erosion**. Especially ploughing destroys the original surface soil structure producing an artificially mixed Ap horizon, being well aerated, having higher SOM mineralization rates, and reduced aggregate stability. The consequences of accelerated erosion

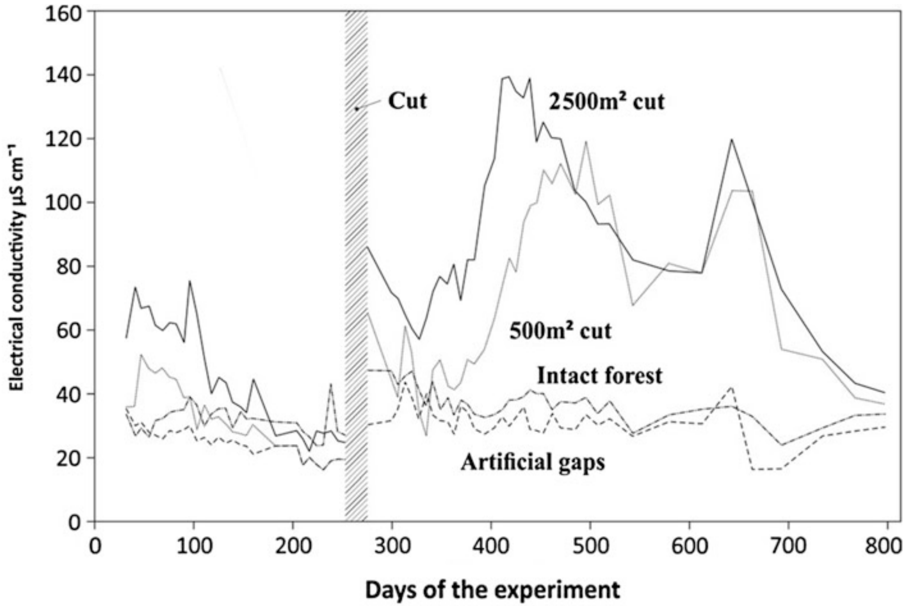


Fig. 6 Electrical conductivity, as an index of the ionic concentration in soil water, before and after clearing 2.500 m^2, 500 m^2 and gaps in a premontane rainforest of Costa Rica (Parker 1985)

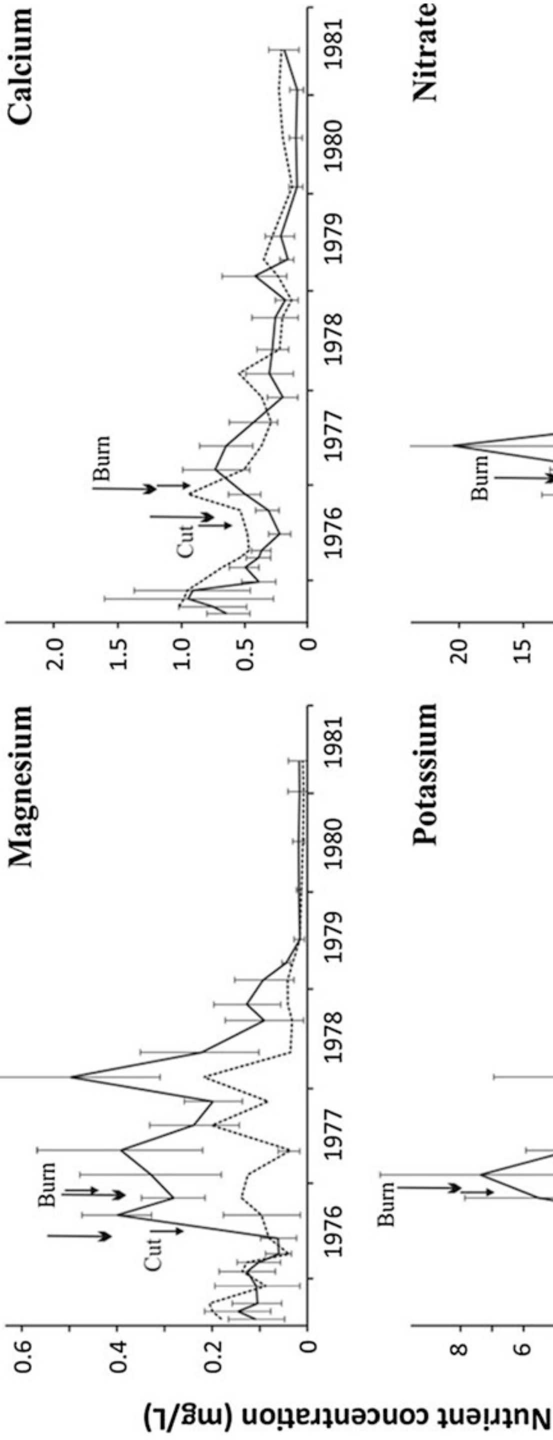


Fig. 7 Concentration of Mg-, Ca-, K-, and NO_3-ions in the soil water after tree cutting and burning (Uhl and Jordan 1984)

are quickly decreasing soil fertility, crust formation on soil surfaces, accumulation of colluvial sediments in lower slope position and in valleys, and inundation in the lowlands. Large-scale destruction of watershed forests results in the deterioration of streamflow regulation with decrease of dry-season flows and flood flows during the rainy season (Bonell and Bruijnzeel 2005). In advanced stages of soil destruction the whole solum can be removed, and even pioneer tree species cannot take a foothold; the result is a type of "savannization." Yet secondary forests are the guarantee for soil regeneration. "**Shifting cultivation**," practiced successfully for a very long time, is based on this principle: firstly, the clearing by fire, followed by about 2 years of agricultural utilization, then regeneration through at least 15–20 years of secondary forest growth. According to Bruijzeel (1998), reviewing the soil hydrochemical changes accompanying tropical forest disturbances of different intensity, even 30–60 years are necessary for complete replenishment of lost nutrients via mineral weathering and inputs by rainfall. Because of population pressure, the needed forest reserves for soil regeneration are more and more lacking, so that shifting cultivation occurs with shorter and shorter regeneration intervals, which finally leads to the exhaustion of the soil. An alternative to shifting cultivation might be **agroforestry.** Schroth and Sinclair (2003) discussed the value and utility of different methods available for evaluating soil fertility development under agroforestry.

Due to the generally low nutrient supply of many tropical soils intensive agriculture and plantation forestry with fast-growing tree species are often only sustainable if **mineral fertilizers** are applied. Mostly deficient is phosphorus and nitrogen; on sandy quartz-rich soils also potassium and magnesium stocks may be restricted. The application of lime increases microbial activity and pH and diminishes acidification and aluminum toxicity. Monocultures are susceptible to pests, and biocides must be applied frequently. **Drainage** of hydromorphic soils supports aeration and stimulates SOM mineralization. Mangrove soils experience drastic acidification after drainage. Irrigation can evoke hydromorphic features like in paddy rice soils. Soils of heavily urbanized and industrialized regions experience high inputs of organic and inorganic pollutants often accumulating in the SOM. Construction of roads, buildings, and mining correlate on the one hand with the removal of soils and sediments, on the other hand with their accumulation elsewhere. One must distinguish between the accumulation of natural substances and artificial ones like demolition waste, furnace slag, ash, and garbage. Soils developing from natural substances are classified as **Anthrosols** (see page 156, section "Anthrosols (AT)"); those developing from artificial materials are classified as **Technosols** (see page 159, section "Technosols"), sometimes used for afforestation and grazing.

In the arid and semiarid tropics, human activity leads additionally to long-term changes in the pedosphere. Many of the numerous examples of failed **irrigation** projects can be included here. Even by using low-salt river water, the accumulation of salt and the development of saline soils occur, if the principles of desalting are not obeyed. In the semiarid Sahel region, for example, especially in areas surrounding wells that were dug 40–50 years ago, **overgrazing** has now led to the catastrophic destruction of vegetation and soil. The wells allowed the nomadic herdsmen to increase the numbers of grazing animals, with the result that the capacity of these fragile ecosystems was exceeded. When years with low precipitation are added, the vegetation and the soils at a large circumference round wells and settlements are destroyed. Erosion by wind and water is further increased and has the advancement of **desertification** as a consequence.

Finally, **terracing of slopes** has to be mentioned, since it always leads to great soil changes. Examples can be found in the Andes of South America, where during early high cultures large areas were terraced. But even in Africa, in the region of Jebel Marra (Sudan), and in Southeast Asia, there are large terrace systems. In Asia they are widely utilized for rice cultivation.

From these examples, the human influence on soils and soil properties becomes evident. Regarding changes in climate due to the greenhouse effect and the destruction of the ozone layer, it seems as yet too early to satisfactorily quantify their consequences. Soil development, either current or future, is therefore a function of the quantitative and qualitative expression of the soil-forming factors. Their effects occur over time, the reason why Jenny (1941) included time as one of the soil-forming factors.

Time

In the course of time soils tend to be in equilibrium with the environmental conditions. At this time one speaks of a **ripe soil** or a **climax soil**. The forming from an initial soil toward a ripe soil can be studied along **soil chronosequences** including soils of different age developed under comparable environmental conditions. Changes in the spectrum of influencing factors result in changes of soil development. This is especially the case if there are changes in climate or an increase or decrease in human activity. Such changes lead to **polycyclic** or **polygenetic soils**. Typical examples are Plinthosols and Ferralsols (sections "Plinthosols (PT)" and "Ferralsols (FR)"); also the soils below the stonelines mentioned in section "Parent Material" are a result of polycyclic genesis. Such soils may be much older than 20 ka. If they developed during the Pleistocene, Tertiary, or even before, they are classified as **paleosols**. Sometimes the numeric age of such soils formed during the younger Quaternary can be quantified by radiocarbon analyses or by optically stimulated luminescence (Frechen et al. 2009). Soils which developed during the more dry Wisconsin ice age under grass savanna, but at present are covered by trees, reveal significant shifts in their $\delta^{13}C$ values (Schwartz et al. 1986). **Fossil soils** are paleosols covered by younger sediments; without such a blanket of fresh deposits the paleofeatures will be changed by recent soil-forming processes (= relict soils). Paleosols are widely distributed in the tropics and may be many decameters thick, whereas most soils in the midlatitudes are only 1–2 m thick and developed during the last 10–12 ka. It would, however, be a mistake to assume that there are only polycyclic soils in the tropics. Where erosion washes away old soil covers, and where sedimentation occurs due to morphodynamic instability, like in hilly and mountainous areas, along coasts, and in river valleys, young, recent soils may also be formed, e.g., Leptosols, Regosols, and Cambisols (sections "Leptosols (LP)," "Regosols (RC)," "Cambisols (CM)," "Podzols (PZ)," "Luvisols (LV)," and "Umbrisols (UM)"). Also Anthrosols and Technosols (sections "Anthrosols (AT)" and "Technosols") belong to the young soils. These age in the humid tropics relatively quickly, since the high temperatures lead to rapid weathering with subsequent leaching of the weathering products. In the arid tropics, in contrast, soils age more slowly despite the high temperatures. Soil humidity is lacking, and any weathering products formed are not subjected to leaching.

In summary, compared to the middle or higher latitudes, the tropics often have a specific constellation of the soil-forming factors, such as high temperatures, at times heavy precipitations, high insolation-dependent energy inputs, and more. They govern the physical, chemical, and biological processes occurring in the pedosphere which will be described now in section "Processes of Soil Formation."

Processes of Soil Formation

Soils generally differ in their properties, for instance, in color, grain size, structure, etc., allowing to distinguish between layers having characteristic features, called **soil horizons**. They reflect the soil-forming processes, and their sequence along a vertical cut through the pedosphere (= soil profile) is crucial for soil classification. Due to the specific constellation of the environmental factors in the tropics (see section "The Tropical Environment and the Soil-Forming Factors)," tropical soils are frequently characterized by particular processes which, in turn, lead to the formation of special horizons. In the simplest terms, two fundamental processes can be distinguished:

– **Processes of transformation,** concerning the breakdown and synthesis of mineral and organic soil constituents and lead to the formation of typical soil compounds like secondary clay minerals and humic substances, as illustrated below:

	Mineral soil phase	Organic soil phase	Structure
Destruction/ decomposition	Weathering of the parent rocks and their minerals	Surface and subsurface litter decomposition	Segregation
Synthesis/ neoformation	Formation of secondary minerals and oxides/hydroxides	Humification	Aggregation

– **Processes of translocation**, conditioned by percolating, ascending, or laterally moving water, with the consequence of dislocation of soil components through mobilization, transport, and immobilization of salts, clay, humus, and sesquioxides. Translocation processes include also mixing and shifting/displacement phenomena (e.g., bioturbation) caused by burrowing soil animals, ploughing by humans, frost pressures, swelling and shrinking, as well as erosion and solifluction. First discussed will be weathering.

Weathering

Any environmental action that leads to the breakdown of rock and mineral structure is termed weathering. It can be either physical or chemical, depending on the processes involved.

Mechanical breakup of rocks can occur by various means. In the high mountains of the tropics, freeze-thaw conditions may be frequent. Cryoclasty results because water, when freezing, expands about 9 vol.%. The pressures exerted in fissures and gaps lead to the disintegration of rock and mineral structure. In contrast to polar and subpolar regions, where permafrost may penetrate to 300-400 m depth, frost in tropical mountains influences soils more superficially.

The **fluctuation of temperature** also destroys rock and mineral structure, because rock sections of different color or exposure absorb radiation to different degrees and expand or contract according to their specific expansion coefficients. Tensions are caused between light- and dark-colored rocks, shaded or irradiated parts, as well as rock surfaces and interiors. Weathering due to temperature fluctuations is not important in the humid tropics but plays an important role in the arid/semiarid and semihumid tropics, as well as in the tropical high mountains. In the dry regions there are large differences in temperature between day and night, which are accentuated by the lack of any prolonged dawn or dusk. In the semihumid tropics, when phases of high insolation and rock warm-up are followed by relatively cold rain showers, desquamation (the chipping away of thin rock fragments) is enhanced. But it is currently well known that weathering based only on temperature fluctuations is relatively ineffective. Only in the presence of water, either fluid or gaseous (steam), can temperature fluctuation effectively lead to the destruction of rock and mineral structures.

In the arid and semiarid tropics **salt burst** may occur, because of volume increases caused by the hydration of salts (Photo 10). **Root burst** has its origin in root growth and thickening (Photo 11).

Photo 10 Destruction of the rock structure due to salt burst (Death Sea, Israel)

Photo 11 Roots of *Cedrus libani*, growing on a Rendzic* Hyperskeletic* Leptosol, evoke mechanical breakup of the rocks by thickening and penetrating into cracks, thus increasing tree stability and supply with water and nutrients stored in the fine earth of the C horizon (Taurus, southern Anatolia)

The blasting of thick rock fragments documented, for example, on the lower slopes of inselbergs is partly connected with the pressure release after exposure.

During the course of **chemical weathering**, the minerals of the parent rock are partly or totally dissolved in the presence of water, hydrogen ions, carbon dioxide, and oxygen. Vegetation influences weathering in the rizosphere through root respiration (CO_2 production), H^+ release, organic acid excretion, and nutrient uptake. The surface litter also is of importance. The production of low molecular soluble organic compounds reacting with inorganic ions due to complexation contributes considerably to the acidification and impoverishment of the soil. A few examples follow:

Weathering induced **by dissolution of minerals** concerns above all gypsum and other salt-containing substrates. Their solubility is a function of water availability and temperature (at 20 °C: gypsum 2.6 g/l, sodium chloride 360 g/I). Generally the solubility of salts increases with temperature. Calcium carbonate is an exception (with CO_2 contents of 0.03 vol.%, 84 mg/l are dissolved at 0 °C but only 58 mg/l at 20 °C). Despite this fact, limestone is more quickly dissolved in the tropics than at higher latitudes, if high amounts of percolating water are at disposal and if the soil solution is rich in low molecular weight organic acids and carbonic acid. The former result from litter decay, the latter through the reaction of CO_2 and water. Acids of these types cause the so-called acidolysis (=acid-induced weathering). For calcium carbonate the reaction is as follows:

$$\underset{\text{less soluble}}{CaCO_3 + H_2CO_3} \rightleftharpoons \underset{\text{easily soluble}}{Ca(HCO_3)_2}$$

The easily soluble $Ca(HCO_3)_2$ will be washed out. Karst phenomena are formed this way (e.g., the tropical cockpit karst of Jamaica and the caves in Yucatan).

The hydrolytic dissolution (=hydrolysis) of salts occurs more slowly than acidolysis. It is based on the dissociation of water:

$$2H_2O \rightleftharpoons H_3O^+ + OH^-$$

Since increasing temperatures increase the dissociation of water, hydrolysis is more effective in the tropics than in the middle latitudes. The mechanism of the reaction is illustrated in a simplified way using orthoclase as an example:

$$KAlSi_3O_8 + HOH \rightarrow KOH + HAlSi_3O_8$$

$$HAlSi_3O_8 + 4HOH \rightarrow Al(OH)_3 \cdot 3H_2SiO_3$$

The end products KOH, $Al(OH)_3$, and H_2SiO_3 have different solubilities. KOH is rapidly washed out; silicic acid as well, since in the humid tropics its solubility increases with increasing temperatures. Because of this, there is in the course of geologic time spans a relative enrichment of Al compounds in the soils, while the Si contents decrease. Both breakdown products can react with each other as long as they are in a reactive form, thereby creating the so-called secondary minerals. This is the reason why, in contrast to the higher latitudes, these newly formed minerals in tropical soils are poorer in Si or even are devoid of it. Sections "Clay Formation" and "Formation of Oxides and Hydroxides" will discuss these events in more detail.

Weathering induced by oxidation is based on the oxidation of divalent Fe, S, and Mn ions by O_2 in the presence of water and microorganisms. The resulting ions have higher valences and different ion diameters, causing crystal lattice instability. The example of pyrite weathering shows that besides brown- and red-colored iron hydroxy-oxides, there are also acids produced which in turn enhance weathering because of acidification:

$$4FeS_2 + 15O_2 + 10H_2O \rightarrow 4FeOOH + 8H_2SO_4$$

For olivine the following is true:

$$4(Mg, Fe)SiO_4 + O_2 + 6H_2O + 4H_2CO_3 \rightarrow 4MgCO_3 + 4FeO(OH) + 4H_4SiO_4$$

In this case, weathering induced by oxidation occurs together with hydrolysis and acid attack.

Finally **weathering due to hydration** is mentioned. It is effective in the arid and humid tropics and is based on the accumulation of water dipoles in the vicinity of

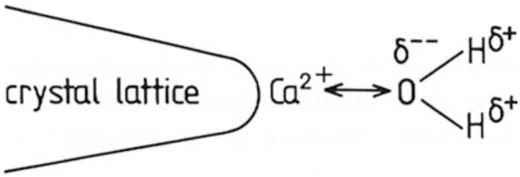


Fig. 8 Accumulation of water dipoles in vicinity of cations at the border of a crystal structure

cations at the border of crystal structures (Fig. 8) or on the incorporation of water into the crystal lattice (e.g., gypsum).

This leads to the loosening and dissolution of cations, which initiates the disintegration of the crystal lattice. In the arid tropics, hydration occurs despite low relative humidities, because the cool night temperatures lead to condensation (dew) and to the wetting of the rock surfaces.

Chemical weathering intensifies if the rocks are mechanically broken into smaller particles. In other words, the larger the particle surfaces and the lower the weathering stability of the minerals, the higher their chemical weatherability. High soil humidity and high temperatures chance weathering intensity.

This explains why in the humid tropics soil formation progresses with special intensity. The occasional presence of strongly weathered soils in arid regions indicates that climatic changes have occurred sometime in the past.

The intensive chemical weathering of many humid tropical soils is always connected with strong leaching of weathering products and concerns especially Si-compounds and cations like Ca^{2+}, Mg^{2+}, and K^{+}. Its consequences on clay formation are described below.

Clay Formation

Clay minerals are small, mostly submicroscopic secondary minerals, which originate during the weathering process. In the fullest sense of the word, the clay minerals include all secondary minerals with particle sizes below 2 μm.

Commonly, however, clay minerals are considered to be only those that contain Si and exhibit a typically layered structure of SiO_4 tetrahedra and Al(OH) octahedra (the so-called phyllosilicates or layer silicates). The structural arrangement of these two fundamental building blocks is shown in Fig. 9 and has already been introduced in section "Igneous Rocks and Their Minerals," during the discussion of the primary silicates with layered structures (mica).

Clay minerals, as understood in this narrow sense, originate either through transformation from primary silicates or through neoformation from end products of silicate weathering. Some of them possess considerable swelling capacities, i.e., they absorb water during humid periods and shrink during dryness. This results in the formation of special soil structures and aggregates. Clay minerals can also absorb nutrients (e.g., cations like K^{+}, NH_4^{+}) and protect them from leaching. They are, comparable to humic substances, of essential significance regarding soil properties and fertility.

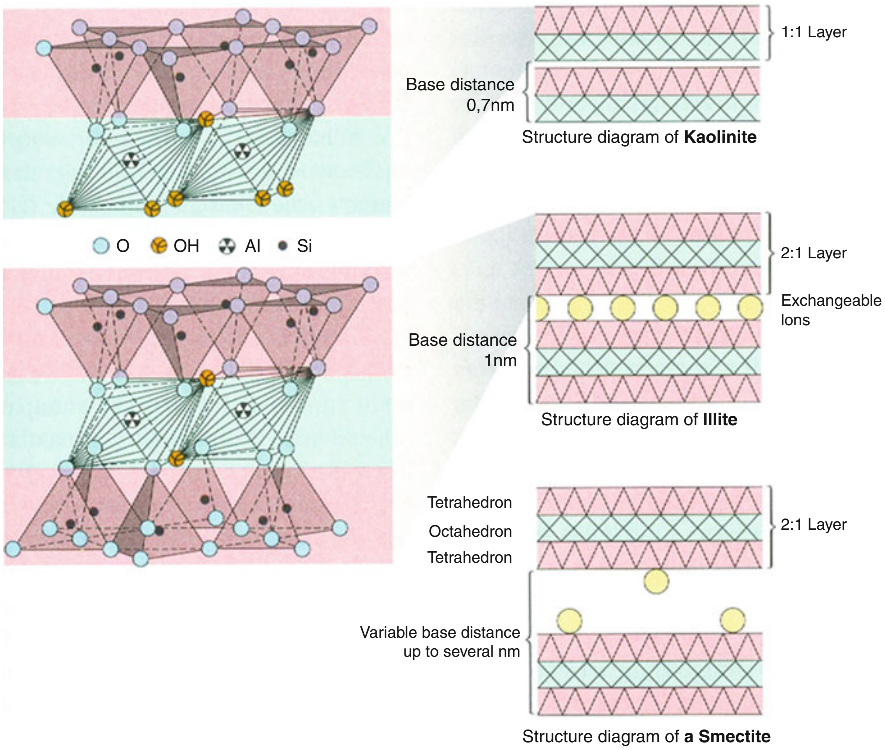


Fig. 9 Structural arrangement of SiO_4-tetrahedra and Al(OH)-octahedra in kaolinite, illite, and smectite (Eitel and Faust 2013)

Various factors influence the type and amount of the clay minerals being formed. They include the mineral compounds of the parent materials, the macro- and microclimatic situation, the pH, and the ion activities of the soil solution. Under the climatic conditions of the humid tropics, the intensive chemical weathering of basic rocks causes high washout rates of Ca, Mg, K, Na, and Si. The soils become enriched with Al and Fe compounds (see section "Weathering"). These conditions may even lead to the formation of Al and Fe deposits (e.g., bauxite). In the past, such Si-poor substrates were called **allites**. In the humid and semihumid tropics, if the soil solution contains enough Si in a reactive form, **kaolinites** are the dominant reaction products. Kaolinites are dimorphic or 1:1 clay minerals, consisting solely of 1 sheet of SiO_4-tetrahedra and 1 sheet of Al(OH)-octahedra. Both sheets are strongly connected through oxygen bridges, forming a so-called two-sheet layer mineral. The distance between the basis of the individual two-sheet layers (= basal spacing or d-spacing) is 0.7 nm. They are also strongly bonded because of hydrogen bonds between the OH-position of the Al- OH -octahedral sheet and the O-ions of the Si-O -tetrahedral sheet. An intercalation between the sheet layers is only exceptionally possible. Kaolinites therefore cannot expand and swell due to the absorption of water in the interlayer space. But urea is a compound that can be intercalated; the early Chinese ceramic industry was based on this secret.

Occasionally the Si^{4+}-ions in the tetrahedral centers may be replaced by Al^{3+}-ions. This phenomenon is called **isomorphous substitution**. It results in a negative charge surplus, which is the reason why kaolinites can exchangeably bind cations at their outer edges. However, the cation exchange capacity (CEC) of kaolinite is very low, only between 7 and 14 cmol(+) kg^{-1}. Kaolinite-enriched soils can therefore adsorb and make available to plants only small amounts of cationic nutrients, such as K^+, Ca^{2+}, Mg^{2+}, NH_4^+. This explains their relatively low fertility. For reasons of completeness, it is mentioned here that another clay mineral in tropical soils has a structure comparable to kaolinite. This is **halloysite**. Its basal spacing is 1.0 nm, because water is intercalated between the two-sheet layers. After heating and air-drying this water is lost and **metahalloysite** is formed with a base spacing of 0.7 nm.

In young soils derived from Si- and especially mica-enriched parent materials or in soils of lower slope position and depressions with accumulation of Si, trimorphic or 2:1 clay minerals may develop. Schematically they consist of a layer of Al(OH)-octahedra, which has reacted with two SiO_4-tetrahedron layers, by sandwiching and the elimination of water forming a three-sheet layer. The Si^{4+}-ions of the tetrahedral sheets as well as the Al^{3+}-ions of the octahedral sheets can be replaced during the formation of the clay minerals with ions of similar diameter (isomorphous substitution: Si^{4+} in the center of the tetrahedron replaced by Al^{3+} and Al^{3+} in the center of the oetahedron replaced by Fe^{2+} of Mg^{2+}). The resulting negative charges can be neutralized through sorption of cations inside or outside of the crystal lattice. If higher-valence ions are introduced into the center of the octahedron, the residual charges may also be positive.

In summary, the properties of important trimorphic clay minerals may be described as follows:

Illite:

- Basal spacing 1 nm (with Mg saturation),
- Relatively tight bonding of the three-sheet layers through K^+ in the interlayer space
- Isomorphous substitution in the centers of the tetrahedra and octahedra
- Cation exchange capacity about 30–40 cmol(+)/kg
- No intracrystalline swelling by water intercalation

Smeetite:

- Basal spacing 1.4 nm (with Mg^{2+} saturation) and 1.8 nm (with Mg^{2+} + glycerin)
- K^+ of the interlayer space replaced by other cations, especially by Ca^{2+} and Mg^{2+}
- Cohesion of the three-sheet layers poor and enlargement through hydration possible (intracrystalline swelling)

- Isomorphous substitution in octahedra, less in tetrahedra
- Cation exchange capacity about 80 cmol(+)/kg and higher
- By addition of K^+, contraction to 1 nm possible

Vermiculite:

- Mainly derived from biotite by oxidation of Fe^{2+} in the octahedron to Fe^{3+}
- Basal spacing 1.4 nm (with Mg^{2+} saturation)
- By addition of K^+, contraction to 1.0 nm and fixation of K^+
- High isomorphous substitution in tetrahedra
- Intracrystalline swelling less than in smectites
- Higher loading than smectites
- Cation exchange capacity about 100 cmol(+) kg^{-1} and higher

There are transitions between illites and smectites as well as vermiculites. They are formed by the successive displacement of K^+ from the interlayer space of the illites because of H^+ bombardments. This causes expanding of the illite lattices firstly at their wedges (=wedge expanded illite). With increasing K^+ loss, the expanding of entire sheet layers occurs, which results in the so-called expanded illite and interstratification of illite; finally vermiculites and smectites can develop. Interstratifications have been combined in the concept of transitional minerals.

The interlayer spaces of trimorphic clay minerals can be intercalated in addition with AlOH-, FeOH-, and MgOH-octahedra. In this fashion the tetramorphic clay (2:1:1) minerals like **secondary chlorites** are formed. Their principal properties are

- Basic distance 1.4 nm (with Mg^{2+} saturation)
- Strong bonding between the sheet layers based on electrostatic forces (tetrahedra are negatively charged, octahedra positively) and the formation of *H*-bonds between the OH-ions of the intercalated octahedral layer and the O-position of the tetrahedra
- No intracrystalline swelling
- Cation exchange capacity low [<40 cmol(+) kg^{-1}]

Finally, the **allophanes** will be shortly mentioned. They are preferentially formed during the alteration of volcanic glasses and are therefore a characteristic mineral of volcanic soils (Andosols, section "Andosols (AN)"). Until recently they were considered to be X-ray amorphous. At present it is known that they consist of tiny hollow spheres which are relatively rich in Al. Because of high isomorphous substitution and enrichment of AlOH-groups, their cation exchange capacity is relatively high. Since the CEC of AlOH-groups varies due to soil pH, allophanes possess a highly **variable charge**. In addition, allophane-rich soils with pH values below about 6.5 can adsorb anions like PO_4^{3-} well (anion exchange capacity). This explains the strong P-fixing capacity of these soils.

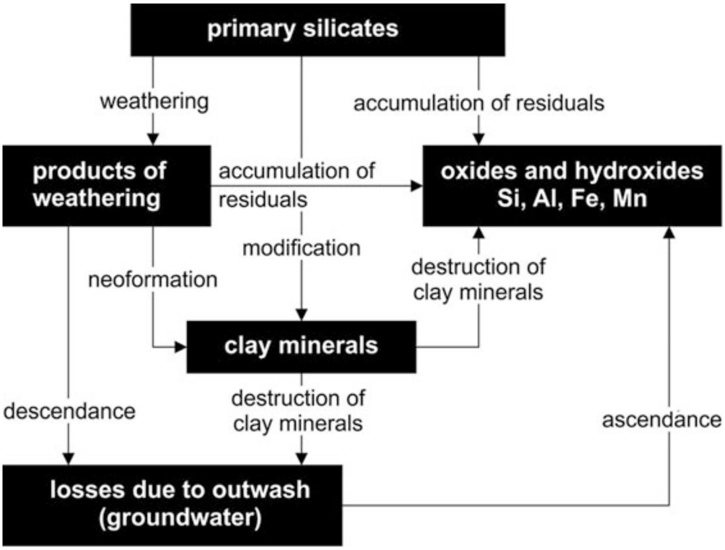


Fig. 10 Formation of clay minerals, oxides, and hydroxides during weathering of primary silicates

Formation of Oxides and Hydroxides

If not leached, the products formed during weathering are the starting materials for the synthesis of secondary minerals. Since weathering occurs usually more quickly than mineral neoformation, weathering products may accumulate, depending on their solubility and the soil water regime (Fig. 10).

This explains why the soils in the arid and semiarid tropics are often saline and enriched with secondary carbonates, gypsum, and SiO_2. In the humid tropics, in contrast, accumulation concerns mostly the (hydroxy)oxides of Fe, Al, Mn, Zr, and Ti. The formation and the properties of Fe and Al oxides and hydroxides (often termed "free oxides," because they no longer are part of the crystal lattice of silicates) will be described in more detail (Fig. 11).

If primary Fe-containing minerals (e.g., biotite, augite, hornblende, olivin) are weathered, Fe^{2+} and Fe^{3+} are fragmented from their crystral stucture and released into the soil solution mainly as $(Fe(H_2O)_6)^{3+}$. Rapid supply of Fe ions supports the formation of poorly crystallized water-holding **ferrihydrid** (previously $5Fe_2O_3$ $9H_2O$). In tropical environments with high temperatures and periodically low moisture contents ferrihydrid can dehydrate and crystallize to **hematite** $(\alpha - Fe_2O_3)$, coloring tropical and subtropical soils red. If only low amounts of Fe-ions become available, for instance, due to complexation with organic compounds, then ferrihydrid crystallizes to **goethite** $(\alpha - FeOOH)$. It is mostly brownish and can be found in all soils of the world. Under low rates of Fe release, Fe-ions in the soil solution may also crystallize directly to goethite. It cannot change by

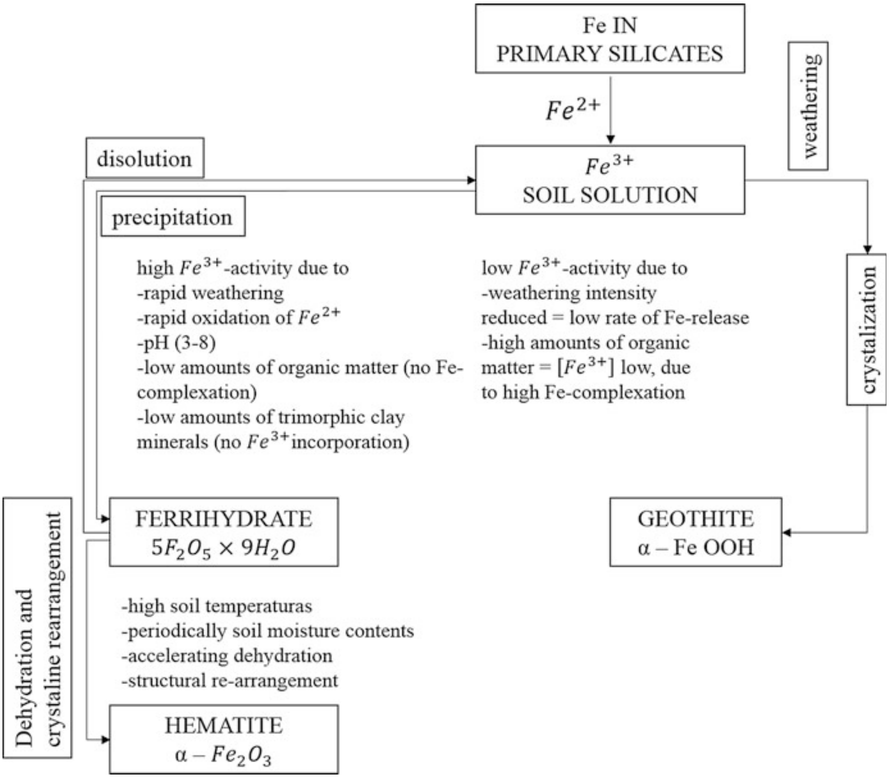


Fig. 11 Factors influencing the formation of hematite and goethite

dehydration to hematite, and hematite is not convertible to goethite by hydration. Nevertheless tropical soils frequently contain both minerals.

Toposequences of tropical soils often have red colors on dry ridges or upper slopes but brown colors on the more humid lower slopes and in depressions. Sometimes tropical soil profiles have yellow to brown surface horizons but bright red, hematite-containing subsurface horizons. This phenomenon may have several origins. It is possible that the profile is stratified, for example, in connection with denudation during climatic changes (e.g., during the Wisconsin or Würm ice age). Proof of this is, for instance, a stoneline at the boundaries between red and brown. Apparently environmental conditions have not allowed the formation of hematite since the accumulation of the surface materials. It is, however, also possible that the hematite of the surface horizons has been destroyed through reduction and complexation caused by soil organic substances and soil microorganisms. The stable goethite remained.

Besides the red hematite and the yellow-brown goethite, tropical soils may contain orange-colored **lepidocrocite** ($\gamma - FeOOH$) and reddish brown **maghemite** ($\gamma - Fe_2O_3$) . The former arises in the carbonate-free environment of water-saturated soils, from the oxidation of Fe^{2+}-containing solutions, the latter at high temperatures (fire) in the presence of organic substances. Maghemite can frequently be found in soils of the subhumid tropics due to the fact that fires often destroy the vegetation cover. Iron oxides in soils may be present either uniformly distributed or after translocation in the form of accumulations. Among them are iron crusts, iron concretions, and so-called mottled horizons (sections "Podzolization," "Hydromorphic Features," and "Ferralization and Plinthization").

Tropical soils are often rich in amorphous and crystalline Al-compounds. While little is known about the amorphous Al-compounds, the crystalline Al-oxides and hydroxides have been carefully studied because they occur in deposits of industrial significance (e.g., bauxite as raw material for aluminum production). Characteristic for strongly weathered tropical soils are **gibbsite** $[\gamma{-}Al(OH)_3]$, **boehmite** $(\gamma{-}AlOOH)$, and **diaspore** $(\alpha{-}AlOOH)$. Gibbsite is formed through the weathering of Al-containing silicates, if the simultaneously liberated compounds are washed out. This is usually the case in the humid tropics; gibbsite is therefore a typical mineral of strongly weathered humid tropical soils. Higher humus contents counteract gibbsite formation, because of the creation of Al-humus complexes. It should be mentioned that through intensive weathering even kaolinite may be destroyed and desilicified. The remaining mineral is gibbsite.

Al-oxides and hydroxides, similarly to iron oxides, can be distributed evenly throughout the soils, or can accumulate after mobilization and translocation. This occurs often in association with iron and is based on the high substitution rate of Al^{3+} by Fe^{3+}.

Similarly to clay minerals, the oxides and hydroxides of Al and Fe have the capacity to adsorb cations. Since this property, based on a negative charge surplus, varies with pH, it is termed **variable charge** (see also section "Clay Formation"). It is caused by a pH-dependent proton dissociation (simplified):

$$\underset{\text{anion adsorption}}{[Al(OH)_2]^+} \;\underset{\substack{\uparrow \\ \text{low pH} \\ \uparrow \\ -H_2O}}{\xleftarrow{+H^+}}\; Al(OH)_3 \;\underset{\substack{\uparrow \\ \text{high pH}}}{\xrightarrow{+OH^-}}\; \underset{\text{cation adsorption}}{[Al(OH)_4]^-}$$

At high pH values the free electrons of the OH-groups serve to fill the electron orbitals of Al and Fe, this leads to a negative charge surplus, which is neutralized through the adsorption of cations. At low pH and high H^+ activity, positive charges arise. Then, oxides and hydroxides of Al and Fe can adsorb anions. Strongly weathered Fe- and Al-enriched tropical soils are therefore termed **soils with variable charge**. Whether the oxides adsorb anions or cations depends on the zero charge of the molecule. This is understood as the pH region where the positive and negative charges are in balance. Above the zero charge, negative charges dominate and the oxides adsorb cations. Below the zero charge, the positive charges dominate and adsorption of anions occurs. For pure Fe oxides the pH of the zero charge (=isoelectric point) is between 8 and 9. Oxide-enriched soils, such as the Ferralsols which are widely distributed in the tropics, usually have subsoil pH values between 4 and 4.5, i.e., Fe and Al oxides are most often positively charged and adsorb anions. However, the adsorption of organic anions often leads to a decrease in the isoelectric point.

Important for forestry praxis is the fact that these soils may have little capacity to adsorb cationic nutrients such as K^+, Mg^{2+}, Ca^{2+}. Should growth-limiting conditions arise, the application of mineral fertilizers may not prove very useful. Only if, after the application of lime, the pH of the soil has risen above the isoelectric point can the cations be adsorbed and protected from rapid leaching.

After this discussion of the processes of soil formation involving the inorganic soil components, the following section is an introduction to the dynamics of the organic matter in tropical environments.

Litter Decomposition, Humification, and Carbon Stocks

As already mentioned, soils contain a gaseous phase (soil air), a liquid phase (soil water), and a solid phase. The solid phase can be subdivided further into inorganic (rocks, primary and secondary minerals) and organic components. Narrowly interpreted, the organic components are not only part of the solid phase but of the liquid phase as well, where they comprise the dissolved organic matter (DOM). Even the gaseous phase may contain traces of organic molecules (like methane).

Since the organic solid substances are greatly in excess, their dynamics are discussed in the following in more detail. Figure 12 illustrates that total soil organic matter (total SOM) can be subdivided into dead SOM and living SOM. By convention, only materials of particle size <2 cm diameter are included.

Dead SOM comprises litter, dead roots, and the corpses of dead soil organisms in different stages of decomposition, but always revealing visible tissue structures.

These are the nonhumic components. They can be transformed and microbiologically resynthesized into new compounds of generally high molecular weight, the **humic substances**, which reveal no visible tissue structures. This process is called **humification**. Both nonhumic and humic substances can undergo mineralization through microbial breakdown into such low-molecular-weight, inorganic substances as CO_2, H_2O, NH_4^+, NO_3^-, etc.

Usually humus is defined as the dead SOM, but sometimes only the humic substances are called humus. In this section humus means dead SOM, which is derived from the aboveground as well as the belowground biomass. The main parent materials of SOM are litter, roots, and the bodies of dead soil organisms (Petersen 1982; Fig. 13). In addition, exudates of roots (rhizodeposition) and microorganisms play an important role, if only as priming substances. Table 3 documents the amounts of organic substances that are available on a yearly basis to various plant associations.

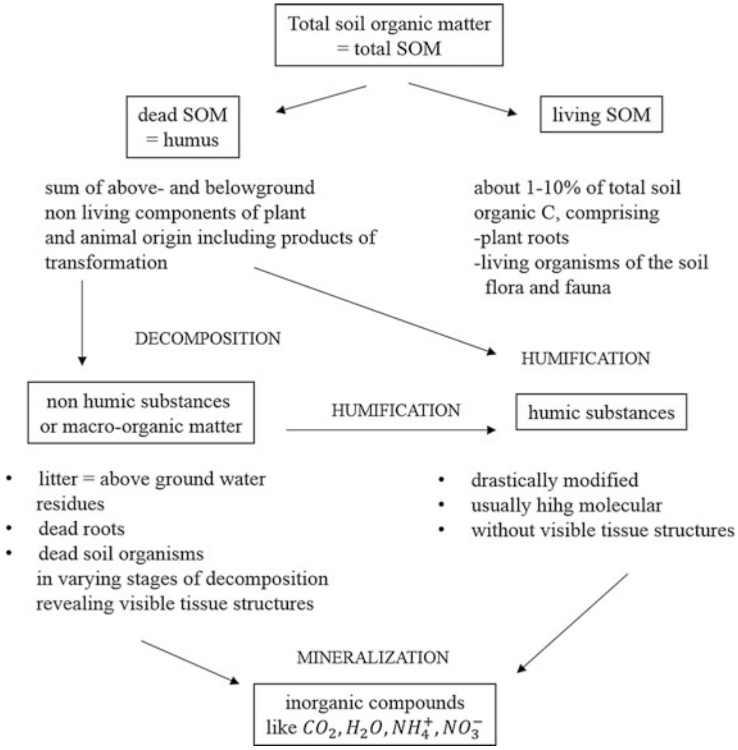


Fig. 12 Concepts and definitions of soil organic matter (= SOM)

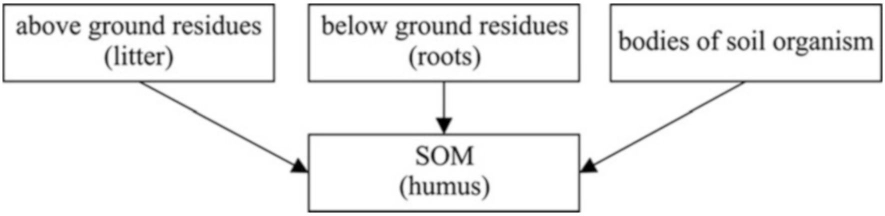


Fig. 13 Parent materials of humus

Table 3 Mean annual amounts of organic parent materials supplied to the soil (Mg ha^{-1} in dry matter) (Coleman et al. 1989; Cuevas 1983)

	Total litterfall	Fine roots
Temperate forest	2–4.5	About 3
Temperate grasslands	1–3	Up to 3
Temperate crops	0.3–2	0.5–3
Tropical rainforests (Amazon basin)	5–10	2–4
Tropical crops (Ultisol, Peru)	4.8–9	1.8–4.2

Table 4 Mean composition of SOM sources (Scheffer and Schachtschabel 2010; Schroeder 1984)

1. Water	Up to 90 % of the fresh weight	
2. Inorganic composition (ash)	0.3–19 % dm	K, Ca, Mg, Na, P, S, Si, trace elements
3. Organic compunds	Carbohydrates >50 % dm	Cell contents; sugar, starch 1–30 % cell walls: pectins, hemicellulose: 9–25 % dm cellulose: 19–47 % dm
	Lignin 12–33 % dm Proteins and other N-containing substances Fats, waxes, resins 1–10 % dm	Cell walls Cell contents: plant origin: 1–10 % dm Soil organisms: up to 65 % dm
4. Elemental composition (% dm)	C = 47 %, O = 44 %, H = 7 %, N = 2 % C/N 4–400	

It is known that rainforest soils, for example, in the Amazon River region, have more aboveground residue inputs than soils in the temperate zones. In the humid tropics, a climatically induced interruption of biomass production such as the typical winter months of the temperate zones is usually absent. There are therefore two or three harvests in the moist warm regions, producing high amounts of above- and belowground residues. Currently there are few reliable data regarding these, especially for the belowground litter. This is the more unfortunate, as there are many indications that the SOM contents of tropical soils are governed less by aboveground inputs but significantly more by the belowground litter.

Also little is known as to the composition of the SOM sources (Table 4). This causes difficulties in evaluating the intensity of decomposition. Sugars, starch, and proteins are easily broken down, whereas lignin, fats, waxes, and resins are decomposed with difficulty. Pectin, hemicellulose, and cellulose take on a middle position. Since the breakdown processes are mediated by the soil flora and fauna, such factors as temperature, water content, pH, and redox potential influence the rate of decomposition, as well as its final outcome.

Decomposition intensity of the primary organic material = function of
- temperate
- water content
- pH
- redox potential
- amount and quality of SOM sources

Many soil organisms have temperature optima between 20 and 25 °C. This explains why the organic parent material in the tropics is usually broken down more rapidly than in cool climates. Generally tropical rainforests have therefore only thin organic surface layers. But water surplus and the concomitant lack of oxygen may slow SOM decomposition rates to the extent that Histosols (section "Histosols (HS)") may be formed. In semiarid and semihumid forests, huge amounts of litter may accumulate during the dry phases, because dryness inhibits the activity of decomposer organisms. This is true also for very acid sites with pH values between 3 and 4. Because of the accumulation of base cations from leaf litter, undisturbed organic surface layers of tropical forests rarely have pH values below 6.5, so that pH-induced disturbances in litter decomposition are of minor importance. Low pH values inhibit decomposition only in the case where after clear-cutting, due to erosion, more strongly acidic subsoil horizons are exposed.

In contrast to mixed natural stands, fast-growing tropical forest plantations sometimes exhibit thick organic surface layers including litter and fermentation layers indicating reduced litter decomposition. Plantations of *Anacardium occidentale, Cupressus lusitanica, Eucalyptus* spp., and *Pinus* spp. are among them. Tree-species litter has often high C/N ratios or contains phenolic substances that can act as inhibitors (tannins). The large accumulation of litter beneath *Tectona grandis* is the result of periodically high rates of leaf fall, after the onset of the dry season. The high Ca content (pH around 7) of teak leaves insures rapid litter breakdown, as soon as the rains begin. The following indexes/ratios allow an approximation for decomposability of the organic parent materials:

$$\frac{\text{lignin}}{\text{protein}} \qquad \frac{\text{lignin}}{\text{nitrogen}} \qquad \frac{C}{N}$$

Regarding the decomposition of the leaf litter of tropical trees, Table 5 represents a first approximation. At close inspection, three phases of decomposition can be distinguished:

Table 5 Decomposability of tropical tree leaf litter

Easy	Medium	Difficult
Acacia senegal	*Acacia mangium*	*Acacia mearnsii*
Albizia lebbeck	*Acacia auriculiformis*	*Anacardium occidentale*
Cedrela odorata	*Acrocarpus fraxinifolius*	*Casuarina equisetifolia*
Dalbergia sissoo	*Azadirachta indica*	*Conocarpus lancifolius*
Leucaena leucocephala	*Brosimum alicastrum*	*Cordeauxia edulis*
Prosopis juliflora	*Ceiba pentandra*	*Eucalyptus camaldulensis*
Triplochiton scleroxylon	*Eucalyptus grandis*	*Eucalyptus deglupta*
	Gmelina arborea	*Eucalyptus saligna*
	Grevillea robusta	*Lophira lanceolata*
	Hyeronima oblonga	*Musunga cecropoides*
	Manilkara zapota	*Nauclea diderrichii*
	Parkia biglobosa	*Pinus* spp.
	Swietenia macrophylla	
	Terminalia ivorensis	
	Terminalia superba	
	Tectona grandis	
	Vochysia hondurensis	

- The first phase is activated by enzymes present in the dying or recently dead cells. Cell wall structure is largely preserved, but in the cytoplasm autolytic reactions transform macromolecular substances into smaller components:

$$\text{Starch} \xrightarrow{hydrolysis} \text{glucose}$$
$$\text{Protein} \xrightarrow{hydrolysis} \text{amino acids}$$

  Some mineral nutrients may be retranslocated from senescent cells, i.e., before leaf fall, into plant parts that remain alive, where they are stored. Others, after cell death, are subject to increased leaching by rainwater.
- The second phase is characterized by mechanical litter breakdown due to biting animals, without significant chemical changes. Both the macro- and mesofauna contribute to this action. In addition to size reduction and surface enlargement of the litter particles, there is an intensive mixing with the mineral particles of the soil, for example, by burrowing and pushing the aboveground residues into deeper horizons due to earthworm activity (= bioturbation), or by mixing activities during food intake and digestion (feces).
- The third phase concerns the microbial decomposition of the cells. Recognizable tissue structure is abolished, since lignin and cellulose are also broken into their monomers. These compounds, especially the polysaccharides, represent a major energy source for sustaining the life cycles of the soil microflora. Through biological oxidation, organic C, H, O , N, S containing compounds are broken down into inorganic, mineral end products. This sequence of reaction is termed **mineralization**.

By far not all the aboveground and belowground organic resources are mineralized to CO_2, H_2O, etc. Many plant substances, but especially lignin, are biochemically modified into new, amorphous compounds, often of high molecular weight, the so-called humic substances. They may also arise by another pathway, namely, through condensation from low molecular weight hydrolytic products. The metabolic and autolytic products of the decomposer organisms play a significant role during these processes which are probably catalyzed by Fe, Al and Mn. During litter decomposition and humification there is a decrease in polysaccharides. This fact has been documented by ^{13}C – NMR spectroscopic studies of Liberian virgin forest soils (Zech et al. 1989). Furthermore, the amounts of aromatic *C*-compounds remain relatively constant or slightly increase. Increased humification is correlated with a decrease of methoxyl and phenolic groups and an increase in carboxyl groups. Humic substances are therefore not, as has been assumed heretofore, rich in phenolic structures.

The TOC contents and stocks in tropical soils vary considerably according to variations of climate, vegetation, rootability, and grain size of the soils, groundwater level, bulk density, stone contents, pH, and land use intensity. Litter usually contains ~40–50 % TOC, the A horizons below forest ca. 2–3 % decreasing to less than 1 % in the B horizons (exceptions are Vertisols and Andosols). Forest clearing and long-lasting agricultural land use result in a decrease of ca. 50–60 %. On Acrisols in Sumatra, Guillaume et al. (2015) described a decrease of surface soil TOC contents of 70 % and 62 %, respectively, after 15 years of the conversion of lowland rainforest into oil palm and rubber plantations. Desert soils contain generally less than 0.4 % TOC due to the low input of plant residues. Their TOC stocks are often only a few tons per hectare, down to about 1 m of soil depth. At sites with increased biomass production, the TOC stocks also increase, for example, to 100 Mg ha^{-1} and 1 m soil depth, in the soils of the subhumid tropics. The soils of the tropical rainforests and monsoon forests may exhibit up to 200 Mg per hectare. Tropical mountain soils, if not strongly eroded, may be especially rich in humus. Global estimates allow the assumption that the annual loss of TOC from the world soils varies between 2.5 and 7.4 Pg, corresponding to 0.2–0.3 % of the total soil organic carbon stocks (~1,500 Pg/100 cm soil depth) existing in the soils of the world (Buringh 1984; Batjes, 1996). Maximum TOC losses affect soils of the humid and subhumid tropics especially in connection with forest destruction due to accelerated surface soil erosion and humus mineralization under warm and humid conditions. This has serious consequences not only with respect to the emission of greenhouses gases but also for soil fertility which for many tropical soils is closely related to their SOM reserves. Humus stores not only the macronutrients N and S but also P, and with decreasing SOM the organic P compounds then are fixed as insoluble Al/Fe-phosphates, which are heavily available to most plants. While there generally are a number of organic *P* fractions in forest soils, for example, mono- and diester phosphates, as well as pyrophosphates, in eroded, degraded agricultural soils, where humus has essentially been lost, *P* occurs preferentially as heavily soluble Al and Fe-phosphates (Zech et al. 1989–1990). The remaining humus-poor, mineral soils become crusty and subject to further erosion, and the contents of toxic aluminum increase.

To improve soil fertility the application of nutrients in the form of mineral fertilizers often does not result in the desired success, because kaolinitic, oxide-rich, and humus-impoverished tropical soils have only a low ion adsorption capacity; after heavy rains, most of the fertilizers are leached out and lost. Only after the buildup of significant amounts of humus, for example, during fallow periods and regeneration of the secondary forests is there an increase in N, P, Ca, Mg, and S contents. In gardens or smaller fields, composting or the application of biochar may achieve this, as documented by research results of the anthropogenic terra preta do indio of the Amazon basin (Zech et al. 1990; Lehmann et al. 2003; Glaser and Woods 2004). Within soil profiles the SOM may be shifted further down by the action of burrowing soil animals or in connection with podzolization as dissolved organic matter (DOM). Such transport processes are discussed in the next section.

Transport Processes

Transport processes include mobilization, translocation, and immobilization of the transported materials. Mixing and separation of the soil compounds on the soil

Table 6 Processes of turbation in soils

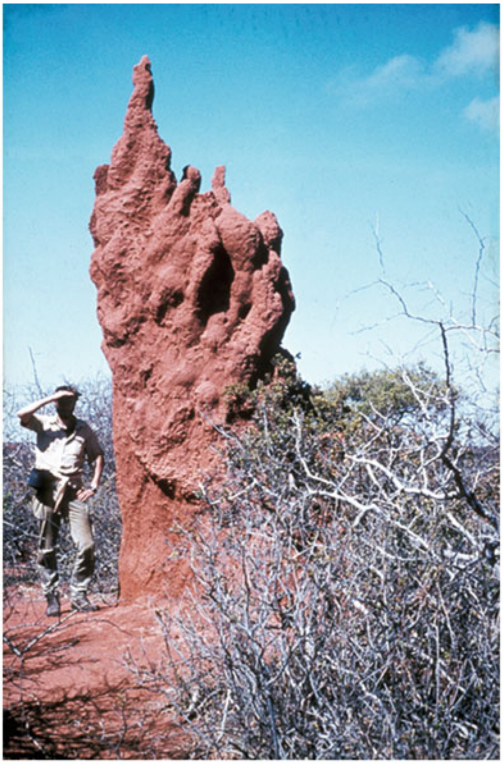
Encompasses mixing and at times also the sorting of soil materials. One differentiates:
Bioturbation is the mixing of soil substances by digging and burrowing animals (earthworms, termites). Can lead to the formation of thick, humic Ah-horizons, in which layers of litter are more or less intensively or deeply worked into the mineral soils. This inhibits the formation of thick raw humus deposits. Termites favor the decomposition of SOM. Humans also influence the appearance of the soil horizons through digging, hoeing, ploughing, and fertilizing
Cryoturbation is the mixing that occurs in connection with freeze-thaw cycles. It causes the formation of stone stripes and of polygonal structures; is widely distributed in the tundra zone and in the high mountain regions of the tropics
Peloturbation, also called hydro- or turgoturbation; typically it occurs in the semiarid/semihumid tropics, where through pronounced changes of drying and wetting, the soils undergo shrinking and swelling cycles. This induces mixing, especially in smectite-rich soils, because at the beginning of each rainy season, clay and SOM are washed into the deep desiccation fissures. Peloturbation characteristics include powerful humic surface horizons, slickensides, stress cutans, self-mulching, and gilgai reliefs (cf. section Vertisols (VR))

surface or within the soils themselves also belong to the transport processes, if they bring about typical, soil-related features. Transport processes are caused by humans, soil animals, water, and wind. Turbation processes will be examined first.

Turbation

Turbation encompasses the mixing and in part also the sorting of soil materials by humans and animals (**bioturbation**), frost (**cryoturbation**), and **peloturbation**, which is defined as the mixing that occurs in connection with shrinking and swelling of smectite-rich soils during dry and wet periods (Table 6). Tropical soils are affected significantly by the action of **termites** both in a chemical (organic matter decomposition, *C*-accumulation, nutrient cycling) and a physical sense (aggregation, permeability). The population density and the specialization of the termites are important in this connection. Population density is apt to vary considerably; the maximal numbers are about 3,000 animals per square meter. Termites may either live aboveground (epigeal), e.g., in trees (dead or alive) and termite mounds (Photo 12), or belowground (hypogeal); they are builders of diffuse nest systems or mounds from soil materials mixed with saliva, thus influencing soil structure. One distinguishes between litter, grass, wood, and humus consumers; metabolic end products are e.g. CO_2, H_2O, and CH_4. Some termites have symbiotic bacteria in their gut fixing nitrogen. Others produce polycyclic hydrocarbons to protect their nests against pests.

Termites which forage for litter are known to transport these materials over a distance of more than 50 m, for instance, to fungus gardens. This, in zones of high population density, may lead to significant decreases of the “litter standing crops” around termite mounds. According to the figures summarized by Wood (1988), termites may consume up to 80 or even 100 % of grass litter produced in savanna environments. Woody litter consumption may vary between 17 % and 91 %. Wood-consuming termites and ants provoke remarkable damages in tropical forestry especially in plantations with exotic tree species. Alternatives are the application a



b

Photo 12 (**a**) Termite mounds in Central Somalia (Jesomma formation). (**b**) Terminte mounds in the bas fond of Paoua, Central African Republic

Photo 13 Peloturbation of soils rich in smectite

of insecticides or selection of relatively resistant tree species like *Tectona grandis*, *Dalbergia sissoo,* etc.

In tropical rainforests, humus-feeding termites are abundant. They are able to digest humus by depolymerization. This may contribute to the observed low C-contents in the surroundings of termite mounds. This finding also points to a clear difference between the activities of termites and **earthworms**. Soils with high earthworm activity have as a rule humus-rich, deep, Ah horizons; termite-rich soils, as far as is known at present, become impoverished in SOM. In tropical soils earthworms sometimes produce up to 260 kg cast per ha and year (Scheffer and Schachtschabel 2010), thus significantly contributing to bioturbation, SOM, and aggregate stabilization.

While cryoturbation in the tropics occurs solely in the high mountains, peloturbation (Photo 13) is widely distributed, especially in the arid and semiarid regions.

Salinization, Calcification, Sodification, and Silification

These processes are typical for the arid and semiarid tropics; they are characterized by substantial accumulation of water-soluble salts such as chlorides, nitrates, sulfates, or carbonates of Ca, Mg, or Na and of Si oxides in the soil or on the soil surface (Fig. 14). **Salinization** is defined as accumulation of salts easier soluble than gypsum, and **calcification** concerns the accumulation of carbonates (mainly $CaCO_3$ and $MgCO_3$). If soils rich in sodium salts are leached, then Na^+ may accumulate, a process called **sodification** (details see Figs. 15, 16, and 17). Such

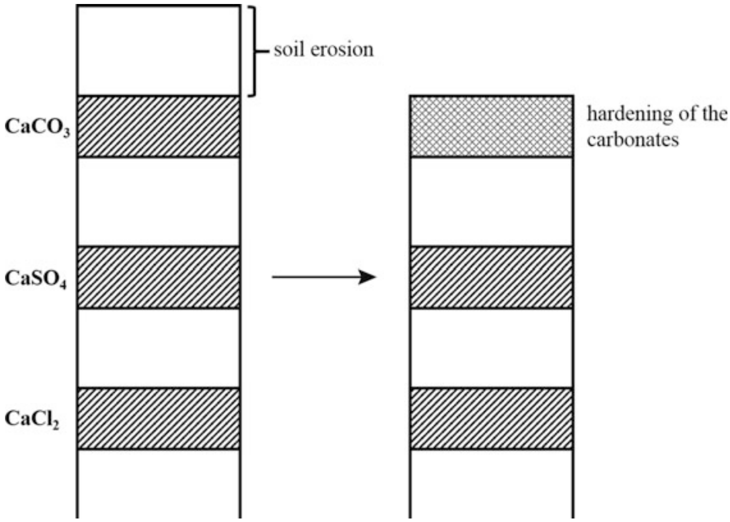


Fig. 14 Enrichment of carbonates, sulfates, and chlorides (example: calcium carbonate, calcium sulfate, calcium chloride) in arid soils, from percolating water. After erosion of the surface soil layers, hardening of the carbonates occurs

phenomena are often induced by anthropogenic activities like improper irrigation. **Silification** is defined as the formation of secondary Si oxides (Fig. 18).

When mobilization occurs in the presence of percolating water, salt precipitation depends on salt solubility and the amount of percolating water available in the soil profile. With increasing soil depth first carbonates, then sulfates, and far below chlorides accumulate. When mobilization and transport occur by ascending water, the sequence (of the series) is reversed.

On slopes, lateral transport of salts is also possible due to interflow, with the accumulation occurring in the lower parts of the slope or in depressions. Accumulation may occur in a diffuse mode (e.g., as soft powdery lime), discontinuously (e.g., as pseudomycelia, cutanes, soft and hard concretions, veins), or continuously (crusts, e.g., calcrete, caliche, salcrete, tosca de pampa). The latter develop after intensive lime or salt accumulations. Often these crusts are exhumed enrichment horizons, i.e., they have been exposed and partially hardened only after erosion and the loss of the surface soil (Fig. 14, Photo 14).

Salt crusts (Photo 15) and carbonate crusts often inhibit tree growth. Finely distributed carbonates may induce chlorosis due to Fe and Mn deficiencies. Massive incrustations make root penetration difficult. Forest management of soils rich in easily soluble salts (e.g., Solonchaks rich in NaCl) is also challenging, and only salt-tolerant tree species like tamarix, artemisia, or *Casuarina equisetifolia* can be recommended (Photo 15).

During chemical weathering of silicates, silica is mobilized and leached. Under warm-humid tropical conditions it is easily soluble and leached into the discharge

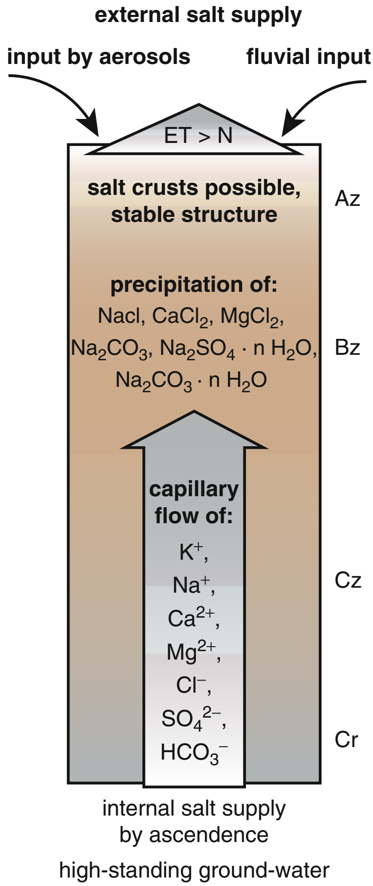


Fig. 15 Salinization (Zech et al. 2014)

system. In arid and semiarid environments dehydration and crystallization occurs (details see Fig. 18). Often Si oxides are cementing primary particles forming concretions (durinodes) and crusts (duripans, silcrete, petroduric horizon). Most likely such Si-rich layers are of polygenetic nature.

Lessivation

Lessivation is defined as the transport of clay particles by percolating water. Besides clay minerals, other clay-sized particles, such as oxides, hydroxides, and organomineral compounds can also be affected. The fine clay fraction of <0.2 μm is especially lessivation prone. In the course of clay transport, the surface soils become clay impoverished and acquire a pale brown coloration. The clay accumulates in the deeper soil horizons, forming the so-called argic horizon (List in "Annex 2"); this is generally accompanied by color intensification (Photo 16). The finger probe and the thin, shining clay skins (cutans, argillans; Photo 17) at the surface of the aggregates

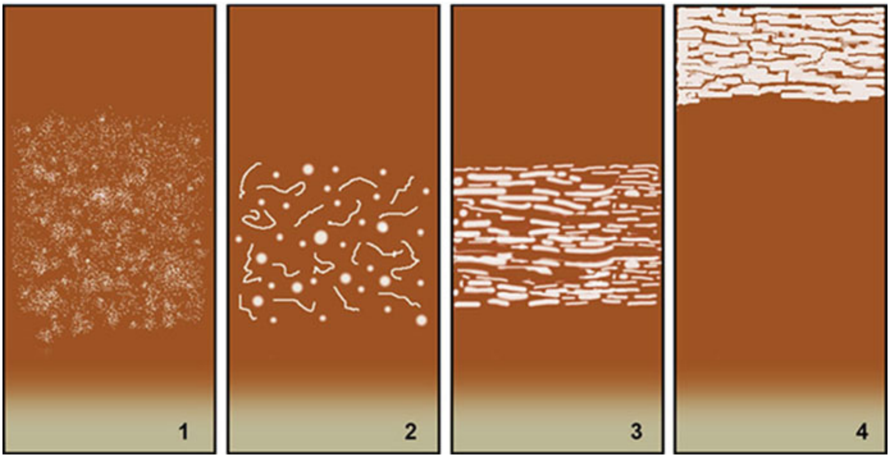


Fig. 16 Calcification: $CaCO_3$-accumulation may occur in a in diffuse mode (=1), discontinuously (=2), or continuously (3=platty, 4=massiv crust) (Zecht et al. 2014)

further confirm clay accumulation in the soil. Since also strongly swelling clays exhibit the pressure-induced cutans at aggregate surfaces, the exact differentiation between the cutans formed by lessivation and the so-called stress cutans is possible only after micromorphological tests.

Lessivation can be subdivided into three partial processes, as follows (details see Fig. 19):

– Mobilization
– Transportation
– Precipitation, accumulation

The prerequisites for clay mobilization in the surface soil are low electrolyte contents in the soil solution, which may occur after heavy rain showers or during snowmelt in the high mountains. Lime or salt enrichment inhibits lessivation, since clay transport is optimal only between pH 6.5 and pH 5.0. Above pH 7, clay particles are stabilized by Ca^{2+} and Mg^{2+}, below pH 5 by Al^{3+} and Fe^{3+}. These multivalent cations form linkages between the clay particles, thereby reducing their mobility. Monovalent cations such as K^{+}or Na^{+}, in contrast, cannot form bridges between the clay particles but can hydrate strongly, thereby encouraging mobilization (see section "Solonelz (SN)"). In addition, kaolinite-rich, nonswelling clays are transferred less efficiently than strongly swelling smectite (see section "Vertisols (VR)"). Nevertheless, kaolinites are also shifted, since lessivation concerns not only peptized colloids but also the coagulated phase which is transported mechanically by the percolating water, mainly into large pores and fissures. Neither the peptized nor the coagulated colloids can be transported into fine pores. Clay migrates in fine-textured soils only in the presence of desiccation fissures or if sufficient numbers of

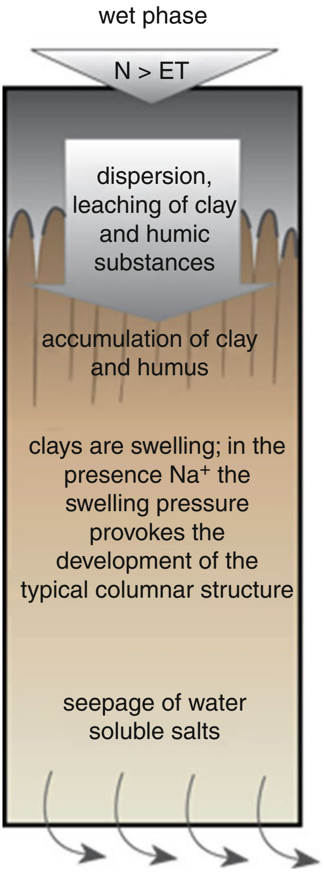


Fig. 17 Sodification (Zech et al. 2014)

large pores arise because of bioturbation. In this instance, clays will accumulate at the base of such dry cracks or rough pores. An increase of Ca^{2+} or Al^{3+} in the subsoil or desiccation through evaporation (at the beginning or during the dry period) and transpiration may cause flocculating in the subsoil.

This explains why lessivation occurs preferentially under climates with wet/dry alternations. Dry periods enhance the formation of the rough pores, cracks, and fissures and counteract the loss of base cations, like Ca^{2+} and Mg^{2+}. This insures that the soil remains for relatively long periods in the pH region of 6.5–5, which favors lessivation. Heavy rain downpours, which are typical for wet/dry alternating climates, favor the advent of fast-moving percolating water, as well as the mechanical migration of clays from surface soils to the deeper horizons. These then may become even denser and periodically may become water logged. For semiarid sites this phenomenon has to be positively evaluated, because it may improve the water supply to the forest stands.

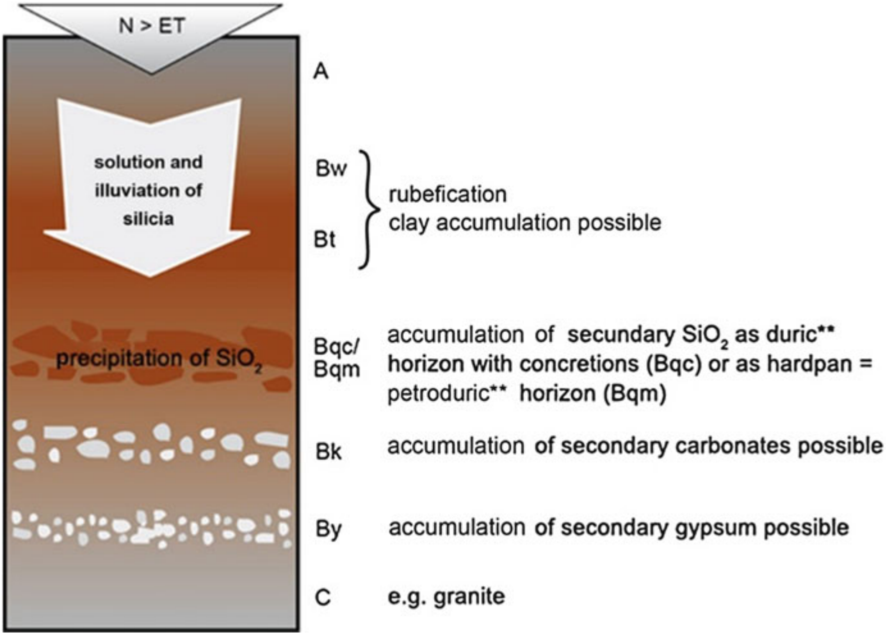


Fig. 18 Silification (Zech et al. 2014)

Photo 14 Limestone crust in Isreal. If the solum above a hard pan (consisting of carbonate, gypsum, or Si-oxides) is thick enough to supply plants with nutrients and water, silvicultural land use may be successful. Otherwise ranching or protecting as natural reserve is recommended

Photo 15 Salt crusts at the surface (external Solonchak) of silty unconsolidated basin sediments (Puerto Madryn, Argentina)

Many tropical soils show the signs of lessivation, for example, Acrisols, Alisols, Lixisols, and Nitisols (see section "Reference Soil Groups and their Use in Forestry"). Their clay-enriched subsoil horizons are, however, not always the result of lessivation. Often soil stratification due to erosion and accumulation is evident, with stonelines at the boundary between the clay-rich lower soil layers and the clay-poor upper soil layers. In this case textural differentiations between the upper and lower soil horizons are not the result of lessivation but indicate erosion discordances. Other processes leading to higher clay contents in the subsoil in comparison to the surface soil layers are, for instance,

– Advanced pedogenetic clay formation during dry periods when the subsoil is still wet whereas the surface layer is already dry
– Activity of ants and termites transporting coarser-textured material to the surface
– Destruction of clay in the surface layer, or selective clay removal from the topsoil

Podzolization

Podzolization is defined as the vertical shift of low molecular weight organic substances, usually together with Fe, Al, and Mn complexes (Fig. 20). The occurrence of this process is dependent on high H^+ activities, which result in the

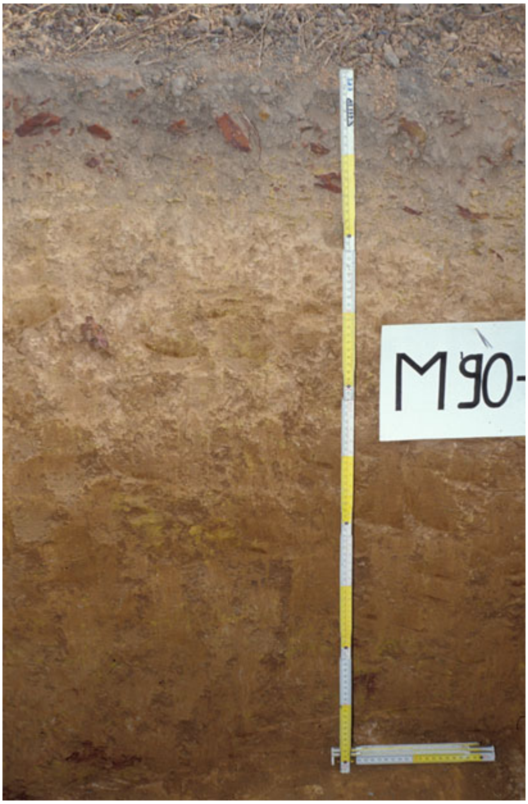


Photo 16 The dark subsoil is the result of clay lessivation from the grayish surface layer (Acrisol, Madagaskar)

destruction of the primary and secondary clay minerals and the concomitant liberation of Fe, Al, and Mn ions. The low molecular weight organic molecules, which are present at higher concentrations because of the microflora's changed activity at low pH, react with the ions forming chelates.

The organic complexing compounds are derived from vegetation (e.g., leachates of the canopy), the forest floor, and root litter. Chemically, they are acids rich in carboxylic groups, sugars, polyphenols, and fulvic acids. At low pH values <3 also noncomplexed Fe may be displaced as Fe^{2+} or as peptized Fe colloid. Fe, Al, and Mn chelates are subject to transport from the surface soil layers to the subsoil.

Mobile Al forms are

– Al^{3+} (released at pH < 5)
– Peptized Al colloids (in sol state)
– Al organic chelates
– Aluminates, formed at high pH values ($>$8–9); not relevant for podzolization

The following list illustrates some differences between podzolization and lessivation:

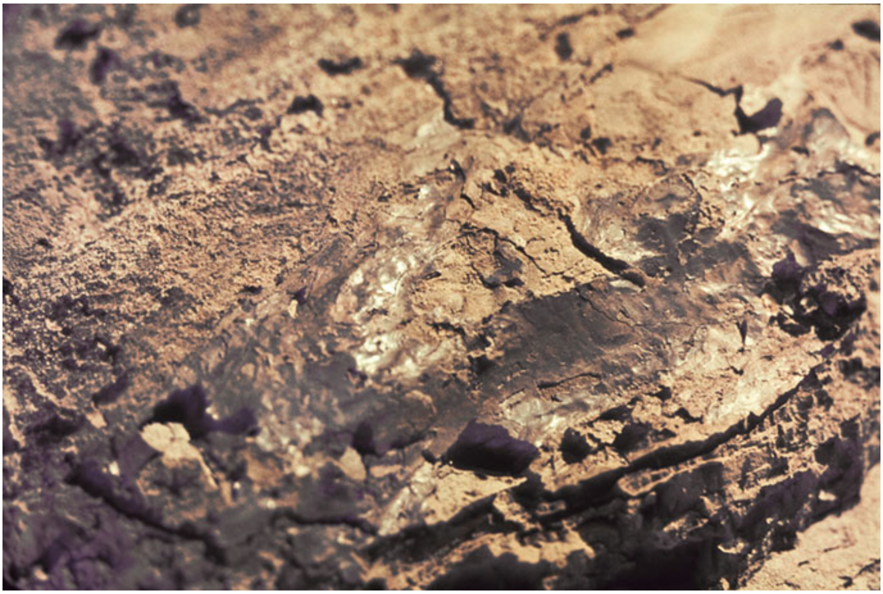


Photo 17 Clay cutans develop due to lessivation or stress

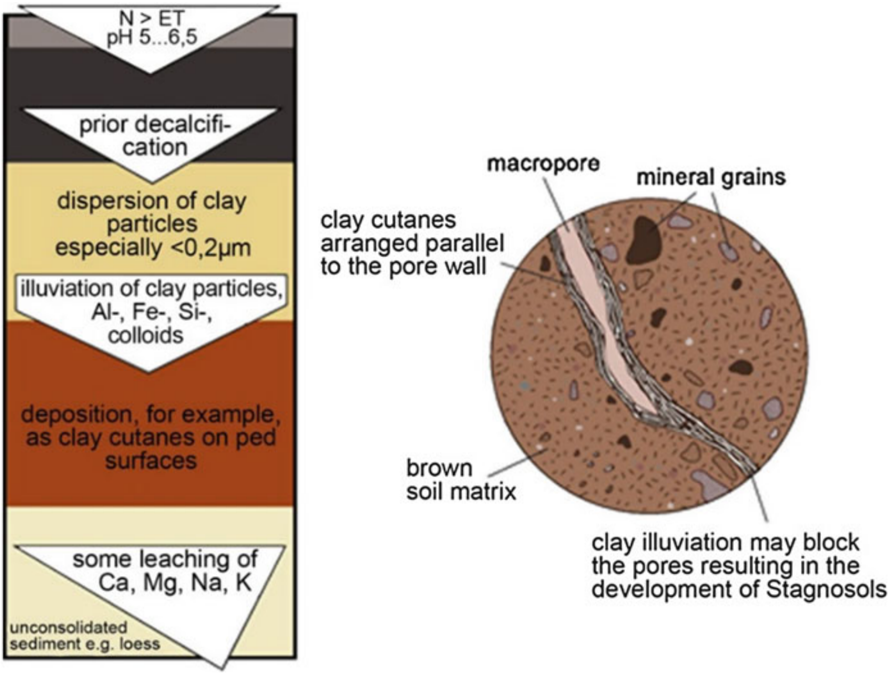


Fig. 19 Lessivation (Zech et al. 2014)

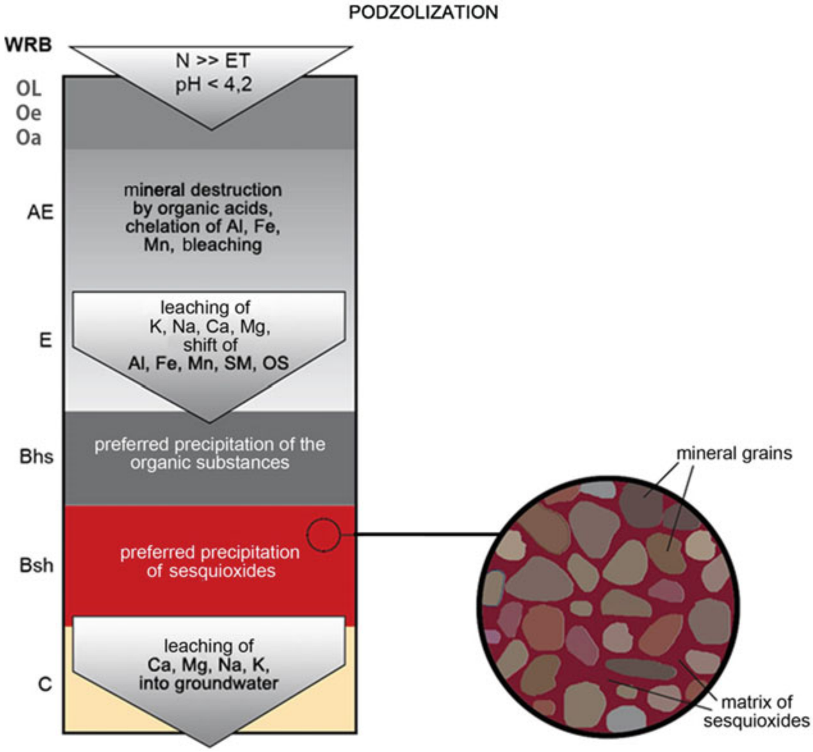


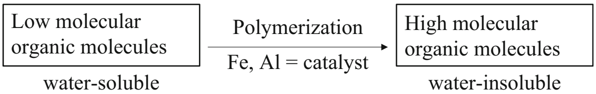
Fig. 20 Podzolization (according to Bridges 1979; modified by Zech et al. 2014)

Lessivation	Podzolization
pH 5–6.5 Mechanical transport esp. of the fine clay fraction with the percolation water in peptized state Creation of a clay-impoverished upper soil and clay accumulation in the lower soil layers	pH 3–4, Destruction of the clay fraction and transfer of the breakdown products in ionic form, as peptized colloid in sol state and as chelate after reaction with water-soluble organic compounds Development of a bleached eluvial E- horizon and a dark or reddish brown illuvial (spodic**) horizon

The substances mobilized in the upper soil migrate with the percolating water downward, where they precipitate. The result is a bleached eluvial or albic horizon in the upper soil and a dark or red-brown illuvial or spodic horizon in the lower soil profile. Its formation can be explained according to the following mechanisms:

– Deeper soil horizons may contain more Fe and Al (= Me). This increases the $\frac{Me}{C}$ quotient of the solution, and solubility decreases.

– The high Fe and Al concentrations in the deeper soil layers catalyze the polymerization of low molecular weight organic compounds:



– pH increase in the subsoil induces
  • Microbial breakdown of chelates, high molecular weight organic water-insoluble molecules
  • Flocculation of the peptized Me colloids
  • Precipitation of Fe^{2+} and chelates
  • Accelerated polymerization of low molecular weight organic acids
– Decreased water movement due to decreasing pore diameters
– Oxidation of Fe^{2+} to Fe^{3+}

In general podzolization is typical for humid, cool climates, since under these conditions microorganism activity is low, fungi dominate, organic materials accumulate above the mineral soils as more, and large quantities of percolation water are available for the transport of solubility products. Nevertheless, podzols also occur in the tropical lowlands and in the subtropics of Australia and South America, as will be discussed in more detail in section "Podzols (PZ)." Since at low pH the mineralization of organically bonded N, S, and P is low and also Cu and Mo are transported along with the sesquioxides, podzols usually have little fertility. The establishment of monocultures with pines and cupressus promotes podzolization. Podzolization occurs in well-aerated substrates, at relatively high redox potentials. But transport of Fe and Al also may occur at low redox potentials mainly in hydromorphic soils. This is discussed below.

Hydromorphic Features

Permanent or periodic oxygen deficiencies in soils influenced continuously or at intervals by water lead, in dependence on the redox potentials, to a mobilization and shift of Fe and Mn. This in turn causes the formation of so-called hydromorphic features, for example, red and yellow mottles. One differentiates between **gleyization** and **stagnization**.

Gleyization (Figs. 21 and 23) concerns mainly the soils influenced by groundwater in depressions and lowlands (Gleysols, Solochaks, see section "Reference Soil Groups and their Use in Forestry"). It also occurs in the deeper soil layers of extensive peneplains. The constantly wet, water-saturated subsoils contain Fe^{2+} and Mn^{2+}, due to the low redox potential. Both ions can move laterally either by mass flow or diffusion or ascend by capillary action.

Since the surface soils are, at least sometimes, not saturated and therefore aerated, Fe^{2+} and Mn^{2+} oxidize and accumulate as soon as they are in contact with air. This leads preferentially to rust spots at the aggregate surfaces or at the walls of rough pores (exped). If Fe and Mn oxides are deposited in large amounts, crusts may also be formed in this way.

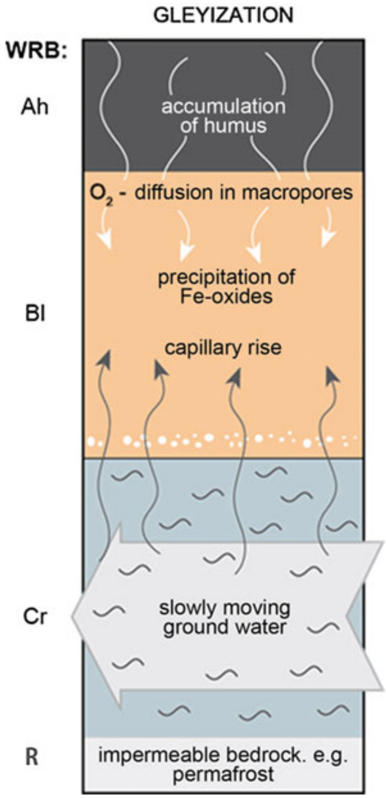


Fig. 21 Gleyization (Zech et al. 2014; modified)

Stagnization (Figs. 22 and 23) concerns most often the peneplains of the semiarid and subhumid tropics with pronounced rainy and dry seasons. It occurs, for instance, when rainwater saturates the surface soil but cannot seep away through a clay-rich subsoil. Stagnization is therefore a typical phenomenon of strongly lessivated soils. During the dry periods fissures and cracks open up, which, together with the large pores, are quickly filled with water during heavy rains and at the beginning of the rainy season. This leads to a decrease in redox potential and the reduction of Fe^{3+} and Mn^{4+}. Mainly due to diffusion, Fe and Mn move in ionic form into the interior of the soil aggregates, or as chelates if enough low molecular weight organic substances are at disposal in the soil water. Oxygen included inside the aggregates oxidizes some Fe and Mn ions causing precipitation of the oxides in the interior of the peds.

With the beginning of the dry season the soil starts to desiccate, firstly along the large pores and fissures. Fe^{2+} and Mn^{2+} may now diffuse from the interior to the exterior of the aggregates. This "back" diffusion is less effective than the diffusion in the interior of the aggregates. Oxygen again penetrates to the inside of the aggregates and oxidizes Fe^{2+} and Mn^{2+}. This is the reason for red and yellow mottling inside the aggregates (inped) with the simultaneous bleaching of the

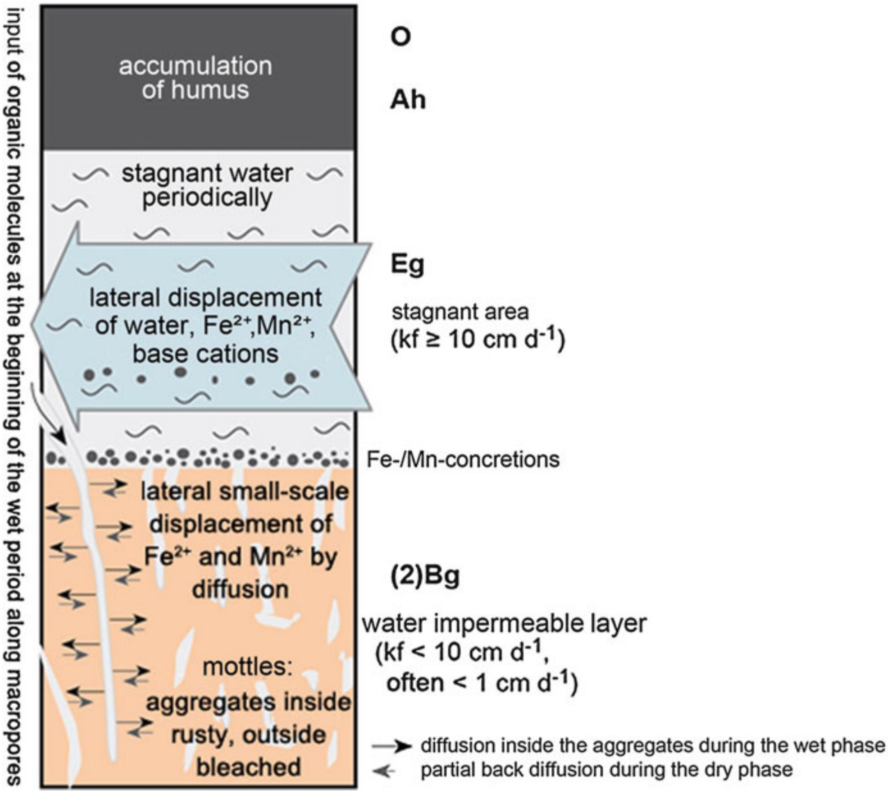


Fig. 22 Stagnization (Zech et al. 2014)

aggregate surfaces. Stagnization is therefore characterized by the occurrence side by side of bleached and red/yellow mottles, whereas gleyization is seen as rust spots in the oxygen-rich upper part of the soils and blue-green reduction colors in the oxygen-deficient subsoils.

Hydromorphic features include also concretions. These are defined as brown or black amorphous or crystalline Fe^{3+}, Mn^{3+}, or Mn^{4+} enrichments with diameters up to several cm. Rapid, frequent changes from wet to dry favor their genesis. Tropical soils contain often very thick concretion layers (gravel layers), because of soil removal, denudation, and selective accumulation. Such sites have few nutrient reserves and only poor potential for plant growth.

Finally, the frequent change in redox potential in connection with wetness and desiccation of the solum may lead to soil acidification. The simplified reaction is as follows (see ferrolysis in Brinkman 1979):

$$Fe(OH)_2 + HOH \underset{\text{reduction}}{\overset{\text{oxidation}}{\rightleftarrows}} Fe(OH)_3 + H^+ + 1e^-$$

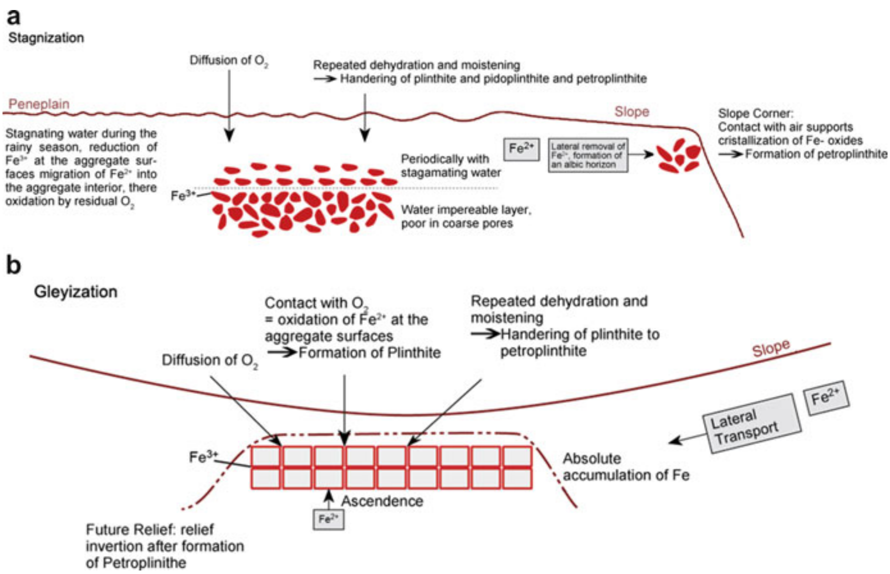


Fig. 23 Plinthization (Zech et al. 2014)

The H^+ concentration created during oxidation accelerates the destruction of the clay minerals, especially on clay aggregate surfaces; it is detrimental to the fertility of the respective sites.

Ferralization and Plinthization

"Ferralite" is an older name for Fe- and Al-enriched residues in regions characterized by strong weathering. They occur in the humid tropics of today or in areas that had a humid tropical weathering regime in the past.

Processes that lead to the formation of ferralites are combined in the concept of **ferralization** simplified as follows:

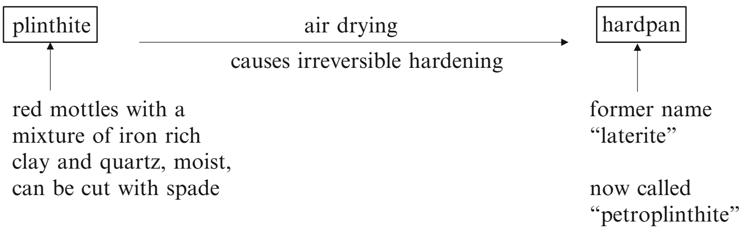
Destruction of weatherable silicates by intensive leaching of *Si, Ca, Mg, K, Na*	+	Relative accumulation of *Fe*- and *Al*-oxides, kaolinite, *Al*-chlorides zircon, turmaline, anastase	= ferralization

Ferralization leads to the development of ferralic *B*-horizons, which are diagnostic for Ferralsols (sections "Soil Horizons (after FAO 2006; WRB 2014)" and "Ferralsols (FR)"). Fe and Al accumulate not only in a relative sense, through the preferential impoverishment of other minerals, but also in the absolute sense. As is seen in Fig. 23, the deeper soil layers of the semihumid and especially the humid tropics are permanently wet (gleyization). The Fe^{2+} set free during weathering is not oxidized to Fe^{3+} but remains mobile. It may move laterally with the water flow

Photo 18 Petroplinthite

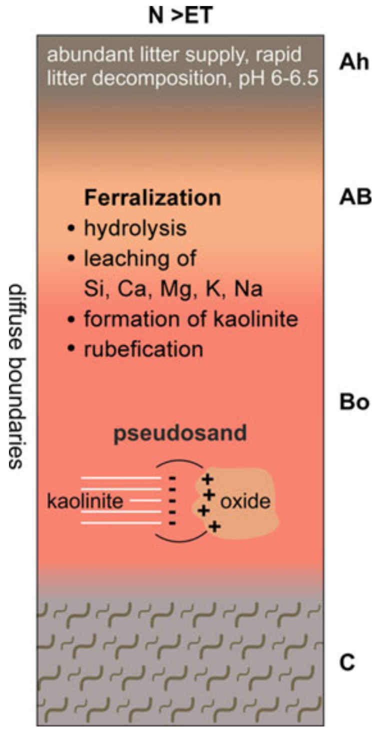
and then be oxidized and deposited at the edges of the slope. This mechanism explains the frequent occurrence of iron crusts at the borders of plateaus, or slopes and the development of Fe (and Al)-enriched materials in depressions. This sesquioxide enrichment is an absolute one, and the soft material is called **plinthite** if it hardens after exposure to the air (then called **petroplinthite**; Photo 18). This may happen in connection with climatic fluctuations or due to tectonic uplift.

Parts of the Fe^{2+}, however, may reach the groundwater level of depressions or hollows due to ascendance. At the contact zone with the oxygen from the air, Fe-enriched horizons are created by gleyization (section "Hydromorphic Features"). The Fe present in the deeper soil layers of extended peneplains is not only subjected to lateral transfer but also to ascendance during drier periods (Fig. 23). This again gives rise to an absolute iron enrichment, often as red mottles above a bleached zone probably due to a combination of gleyization and stagnization. Such horizons with commonly red mottles usually in platy, polygonal, or reticulate patterns within a mixture of iron-rich clay and quartz are called plinthite as long as the material is soft (FAO 1988). They are characterized by irreversible hardening, as soon as they are exposed to the air.



The formation of plinthite is called **plinthization**. It is limited to areas of prolonged, very intensive weathering.

Fig. 24 Soil-forming processes of Ferralsols (Zech et al. 2014)



As mentioned, ferralization and plinthization are a consequence of intensive weathering. In ferralization the relative enrichment of sesquioxides predominates, while plinthization is characterized by absolute sesquioxide enrichment (for more details see Fig. 24). The soils involved are poor in nutrients. The iron/aluminum concentrations in acid substrates may even cause toxicity and *P* deficiency. Demanding tree species cannot grow fast in this environment, and crust formation may further limit land use.

Soil Erosion

Soil compounds are transported not only within the soil profile but also at the soil surface. This phenomenon is based on the exceedance of the mechanical stability and includes mass displacement, as well as water and wind erosion.

Mass displacements occur under the influence of gravity, when the shear resistance between exposed rock overhangs or soil bodies decreases (gravity stronger than cohesion). This is often the case after heavy rains. Depending on slope inclination and specific substrate properties (clay content, swellability, smeary consistence) either slow or rapid mass movements may occur. Examples are soil creep, landslides, and solifluction. Mass displacement is a frequent phenomenon of the humid tropics, especially in regions with high relief energies. In the recent past, the large increase in deforestation has accelerated its occurrence. If saprolites appear at the site of mobilization, mass displacement has negative effects on soil fertility. Great damage may be caused by landslides in regions of afforestation, and in some cases protective walls or terraces may have to be erected. Within the framework of land and soil conservation, steep, slide-prone slopes should be set aside as protected areas with only careful forest management in order to preserve the protective function of the trees.

When water causes the displacement of soil-surface materials, water erosion occurs. Strictly speaking, this is a natural process, which, as time passes, is subjected to certain fluctuations. Water erosion is enhanced due to tectonic uplift, as well as by increase of rain intensities in connection with climate variation. It is now a well-established fact for many tropical forest regions that during the Quaternary climate became periodically cooler and drier, with the dense forests disappearing as a consequence. After heavy rainfalls the fine surface soil was washed away, while the heavier components such as quartzite or Fe/Mn concretions accumulated at the erosion surface giving rise to the so-called stonelines. These too were subjected to displacement as is shown by the deposition of powerful gravel layers. Apparently such phases of tropical forest decline and intensive erosion on the one hand and geomorphological stability with re-expansion of trees and intensive soil forming on the other occurred repeatedly. Human impact on soils generally accelerates water erosion and affects soils negatively, because soil removal concerns first of all the fertile surface horizons. This is especially true for kaolinitic, oxide-rich tropical soils that store nutrients preferentially in the upper humus layers. If soil erosion includes the impoverished unfertile soil layers and exposes layers rich in primary minerals this may, however, be judged as positive soil rejuvenation. The same holds true for the accumulation of fertile sediments in alluvial areas such as the Nile valley.

Water erosion occurs in the arid and humid tropics in the form of sheet (denudation), rill, and gully erosion (Photo 19). The rapid destruction of tropical forests, accompanied by a change to agriculture, as well as overgrazing, accelerate soil removal. Erosion on agricultural fields is called tillage erosion. Erosion rates up to 100–1,000 Mg ha^{-1} $year^{-1}$ have been reported from tropical mountains with volcanic soils and high rainfall intensities and also from Madagascar. A quick establishment of forest plantations can sometimes minimize the damage. Certain tree species, such as *Eucalyptus* or *Tectona grandis,* in monocultures, however, may also hasten soil erosion. Sarrailh (1991) found that in French Guyana soil erosion increased from 0.5 to 16.7 Mg ha^{-1} $year^{-1}$, in connection with the clear-cutting of the rainforest and its replacement with pine plantations. In Sumatra up to 35 cm SOM-rich surface soil was washed away within 15 years after converting the rainforest into oil palm and rubber plantations (Guillaume et al. 2015).

In contrast to water erosion, wind erosion plays only a minor role in the humid tropics. Its greatest impact is on arid and semiarid areas and on the vegetation-free high mountain chains. Wind erosion gives rise to stone plasters in the regions where fine-textured materials are blown away and to accumulation, in the form of dunes and sand covers, in areas where sedimentation occurs.

Wind erosion affects soil fertility. Deflation areas are impoverished, and sedimentation areas may become covered by sand. The deposit of nutrient-enriched

Photo 19 Gully erosion in the Nitisol landscape of southern Ethiopia

sediments improves the soils (Harmatan). Increased destruction of the vegetation by drought, overgrazing, or firewood harvests in endangered regions such as the Sahel undoubtedly accelerates wind erosion, which in this case is a critical component of desertification (Photo 20). The establishment of windbreak plantations (e.g., *Prosopis, Acacia senegal, Eucalyptus camaldulensis,* and others), the reduction of grazing cattle, and agricultural use under controlled conditions may all contribute to lessening the consequences of desertification. The height of such windbreak hedges multiplied by 20 allows a rough approximation about the area with reduced wind speed.

Soil Structure

The physical, chemical, and ecological properties of a soil are derived from the properties of the individual phases (minerals, SOM, water, air). Their spatial distribution, defined as soil structure, characterizes individual soils and is used for purposes of classification. The concept of soil structure includes not only how the solid-phase particles (soil structural units) are distributed but also the arrangements of the pore spaces that are filled either with water or air (pore volume).

One distinguishes between various structural types (Fig. 25). If the particles lie side by side in isolated fashion, as is the case in coarse sandy soils, this is called Single-grain structure. If they form a structured, coherent mass, it is called massive structure. According to particle shape, the following structural types can be distinguished in addition: crumble, polyhedral, prismatic, columnar, platy, angular, blocky, and subangular blocky.

Photo 20 Wind eroson in the Sahelian zone of Senegal

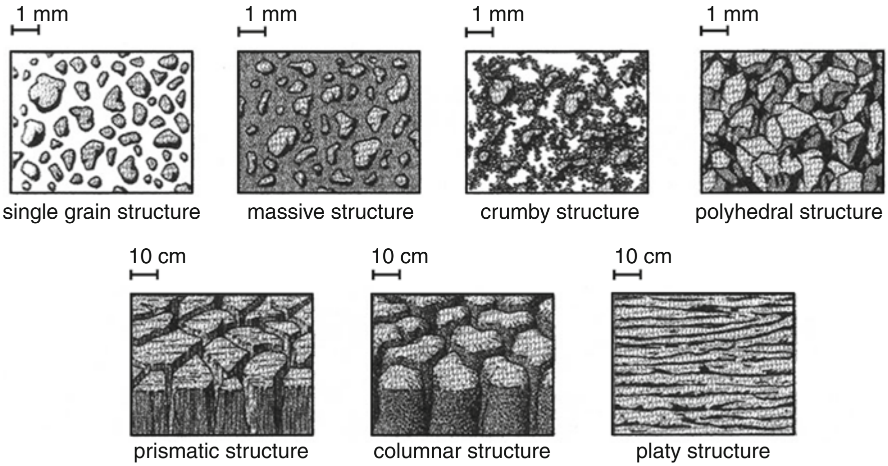


Fig. 25 Main soil structural types (Schroeder 1984)

In biologically active soils, structural units are also formed from the feces of the soil animals. Mineral compounds, humus, as well as fungal and bacterial cultures may become cemented together in their intestinal tract. Fine roots may enhance certain structures. Soils rich in smectites swell and shrink considerably in humid/arid change climates, which leads to the formation of prisms. High salt contents favor aggregation as does the sorption of multivalent cations (Ca^{2+}, Fe^{3+}, Al^{3+}). In Ferralsols (see section "Ferralsols (FR)") Fe and Al oxides link together the clay matrix, so that the finger probe may simulate increased sand content (pseudosand).

An overview of these descriptions shows that there are processes in tropical soils that are at least in part distinctly dissimilar in intensity as well as in direction from those occurring in the temperate and cool climates. These processes lead to typical soil characteristics, the soil horizons, which are described below.

Soil Horizons (after FAO 2006; WRB 2014)

According to FAO (1988), a soil horizon is defined "as a layer of soil, approximately parallel to the soil surface, with characteristics produced by soil-forming processes." Soils with comparable, largely corresponding criteria, i.e., similar sequence of horizons and comparable horizon properties are combined into soil units. At a first level, they are classified according to WRB 2014 into **32 Reference Soil Groups (RSGs)** which "are differentiated mainly according to characteristic soil features produced by primary pedgenetic processes." Many RSGs, for instance, Ferralsols, Acrisols, and Podzols, are representative of major soil regions of the world's soil cover. At a second level of classification "soils are differentiated according to soil features resulting from any secondary soil-forming process that has significantly affected the primary characteristics. In many cases, soil characteristics that have a significant effect on land use are taken into account" (WRB 2014). These features are described by **qualifiers** which are put in front (= **principal qualifiers**) and behind (= **supplementary qualifiers**) the name of the corresponding RSG. In addition, WRB 2014 has introduced **subqualifiers** by combining the name of qualifiers with **specifiers** (e.g., Epi-, Endo-, Thapto-). In section "Reference Soil Groups and their Use in Forestry," the RSGs are introduced, while the qualifiers and subqualifiers, important for soil classification at the Second Level, will only exemplarily be taken into consideration because it would go beyond the scope of this article to introduce them all. Readers interested are referred to WRB 2014 including update 2015. In the present section "Soil Horizons (after FAO 2006; WRB 2014)" firstly the most important horizons and their characteristics are described.

The so-called master horizons and layers of a soil profile are designated by capital letters. Lower-case letters may be added to the capital letters to qualify the characterization of the master horizons. Important symbols for the master horizons and layers are listed in Table 7. Transitional horizons are indicated by the combination of two capital letters like AB, where the first letter characterizes the dominant features. *A*/*B* means that a horizon consists of intermingled but identifiable master horizons, the first one being dominant.

Table 7 Symbols and summarized definitions of master horizons and layers (FAO 2006)

H:	Organic material (SOC $\geq$ 20 % by mass), undecomposed or partially decomposed Formed from organic deposits at the soil surface under prolonged periods of waterlogging Typical surface horizon of wet soils, like Histosols, but may now be artifically drained or buried below the surface
O:	Organic material undecomposed or partially decomposed Formed from litter (leaves, twigs, moss, lichens) at the surface without water saturation for more than a few days per year under well-drained conditions Typically for acid forest soils (e.g., raw humus) with reduced biological decomposition and bioturbation of the aboveground litter In tropical rainforests 0 horizons usually are only some centimeters thick Comprising the fresh litter layer and the partly decomposed but intensively rooted fermentation layer
A:	Mineral horizon commonly at the surface or formed below an O horizon, with at least one of the following properties: The humified organic material is mixed with the mineral phase due to biological activity Usually darker than the adjacent underlying horizons, due to accumulation of SOC Having properties resulting from cultivation (e.g., a ploughed layer), pasturing, etc.
E	Mineral horizon commonly near the surface below an O or A and above a B, rich in resistant minerals of the sand and silt fraction, due to leaching of clay, Al, Fe, and SOC Usually lighter in color than the underlying B All or much of the original rock struture has been obliterated
B	Mineral subsurface horizon, differentiated from the parent material by color, structure, and chemical composition, having at least one of the following properties: Accumulation of clay, Fe, Al, SOM, carbonate, gypsum, or SiO2 (alone or in combination) as indicated by surface leaching (as) in Podzols, Alisols, Acrisols, Luvisols, Lixisols, Calcisols, Gypsisols, Durisols Residual enrichment of Fe, Al due to intensive weathering and impoverishment of Si, Ca, Mg, K (see section "Ferralsols") Clay formation and oxide liberation due to in situ weathering without excessive leaching of Si (as in Cambisols) Evidence of removal of carbonates Having particles covered by sesquioxides coloring the horizon more dark or more red than the overlying and the underlying horizons without illuvation Obliteration of all or much of the original rock structure
C	Unconsolidated mineral horizon or layer which can be dug with a spade usually underlying the solum; not or only weekly influenced by pedogenetic processes but may be influenced by processes not originating from the soil surface; included are layers formed by shells, corals, and diatomeceous earth in the tropics the C horizon may be preweathered (saprolite) or consist of resistant gravel horizons may show signs of chemical alteration and may contain accumulations of carbonates, gypsum, SiO_2, and other easily soluble salts as long as the rock structure is not significantly changed root development is possible
R	Layer of continuous hard bed rock, cannot be dug with a spade No significant root development, except through cracks
I	Ice lenses and wedges containing $\geq$75 % ice by volume
L	Limnic material (organic or mineral) deposited in a body of water
W	Water layers in soils or water submerging soils; permanently or cyclic within 24 h (e.g., tidal water)

The capital letter of a master horizon often is followed by a lower-case letter as suffix for further characterization. For instance Ah, Bh, Bs:

Ah = master A horizon with accumulation of humus
Bh = master B horizon with accumulation/illuvation of humus
Bs = master B horizon with accumulation of sesquioxides

More details about suffix letter designation are summarized in Table 8 and the conventions for their use described in the *Guidelines for Soil Description* (FAO 2006).

In general not more than three suffix letters are used:

Btyz = master B horizon with accumulation of clay (= t), gypsum (= y), and easily soluble salts (= z)
Suffix t has precedence over all other symbols.
Suffix b is always written last.
Suffix @ is always used last and cannot be combined with b.

Sometimes it is necessary to further subdivide thick horizons. This can be done by adding Arabic numerals as suffixes to the letter symbol, for example, ***Ah**1* – ***Ah**2* – ***Ah**3*. Lithological discontinuities are characterized by Arabic figure prefixes, e.g., *Ah-Bws-2Boc-3R* (Fig. 26).

It should be stressed that the letter symbols merely reflect a qualitative estimate, due to the description and interpretation during fieldwork, based on the ideas of the field staff about soil-forming processes, possibly occurring in the soil profile causing the observed properties.

Besides a mere soil profile description, quantitative definitions of the soil horizons and soil properties are necessary for soil classification, using field *and/or* laboratory measurements. These quantitatively defined soil features are called **diagnostic horizons**, **diagnostic properties,** and **diagnostic materials**. They are used for identifying and separating RSGs and qualifiers, and for characterization they are labeled with **, whereas the qualifiers are labeled with *. Annexes 1, 2 and 3 inform about General Definition of diagnostic features and Annex 4 about summarized definitions of the Qualifiers mentioned in the Chapter 1 according to WRB 2014.

Reference Soil Groups and Their Use in Forestry

After the discussion of the processes of soil formation (section "Processes of Soil Formation") and the characteristics they provoke in the pedosphere (section "Soil Horizons (after FAO 2006; WRB 2014)") in the following the Reference Soil Groups according to WRB 2014 are dealt with special reference to the forestry use in the tropics and subtropics.

Table 8 Summarized suffix letter designation (FAO 2006; Zech et al. 2014)

Suffix	Description	To be combined with
a	Highly decomposed organic material with less than one-sixth (by volume) visible plant remains)	H, O
b	Buried genetic horizon	Mineral horizons not cryoturbated
c	Hard concretions or nodules	Mineral horizons
c	Coprogenous earth of aquatic systems	L
d	Dense layer, no root penetration	Mineral horizons strongly compacted (no suffix m)
d	Diatomaceous earth	L
e	Moderately decomposed organic material	H, O
f	Frozen horizon	Not in I and R
g	Influenced by stagnic water	No restriction
h	Accumulation of organic matter	Mineral horizons
i	Slickensides	Mineral horizons
i	Slightly decomposed organic material	H, O
j	Accumulation of jarosite	No restriction
k	Accumulation of secondary carbonates	No restriction
l	Mottling (gleying) at the capillary fringe	No restriction
m	Massive cementation or induration due to pedogenetic processes	Mineral horizons
m	Marl	L
n	Pedogenic accumulation of exchangeable sodium	No restriction
o	Residual pedogenetic accumulation of sesquoxides	Mineral horizons
p	Ploughing or other human disturbance	O, H, A (disturbed E, B, C are designated as Ap)
q	Accumulation of pedogenetic SiO_2	Mineral horizons
r	Nearly permanently strong reduction	No restriction
s	Illuvial accumulation of sesquoxides	B
t	Illuvial accumulation of silicate clay	B, C
u	Urbane and other human-made materials	No restriction
v	Layer containing plinthite	Mineral horizons
w	Development of color and structure due to pedogenetic processes	B
x	Fragipan properties	Mineral horizons
y	Pedogenetic accumulation of gypsum	No restriction
z	Pedogenetic accumulation of salts more soluble than gypsum	No restriction
@	Evidence of cryoturbation	No restriction

Mature Soils of the Humid and Subhumid Tropics

Plinthosols (PT)

Definition. Plinthosols are strongly weathered soils with a plinthic** (soft, symbol Bv), pisoplinthic** (hard concretions, symbol Bvc), or petroplinthic** (hardpan,

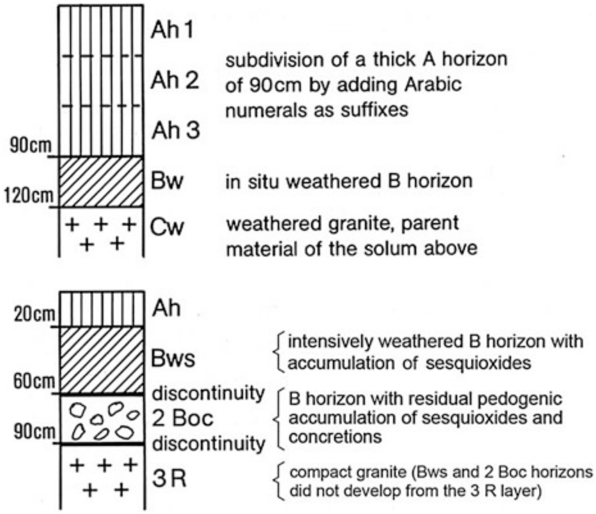


Fig. 26 Examples for the characterization of soil horizons using capital letters, lower-case letters, and Arabic numerals

symbol Bvm) horizon, starting ≤50 cm from the soil surface. Also soils with a plinthite** horizon starting ≤100 cm from the soil surface and having directly above or below its upper limit a layer ≥10 cm with stagnic** properties and periodically reducing conditions are classified as Plinthosols. They have an *Ah-(E-)Bv-C* or *Ah-(E-)Bvc-C* or *Ah-(E-)Bvm-C* profile derived from basic but sometimes also from acid rocks. Plinthite is a mottled, iron-rich, but humus-poor mixture of kaolinitic clay, quartz, and other constituents of intensive weathering (e.g., gibbsite), which becomes irreversibly hard during air-drying changing to a layer of hard concretions or nodules (= pisoliths) or to a continuous or fractured hardpan. Plinthosols are characterized by the accumulation of Fe (hydr-) oxides, originating from the parent material by residual accumulation and/or brought in from other parts in the landscape by groundwater or seepage water. In addition, they show redoximorphic features due to the influence of groundwater or stagnating surface water. **Properties.** The soil-forming processes dominating in Plinthosols are plinthization and ferralization already described in section "Ferralization and Plinthization" (see Figs. 23 and 24). They provoke the specific horizons of Plinthosols with their characteristic physical, chemical, and biological properties which are summarized in Table 9. In Fig. 27 the depth profiles of selected proxies of a Stagnic* Albic* Pisoplinthic* Plinthosol are shown.

Regional Distribution. Plinthosols are found in flat or gently sloping areas with a fluctuating water table and/or stagnating surface water. Their worldwide extent is estimated at ca. 60 million ha. In the humid tropics with long-lasting rainy periods and under a rainforest cover soft plinthite is usually dominating (e.g., eastern Amazon basin, Congo basin, SE Asia), whereas in the subhumid tropics with drier forests and savannas plinthite frequently has changed to continuous hardpans or pisolithic soils due to repeated wetting and drying (e.g., Cerrado region in Brazil, N Astralia, India). This may occur during seasons with fluctuating water tables,

Table 9 Properties of Plinthosols

Physical properties
With plinthic** horizon: high density, often massive structure and water logging, can be dug by spade, fluctuating water table
With petroplinthic** horizon: indurated layer, cannot be dug by spade, may have water logging, cracks are possible
With pisoplinthic** or fractured petroplinthic** horizon: can be dug by spade, low fine earth contents,
Low water storage capacity
Chemical properties
Rich in sesquioxides (e.g., goethite, hematite, gibbsite, partly also rich in *Mn*) and dominance of kaolinitic clay
Nearly no easily weatherable primary minerals in the sand and silt fraction but rich in resistant minerals like SiO_2, TiO_2, $ZrSiO_4$
Low stocks in SOC, *N* and *P*
pH(H_2O) in the surface soil layer of forested soils ~5–6, in the subsoil lower
BS in the topsoil generally low, in the subsoil partly very low
CECpot generally low, mostly $\leq$16 cmol(+)kg^{-1} clay
Variable charge due to the dominance of sesquoxides and low pH
High P fixation and partly Al toxicity
Biological properties
Soil fauna less active
Rootability reduced or not possible
Plants may suffer from water stress during the dry season

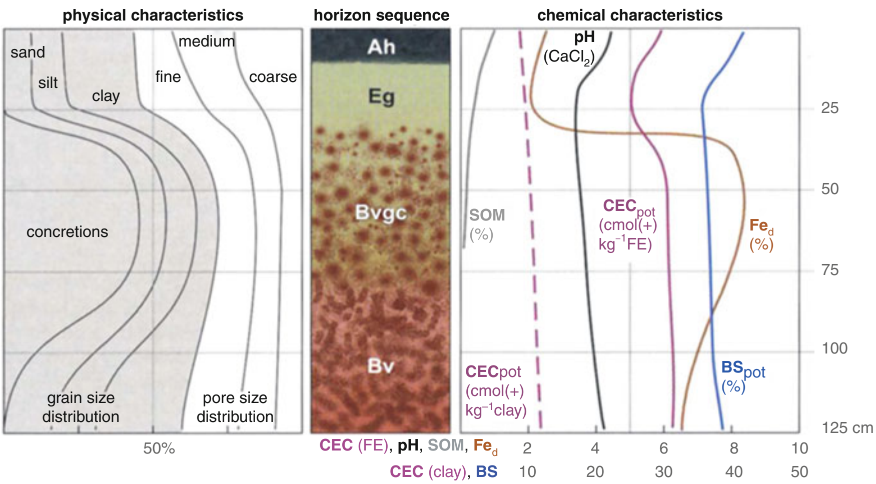


Fig. 27 Depth profiles of selected physical and chemical proxies of a Plinthosol with Pisolithitic* (Bvc), Stagnic*, and Albic* (Eg) qualifiers

after tectonic uplift and climate change toward increased aridity. After erosion of the topsoil pure concretionary layers may be formed. In the Sudano-Sahelian zone typical morphological features are petroplinthic crusts on top or on the border of peneplains and exposed landscape elements. According to the US Soil Taxonomy many of these soils are classified as Oxisols, Alfisols, and Ultisols, for instance, as Plinthaquox, Plinthoxeralfs, or Plinthudults or as Sols gris latéritiques (France).

Forest Management. Since Plinthosols have only a low agricultural potential they are used for grazing or in forestry, but their potential for silviculture is also limited due to frequent waterlogging in bottomlands, high density, low nutrient stocks, and drought during the dry season on soils with petroplinthic** and pisoplinthic** horizons. After clearing the natural forests, causing accelerated topsoil erosion, the potential danger of hardening will even increase.

In SE Liberia yield data of the rainforests growing on Plinthosols associated with Ferralsols and Gleysols have been found to be significantly correlated with the Corg, *N*-, and *P*-reserves of the soils (Zech and Forster 1986), but no symptoms of mineral deficiency could be observed. Results of ^{31}P NMR spectroscopy and P adsorption experiments suggested the existence of an intact natural P cycle essentially based on organically bound P which may be rapidly disturbed by deforestation and SOM mineralization (Forster and Zech 1993). Pine plantations established along this catena failed, developing multiple mineral deficiencies. Only species like *Acacia auriculiformis* grew well. Reforestations on Petric* Plinthosols are even suspicious to drought during the dry season (Zech and Drechsel 1992). Chave et al. (2010), studying litterfall in South American tropical rainforests, found no consistent variation between Plinthosols, Ferralsols, Acrisols, and other soil types. Across old-growth tropical rainforests total litterfall averaged 8.61 ± 1.91 Mg ha^{-1} year^{-1}, and on Plinthosols the corresponding values were 7.23 and 7.90 Mg ha^{-1} year^{-1}. Tom-Derg et al. (2014) evaluated the regeneration potential of remnant forests (with *Anogeissus leiocarpus* Guill&Perr, *Alaeis guineensis* Jacq., *Ficus* and *Terminalia* spec., etc.) growing on Plinthosols in the transitional zone of Ghana. They recommended the establishment of plantations with exotic and indigenous tree species on these soils characterized by hardpans in an average depth of only 42 cm. In Matto Grosso (Brazil) Petric* Plinthosols were studied by Filho Carvalho (2008) with the objective to identify their suitability for the establishment of *Eucalyptus* plantations. Similar trials were carried out on Plinthosols in southern Brazil with *Leucaena* species (Kaminski et al. 2005). Well known is that cashew and cacao plantations were successfully established on Plinthosols with pisoplinthic** horizons in India and in western Africa. Also productive home gardening on Plinthosols is reported from Ghana (Fening et al. 2005). In South Africa the effects of long-term agricultural land use of Stagnic* Plinthosols (Dystric*, Siltic*) were studies by Lobe et al. (2001). After 90 years of cultivation about 65 % of SOC and 55 % of N were lost in comparison to the grazed control plots. The most pronounced decrease of SOC and *N* occurred already after 10–15 years of cultivation. To increase soil fertility and sustainability the authors recommended green manuring despite grass fallow (Photos 21 and 22).

Photo 21 A Plinthosol with a Petroplinthic** horizon starting ≤50 cm from the soil surface and being at least ≥10 cm thick is classified as Petric* Plinthosol

Ferralsols (FR)

Definition. Ferralsols are red to yellow, deeply weathered soils of the humid and subhumid tropics with deep A-Bo-C profiles and diffuse boundaries between the horizons (Photo 23). The diagnostic layer is the ferralic** horizon, a mineral subsurface horizon starting ≤150 cm from the soil surface and resulting from long and intense weathering. It is rich in resistant minerals such as (hydr-)oxides of Fe, Al, Mn, Ti and has a texture of sandy loam or finer with normally <10 % water-dispersible clay. The clay fraction mainly consists of low-activity clays (e.g., kaolinite), and the sand and silt fractions may be rich in residual quartz. Coarser fragments like pisoplinthic concretions or remnants of a petroplinthic** horizon comprise <80 % by volume. CEC_{pot} is <16 cmol(+) kg^{-1} clay and CEC_{eff} <12 cmol(+) kg^{-1} clay. The amount of weatherable minerals is less than 10 % (by grain count) in the 0.05–0.2 mm fraction. The Bo horizon has a thicknes of ≥30 cm. The dominant process is ferralization (section "Ferralization and Plinthization" and Fig. 24) which proceeds more rapidly in basic parent materials than in acid ones. Mostly the Ferralsols have no argic** horizon.

Properties. The physical properties of most Ferralsols are favorable, making the soils easy to work, but the chemical properties are very poor. Table 10 informs about the main properties, and in Fig. 28 the depth profiles of selected proxies of a Rhodic* Ferralsol are shown.

Regional Distribution. Ferralsols are widespread in the humid tropics on the continental shields of South America, Africa, and eastern Madagascar associated with stable geomorphic landforms of Pleistocene age or older. They also occur in

Photo 22 A plinthic** horizon hardens irreversibly during air drying. The material then can be used for making bricks

humid tropical SE Asia. Their global extent is estimated at some 750 million ha. Ferralsols can be found as relics also in arid zones where they have developed during humid periods in former times. Many of these soils are known as Oxisols (Soil Taxonomy) and as Ferralitic Soils (Russia) (Photo 23).

Forest Management. Tropical rainforests and semideciduous forests are the natural vegetation of Ferralsols. Covered by natural forests the nutrient fluxes are more or less "closed," comprising litterfall, litter decomposition, and nutrient release. Immediate nutrient uptake in the intensively rooted surface horizons exclude heavy losses due to water percolation and surface erosion. Deep-rooting trees can take up nutrient elements from greater soil depth and contribute by litterfall to improve fertility of the topsoil layers. After clearing and burning of the natural forests, SOM is rapidly mineralized, and outwash of nutrients is tremendous because cation retention by the mineral soil fraction is weak (Table 11). Also surface soil compaction occurs especially due to logging operations. Schack-Kirchner et al. (2007), for instance, studied the response in bulk density and saturated hydraulic conductivity by logging machinery on an Amazonian Ferralsol under native forest. It could be shown that under wet soil conditions saturated hydraulic conductivity rapidly declined and surface bulk density increased. The

Photo 23 Rhodic* Ferralsol (Clayic*, Dystric*) with Ah-Bo horizons. Diagnostic is the red ferralic** Bo horizon rich in hematite and kaolinite. It develops due to intensive chemical weathering with residual accumulation of sequioxides

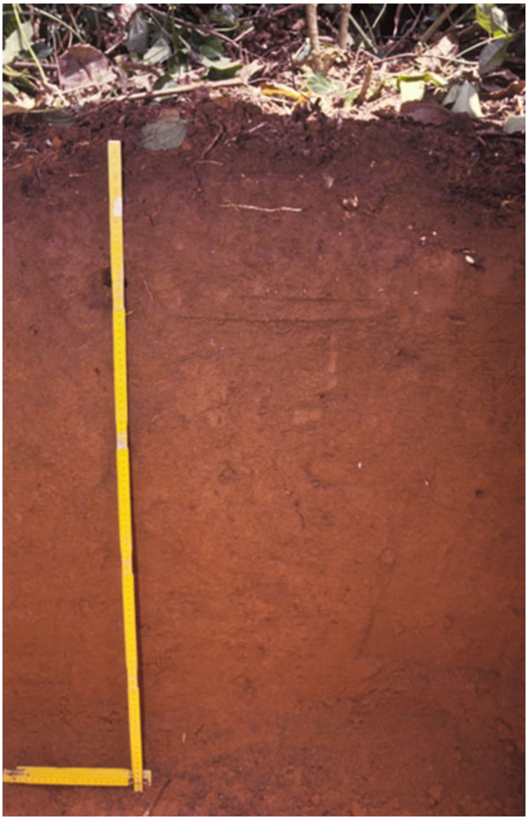


Table 10 Properties of Ferralsols

Physical Poperties
Color of the Bo horizon yellowish (rich in goethite) or reddish (rich in hematite)
Stable microstructure due to the formation of pseudosand, low erosion hazard
Macrostructure friable and easy to cultivate
Low plant available water storage capacity, high infiltration rate, high pore volume
Chemical properties
$pH_{(H2O)}$ in the topsoil below forest about 6.5 due to the accumulation of base cations by litterfall
$pH_{(H2O)}$ in the subsoil about 5 or lower, also BS is low
Low total reserves in base cations
Fe_o and Al_o low, Fe_d and Al_d high
Strong *P* fixation
Al, Mn, and Fe toxicity possible
Biological properties
High microbial activity under tropical rainforests since continuously humid and warm
Roots can penetrate deeply and easily

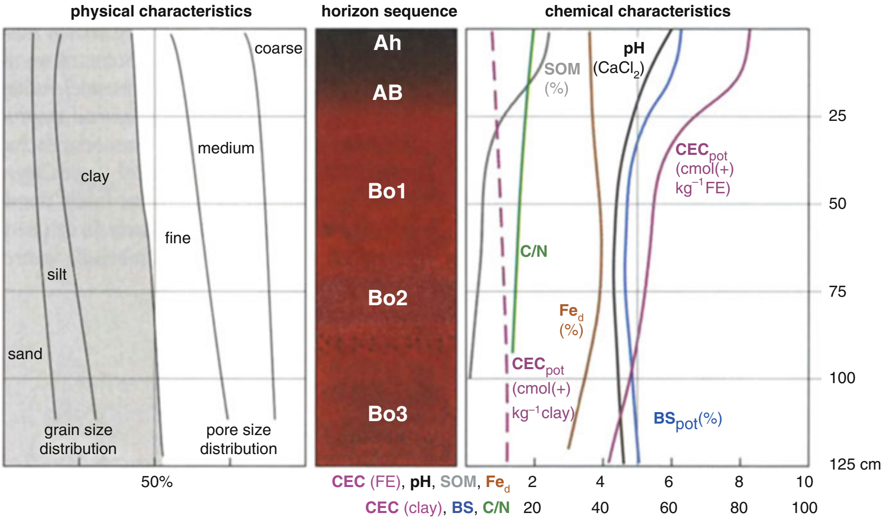


Fig. 28 Depth profiles of selected physical and chemical properties of a Rhodic* Ferrasol (Zech et al. 2014)

Table 11 Effects of clearing and burning the natural forests

SOC, nitrogen and sulfur stocks decrease
CO_2, NO_x, and SO_x emissions increase stimulating climate change
Strong leaching of K, Ca, Mg, NO_3, and NH_4
Enrichment of the topsoil layer with ash and soluble calcium phosphates
Increase of pH, stimulation microbial activity
Surface soil compaction and increased erosion hazard

authors recommended restricted logging operations especially in sloping areas in order to prevent soil erosion. Destroying the forest cover results in the interruption of nutrient cycling. Soil regeneration under secondary forest needs up to 15–20 years. Mechanized clearing (Photo 24) often removes the nutrient-rich surface horizons. That is why "slash and burn" is a better method. Most plant available nutrients are associated within the soil organic matter. Therefore, a humus-saving management is necessary. Liming of very acidic Ferralsols increases soil pH, raises the effective CEC, and combats Al toxicity. Recommended is the repeated application of small doses ($\leq$2 Mg ha^{-1}) of lime or dolomite to avoid decreasing the anion exchange capacity, the destruction of the stabile pseudosand structure, and the accelerated SOM mineralization. Both in agriculture and plantation forestry thorough application of lime and mineral fertilizers can support sustainability (Zhang et al. 2007). In crop production on highly acidic Ferralsols the positive "self-liming effects" of gypsum are well documented, including improved supply with Ca and S besides reduction of toxic Al levels (e.g., Churka et al. 2013). But in tropical forestry gypsum application seems not to be frequently

Photo 24 Mechanized clearing of rainforests with heavy machinery. It results in increased SOM mineralization, soil compaction, and high erosion hazard (Liberia)

Photo 25 Phosphorus deficiency on *Triplochiton scleroxylon* planted on Ferralsols in Ivory Coast. Due to intensive wheathering the *P*-containing minerals like apatites are destroyed resulting in low *P* stocks. In addition *P* is less plant available because phosphate anions are strongly sorbed on sesquioxides

practiced (Herbert and Fownes 1995). In contrast to natural forests fast-growing tree plantations with *Pinus caribaea, Pinus oocarpa, Eucalyptus* sp., *Terminalia ivorensis, Cedrela odorata, and Gmelina arborea* often show multiple deficiency symptoms (Zech and Drechsel 1992). *P* is usually the most limiting factor due to low *P*-stocks and high *P*-fixation capacities of the Ferralsols (Photo 25). To increase the success of reforestation projects on *P*-deficient soils, the application of slow-release phosphate rock (several tons per ha) or more soluble triple superphosphate may be helpful, for instance, in bands, furrows, or directly in the planting hole (Fernandez et al. 2000). Besides *P*, also supply with *N* is frequently adequate, and

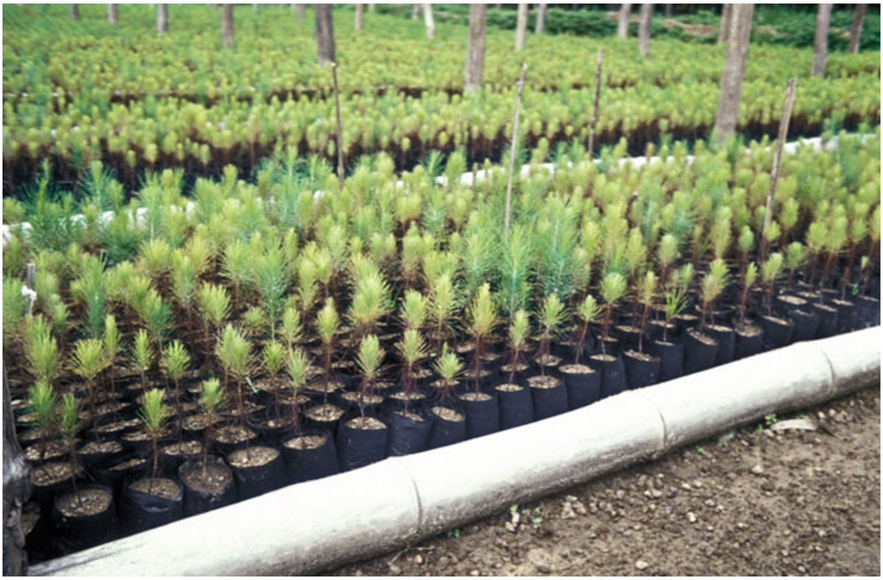


Photo 26 Mineral deficiency of *Pinus caribaea* (nursery in Cape Mount, Liberia). Seedlings were cultivated in Ferralsol material without inoculation with mycchorizas

Graciano et al. (2006) could demonstrate that fertilization with P also increased *N* absorption of young plants of *Eucalyptus grandis*. *Tectona grandis,* a *Ca*-demanding species, is less suited for Ferralsols. In Liberia, planted on Xanthic* Ferralsols, even teak suffered from Mn deficiency because Mn is very soluble at low pH and can be easily leached off the soil. But also Mn toxicity may occur (Becquer et al. 2010). Besides Mn other micronutrients like zinc, copper, and boron may become deficient in Ferralsols. Numerous studies are related to microbial processes of Ferralsols. For example, Menyailo et al. (2003) analyzed the effects of single trees from plantation species and species from primary and secondary forests. They concluded that individual tree species more strongly affected N transformations than *C* respiration. Also a close interrelationship between *C* and *N* transformations in the studied Xanthic* Ferralsols was detected. Agroforestry and the application of charcoal together with manure and mineral fertilizers could be suitable tools for sustainable use of Ferralsols (Atangana et al. 2014; Nair 1993; Young 1997; Lehmann et al. 2003; Steiner et al. 2008). In nurseries the growth of seedlings is strongly improved by inoculation with mycorrhizas (Photo 26).

Nitisols (NT)

Definition. Nitisols are clayey reddish brown tropical soils with deep *Ah-Bo-C or Ah-(E-)Bto-C*-profiles with gradual to diffuse boundaries between A- and B-horizons. The diagnostic layer is the nitic** horizon, a clay-rich subsoil horizon with ≥30 % clay, starting ≤100 cm from the soil surface. It has a stable blocky structure breaking under pressure into polyhedral, flat-edged, or nutty-shaped

Table 12 Properties of Nitisols

Physical properties:
Texture class of the subsoil is clay loam or finer, only few coarse particles >2 mm
Structure of the mineral surface layer is crumby to subangular, in the deeper layers angular blocky
Stable aggregates, hard when dry, friable when moist, then breaking into nut-shaped elements
Low erosion hazard, good workability
In the B-horizon shiny ped faces when moist due to pressure stress, also clay illuvation may occur
High porosity up to 50–60 %, high water permeability, no stagnating water, no reducing conditions
Many medium-sized pores, high available water storage capacity
Chemical Properties
The ratio between active and free iron (Fe_o/Fe_d) is $\geq$0.05 indicating that Nitisols are relatively young soils
Higher amounts of easily weatherable minerals than in Ferralsols and Acrisols
pH(H_2O) 4–7, BS in the topsoil up to 90 %, in the subsoil often low
High *P* sorption may occur but usually no acute P deficiency
Nutrient supply good, high SOM and *N* stocks
CECpot usually higher than in Ferralsols and Acrisols due to higher amounts of SOM and sometimes with smectites, allophanes, imogolites; mostly <36 cmol(+) kg^{-1} clay, partly even less than <24 cmol(+) kg^{-1} clay
Biological Properties
High bioturbation and good rootability
During the rainy season high *C* and *N* mineralization

aggregates with shiny faces when moist. The Bto-layer may satisfy the requirements of an argic** and ferralic** B-horizon, but its clay content is not much higher (<20 % difference over 15 cm) than in the overlying horizon, thus clay illuviation seems not to be a dominant process. In addition, the intermediate CEC of nitic** horizons distinguishes them from ferralic** horizons; also leaching of base cations and Si is less advanced than in Ferralsols, indicating that Nitisols are "younger." But overlapping of argic** and ferralic** with nitic** horizons may occur. Nitisols are lacking petroplinthic**, pisoplinthic**, plinthic**, or vertic** horizons starting $\leq$100 cm from the soil surface, and reducing conditions do not occur above or within the nitic** horizon. Generally Nitisols are rich in sesquioxides (gibbsite, hematite, goethite) with high contents of Fe_d ($\geq$4 %) and Fe_o ($\geq$0.2 %) in the fine earth fraction. The clay fraction is dominated by LACs (kaolinites, halloysites, metahalloysites), but also smectites may be present.

Properties: The main soil-forming processes in Nitisols are humification, high bioturbation, pronounced aggregation, initial ferralization, and in some soils also clay illuviation (see section "Processes of Soil Formation"). Their physical and chemical properties are summarized in Table 12, and Fig. 29 informs about the depth profiles of selected properties of a Dystric* Rhodic* Nitisol (Humic*) derived from volcanic parent material.

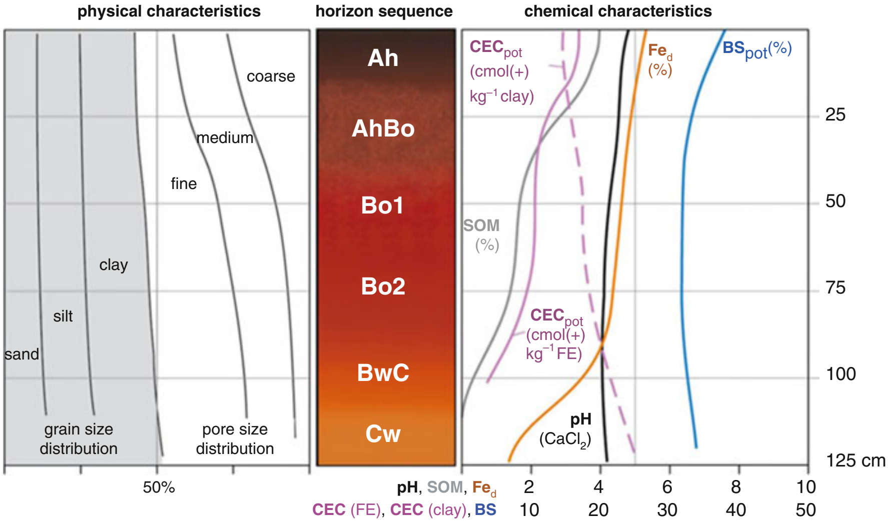


Fig. 29 Depth profiles of selected physical and chemical properties of a Dystric* Humic* Rhodic* Nitisol (Humic*) derived from volcanic parent material (Zech et al. 2014)

Regional Distribution: Nitisols generally develop from intermediate to basic parent material (e.g., basalt, gabbro, diorite) in the savanna zones with pronounced wet and dry seasons, but they also occur under tropical rainforests. Worldwide they cover about 200 million ha, especially in the highlands of Africa (Ethiopia, Kenya, Eastern Kongo, Rwanda, Burundi, Cameroon). Nitisols are represented also at lower altitudes, e.g., in Brazil, Venezuela, Middle America, Cuba, SE Asia, and Australia. In regions with volcanic parent material input of ash may be of relevance. Nitisols are predominantly found at the border of peneplains, in slope position of volcanic landscapes (Fig. 5 below *Podocarpus* Forest), or in karst pokets of limestone plateaus. According to the US Soil Taxonomy Nitisols correlate with Great Soil Groups of Alfisols, Ultisols, Inceptisols, and Oxisols. In France they are classified as Sols fersialitiques or Ferrisols.

Forest Management. The physical and chemical properties of Nitisols are highly favorable, and they belong to the most productive tropical soils, intensively used for crop production. Relatively small areas are available for silviculture. No serious problems are known as far as rootability, water, and nutrient supplies of native forests are concerned. High amounts of amorphous Fe and Al may reduce *P*-availability to some extent. Nitisols used for food and plantation crop production (coffee, tea, cocoa, rubber) should be fertilized with phosphate rock or superphosphate. On steeper slopes erosion might be a problem after clearing and harvesting of the timber.

In the Munessa forest of southern Ethiopia remains of dry afromontane forests exist with 400-year-old specimen of *Podocarpus falcatus* growing on Mollic* Nitisols (Fritzsche et al. 2007). Parts of these natural forests are in the meantime converted into plantations with *Pinus patula*, *Cupressus lusitanica,* and *Eucalyptus globulus*. Twenty-one years after the conversion to monocultures bulk SOC, N, and S concentrations and stocks in soil to 20 cm depth were not significantly changed. But in the sand and silt tractions from the plantation samples a significant reduction was found, yet not visible in bulk soil samples, indicating that the analysis of SOC, *N,* and *S* concentrations in soil particle sizes allows a sensitive detection of initial changes in soil fertility resulting in the conversion of natural forests into tree plantations (Ashagrie et al. 2005). In contrast, deforestation of the natural forest and subsequent agricultural management during 30 years led to a significant depletion of total SOC (63 % = 40.2 Mg ha^{-1}) and N (60 % = 3.1 Mg ha^{-1}) in the fine earth of surface soils (0–10 cm); also the chemical composition of SOM changed markedly (Solomon et al. 2002a). $\delta^{13}C$ values of bulk soils of the natural forests at Munessa were significantly lower (−23.4‰) than those from the corresponding cultivated fields (−15.5‰). Forest clearing and continuous cultivation during 30 years resulted in a loss of 96 % of the initial forest-derived SOC in the sand fraction, while 85 % was lost in silt and 61 % in clay. These results indicate again that SOC in sand and silt is a more labile component than SOC in clay and highly sensitive to changes in SOC stocks in response to forest clearing (Solomon et al. 2002b).

Ashagrie and Zech (2011) studied the input of rainwater to the forest floor and the composition of rainfall and throughfall water in the Munessa natural forest (below *Podocarpus falcatus, Cordia africana, and Punus africana)* and monocultures with *Eucalyptus globulus* and *Cupressus lusitanica* growing on Nitisols. The natural forest and the *Cupressus* plantation intercepted larger proportions (47 %) of the rainfall water compared to *Eucalyptus* (18 %). Annual *N* input (NH_4-N + NO_3-N) per ha and year by rainfall was 2.05 kg. At the forest floor under natural forest only 0.78 kg were measured, under Eucalyptus 0.8 kg, and under *Cupressus* 0.67 kg. Similar tendencies were found for *S* and *P*, indicating uptake of these nutrients from the atmospheric sources. In contrast, elements such as K, Ca, and Mg were leached from the canopy making throughfall more alkaline than precipitation. The figures for *K* (in kg ha^{-1} $year^{-1}$) are given, for example, input by rainfall 0.80, under natural forest 9.28, under *Eucalyptus* 9.01, and under Cupressus 4.02. Thus precipitation seems to contribute to the nutrient supply of the forests under study despite the relatively high fertility of the Nitisols.

In order to increase plantation productivity, improved silvicultural management practices, like intensive thinning, were introduced in stands with *Cupressus, Pinus,* and *Eucalyptus* growing on Nitisols in the Munessa forest. Fourteen months after thinning SOC and nutrient pools in the forest floor layer and in the mineral soil did not change consistently. Interestingly foliar *N* contents in the tree leaves of the thinned plots decreased in comparison to the control plots, likely indicating competitive effects of the forest floor vegetation, strongly expanding after thinning, and assimilating much of the mineralized *N* (Photos 27 and 28). Fourteen months after intensive thinning of the *Cupressus* plantations with removal of 35 % and 75 % of the trees, no significant effects on the microbial utilization of litter-derived N^{15} and C^{13} could be detected between these two treatments, indicating no quick reaction of

Photo 27 Forest floor vegetation below *Pinus*: control plot, not thinned

Photo 28 Forest floor vegetation below *Pinus*: 14 months after thinning

the microbial community on medium and strong opening of the canopy. But between natural forests and unthinned *Cupressus* plantations microbial utilization of litter-derived C^{13} was significantly different, being higher below *Cupressus* during the wet season and reduced during the dry period. These results allow the conclusion that the establishment of *Cupressus* monocultures on Mollic* Nitisols does not rapidly lead to the deterioration of the soil microbial activity (Benesch et al. 2014).

In the Munessa forest Tesfaye et al. (2010) studied the regeneration potential of indigenous tree species. They found that *Polyscias fulva, Pouteria adolfi-friederici,* and *Syzygium guineense* need special and immediate attention for conservation. According to Girma and Mosandl (2012) and Girma et al. (2010) the rehabilitation of degraded natural forests on Nitisols in southern Ethiopia is most successful by enrichment planting with *Juniperus procera* and *Podocarpus falcatus*, whereas *Cordia africana* and *Prunus africana* are difficult to cultivate.

Acrisols (AC)

Definition. Acrisols are strongly weathered acid soils especially of the humid subtropics with an *A-E-Bt-C*-profile if undisturbed or an *A-Bt-C*-profile if eroded. The usually red to yellow subsoil Bt-horizon has higher clay contents than the overlying layer mainly due to clay lessivation (section "Lessivation"). The B-horizon has the properties of an argic** horizon starting $\leq$100 cm from the soil surface, having a low CEC_{pot} <24 cmol (+) kg^{-1} clay and a low BS_{eff} <50 %. The clay fraction consists of low-activity clays. Leaching of base cations, iron oxides, and clay minerals from the surface layers to the subsoil may lead to a bleached eluvial E horizon which can develop the properties of an albic horizon. But Acrisols do not show the interfingering of coarser-textured albic** material into the finer-textured argic** horizon forming whitish vertical and horizontal coatings on soil aggregate surfaces (retic** properties). A-horizons have usually low SOM contents; only if the SOC contents in the fine earth fraction is $\geq$1 % in the upper 50 cm of the mineral layer, the supplemenatry qualifier Humic* is used, and these soils are named Acrisol (Humic*).

Properties. The genesis of Acrisols is mainly characterized by lessivation (section "Lessivation") comprising mobilization of clay and iron oxides in the surface layers and illuvial accumulation of these compounds in the Bt-horizons. This may reduce permeability and cause some hydromorphy (section "Hydromorphic Features"). But the textural differentiation of Acrisols may also be caused by advanced pedogenetic clay formation in the subsoil, by destruction of clay in the topsoil, by accumulation of coarser material in the surface layer due to biological activity, etc. For some Acrisols also initial ferralization may be of relevance (section "Ferralization and Plinthization"). Table 13 informs about the main properties of Acrisols, and Fig. 30 shows the depth profiles of selected physical and chemical characteristics of a Chromic* Albic* Acrisol.

Regional Distribution: Acrisols are typical soils of humid tropical, humid subtropical, and monsoonal regions; they may also occur in warm temperate regions. Topography is mostly hilly to undulating. In the humid tropics they are associated

Table 13 Properties of Acrisols

Physical properties
If dry periods occur, mineral surface layers may show "hard setting," reducing rooting
Silty topsoil layers may have low aggregate stability causing high erosion hazard
Compactness of the Bt-horizon often induces water-logging during the rainy period
Chemical properties
Strongly weathered but less than Ferralsols
Clay fraction with traces of primary minerals and trimorphic clay minerals but kaolinite is dominating
Enriched of stable Fe/Al-oxides
Poor in soil nutrients, nutrient stocks mainly in the phytosphere
CEC_{pot} <24 cmol (+) kg^{-1} clay in some parts of the argic** horizon within ≤50 cm below the upper limit
ph(H_2O) near 5, in the topsoil frequently lower
BS_{eff} <50 % in the major part between 50 and 100 cm from the mineral soil surface or in the lower half of the mineral soil above hard material starting ≤100 cm from the mineral soil surface
Al-toxicity and P-fixation may cause problems
Biological properties
After forest clearing decrease of the biological activity of the soil
Poor rootability due to low pH values, periodical water-logging and "hard-setting" of the topsoil
Bioturbation can be strongly stimulated by application of lime and phosphate in combination with *N*-fixing fodder plants

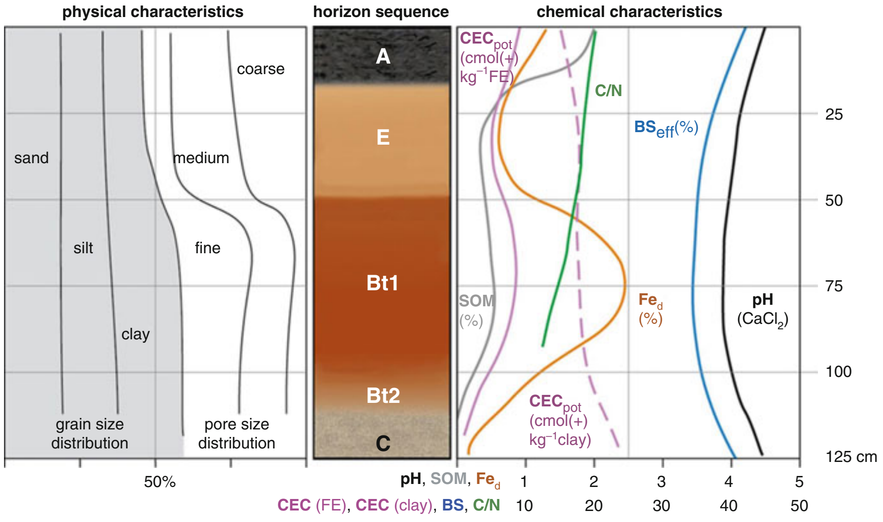


Fig. 30 Depth profiles of a Chromic* Albic* Acrisol derived from Paleozoic metamorphic rock (Zech et al. 2014)

Photo 29 The Atlantic Forest in SE Brazil is called Mata Atlantica and looks similar to a rainforest, soils are mostly Acrisols

with Ferralsols dominating on the old peneplains whereas Acrisols occupy the younger relief generations like slopes and piedmonts. Acrisols derive from a variety of parent materials, frequently from deeply weathered intermediate to acid rocks. They cover about 1,000 million ha worldwide, for instance, in the SE of USA, Middle and South America (Llanos, Mata Atlántica (Photo 29)), East and West Africa, and Southeast Asia. Many Acrisols correlate with Ultisols rich in low-activity clays (US Soil Taxonomy) and with Sols ferralitiques fortement ou moyennement désaturés (France).

Forest Management. Forests ranging from rainforests to open woodland are the natural vegetation of Acrisols; but they are also found under savanna, especially in South America. As shown in Table 13, the physical properties are not very favorable and the chemical ones really poor. Thus the agricultural value is restricted and low–input farming not very promising; but the traditional way of "slash and burn" is widely used. If the fallow period is long enough, regeneration of soil fertility is satisfactory. According to Drechsel et al. (1991a), regeneration capacity of *Cassia siamea, Albizia lebbeck, Acacia auriculiformis,* and *Azadirachta indica* planted on Ferric* Acrisols proved to be superior compared with natural grass/herb fallow in building up surface soil fertility. However, differences with natural bush fallow were not significant. Sometimes also *Anacardium occidentale* is mentioned as adapted to Acrisols, but compaction of the Bt-horizon immediately reduces the potential of this tree. Sustainable cultivation of acid-tolerant crops like oil palm, cashew, rubber, tea, and coffee requires at least low input of mineral fertilizer and lime. Erosion hazard in areas with hilly topography is high, especially after

Photo 30 In northern Madagascar the natural forests growing on Acrisols are widely destroyed by burning. The consequences are intensive mass movement, soil erosion, and inundation in the lowlands. Forest relicts are only conserved in concave slope positions

large-scale forest clearing. The weak structure of the surface horizon favors sealing and erosion (Photo 30). Agroforestry may help to combat degradation of Acrisols without making high inputs necessary.

Bonell et al. (2010) studied in the Western Ghats of India the hydrological conductivity of Acrisols associated with Nitisols under native mixed forests, degraded forests, and plantations with *Acacia auriculiformis*. Lowest surface permeability was found in the degraded forests. Seven to ten years after the establishment of the *Acacia* plantation a progressive restoration of the near-surface permeability was detected. But it remained quite low compared to the native mixed forest. Forest degradation and conversion to agriculture does not only negatively influence physical soil properties but also the chemical and biological ones. Leite et al. (2004), for instance, showed that within 54 years after the conversion of the Atlantic Forest (Photo 29) in Brazil to different tillage treatments, SOC and *N* stocks in the upper 20 cm of Acrisols decreased by 37 % and 32 %, respectively. Da Silva et al. (2012) evaluated soil microbial biomass and activity in Haplic* Acrisols under natural forest, 10 and 20 years regenerated forests, and sugarcane plantation. They found higher microbial activity in forested lands in comparison to cropland.

Alisol (AL)

Definition. Alisols and Acrisols are very similar, both having higher clay contents in the subsoil than in the topsoil, mainly due to clay lessivation (see section "Lessivation"), resulting in an argic** horizon starting ≤100 cm from the soil

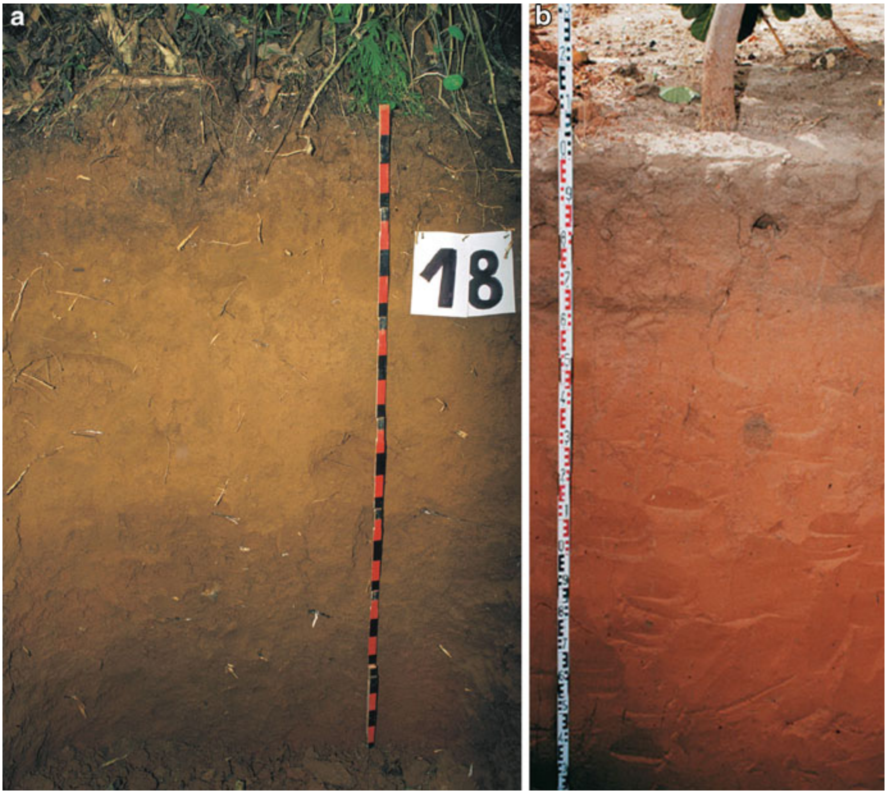


Photo 31 (**a**) Chromic* (Endogleyic*) Alisol with Ah (0–20 cm), E (20–70 cm), and Bt (70+ cm) profile derived from pyroclastic sediments (Zona Norte, Costa Rica). (**b**) Rhodic* Lixisol (Ochric*) with Ah (0–10 cm), E (10–50 cm), and Bt (50+ cm) profile. pH values near 6 due to the aeolian input of base cations (N-Senegal)

surface. They differ in CEC_{pot} of the argic** B-horizon, which is equal to or more than 24 cmol(+)kg^{-1} clay in Alisols and rich in high-activity clays. Alisols have an *A-E-Bt-C*-profile if undisturbed (Photo 31a) or an *A-Bt-C*-profile after erosion. The bleached eluvial E-horizon between the surface A- and the argic** B-horizon indicates the leaching of sesquioxides together with clay minerals, potentially developing the properties of albic** material. Like Acrisols also Alisols do not show the interfingering of coarser-textured albic** material into the finer-textured argic** horizon forming whitish vertical and horizontal coatings on soil aggregate surfaces (retic** properties). Also the argic** B-horizon is acidic due to leaching of base cations; BS_{eff} is $< 50\ \%$ in the major part between 50 and 100 cm from the mineral soil surface or in the lower half of the mineral soil above an indurated layer starting $\leq$100 cm from the mineral soil surface. Generally Alisols have higher contents of exchangeable Al but are less weathered than Acrisols.

Properties. Like Acrisols also Alisols have only a limited value for agriculture. Main limitations concern erosion hazard and *Al*-toxicity. Properties are summarized

Table 14 Properties of Alisols

Physical properties:
Low structural stability of the commonly silty surface horizon resulting in a reduced permeability
High erosion hazard
B-horizons normally have angular blocky or prismatic structures and are often compact inducing water-logging during the rainy season
In subhumid regions water stress during the dry season, development of dessication cracks due to the shrinking of the high-activity clays
Chemical properties:
Generally low SOM contents in the A-horizon
In the clay fraction mainly high-activity clays (illite, vermiculite, smectite, secondary chlorites) besides kaolinite and halloysite; $CEC_{pot} \geq 24$ cmol(+)kg^{-1} clay
$pH_{(H2O)}$ in the subsoil about 5, in the topsoil even lower; $BS_{eff} < 50$ %
Toxic Al levels below the A-horizon, exchangeable Al partly >70 %, often *P*-fixation
Low nutrient contents and stocks, most of the primary minerals are lost
Biological properties:
Low bioturbation, pH is too low
Rootability reduced causing drought stress during the dry season

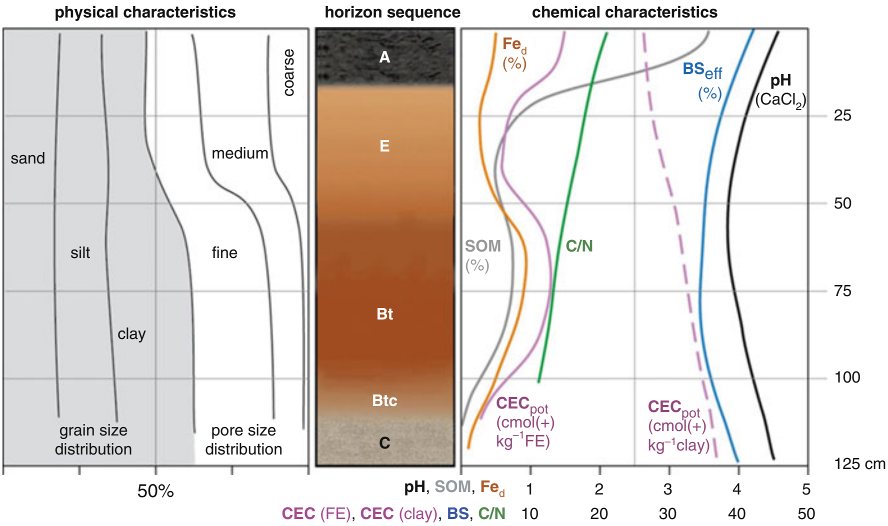


Fig. 31 Depth profiles of selected physical and chemical characteristics of a Chromic* Alisol derived from basic magmatite (Zech et al. 2014)

in Table 14, and Fig. 31 informs about the depth profiles of selected physical and chemical characteristics of a Chromic* Alisol.

Regional Distribution. Alisols are most common in hilly or undulating landscapes of tropical, subtropical, and temperate humid regions; they also occur in monsoonal climates. Alisols derive from a wide variety of parent materials, predominantly from basic and unconsolidated substrates. Among others they occur in South America (Brazil, Venezuela, Columbia, Peru, Ecuador), Central America (Nicaragua, Costa Rica), West and East Africa, southeastern Asia, China, Japan, southeastern USA, and around the Mediterranean Sea. The total area with Alisols is estimated at about 200 million ha. Many of them correspond to Ultisols rich in high-activity clays (US Soil Taxonomy), Fersialsols, and Sols fersiallitiques très lessivés (France).

Forest Management. Fertility of Alisols is low; they are commonly used for subsistence agriculture and extensive grazing. If limed and fertilized, the agricultural potential can be increased due to the high CEC. Liming and fertilzing also allow the sustainable cultivation of acid-tolerant plants like oil palms, rubber, cashew, tea, and coffee. Less is known about the silvicultural potential, as Alisols were only recently introduced as a separate Reference Soil Group. Jahn and Asio (1998) and Asio et al. (1998) described the properties of Alisols covered by dipterocarp forest in Leyte, Philippines. It could be shown that forest conversion to secondary land use decreased SOM, *N*, and available *K*, but pH, available Ca, and Mg tended to increase, likely due to burning. Since Alisols as well as Acrisols are known to be erosion prone (Photo 30), selective logging may better conserve SOM of the surface soil than clear-cutting operations.

Lixisols (LX)

Definition. Lixisols are relatively strongly weathered tropical soils with higher clay contents in the subsoil relative to the topsoil, mainly due to clay migration (section "Lessivation"). They have an *A-E-Bt-C*-profile if undisturbed (Photo 31b) or an *A-Bt-C*-profile if eroded; the C-horizon is mostly unconsolidated and strongly weathered. The brown to reddish brown subsoil layer has the properties of an arigic** horizon starting $\leq$100 cm from the soil surface. CEC is <24 cmol(+)kg^{-1} clay at least in some part of the argic** horizon within $\leq$50 cm below its upper limit, and low-activity clays are dominating. In contrast to Acrisols and Alisols BS_{eff} is 50 % or more in the 50–100 cm depth. By advanced leaching of clay minerals and Fe oxides, the E-horizon of Lixisols may develop the properties of albic** material, but retic** properties which are diagnostic for Retisols are lacking. Besides clay migration textural stratification due to bioturbation and advanced clay formation in humid subsoils compared to dry topsoils in subhumid to semidarid regions may be responsible for the development of argic** horizons in Lixisols.

Properties. BS of Lixisols is high, at least in the subsoil, despite advanced chemical weathering. Responsible for this phenomenon is most likely aeolian input of base cations under the recent climatic conditions. But the chemical and physical properties are not favorable (Table 15). Figure 32 informs about the depth profiles of selected physical and chemical characteristics of a Chromic* Lixisol.

Regional Distribution. Lixisols are most common in subhumid (semiarid) tropical, subtropical, and warm temperate regions with a pronounced dry period. Many of them are supposed to be of polygenetic origin with properties developed during former more humid periods. They occur on old aeolian cover layers and frequently in landscapes (Pleistocene or older) rich in fine-textured, stongly

Table 15 Properties of Lixisols

Physical properties:
The surface soil has low aggregate stability, prone to slaking, high erosion hazard
During the dry season hardening ("hard setting") of the surface soil
Density of the Bt-horizon may cause water-logging during the rainy season
Nearly no pseudosand or pseudosilt structure due to higher pH values (in comparison to Ferralsols and Acrisols) reducing the AEC
Chemical properties:
Dominance of low-activity clays causing a low CEC
Strongly weathered but $BS_{eff} > 50$ % in a depth of 50–100 cm below the surface
pH-value frequently >5, higher than in Ferralsols, Al-toxicity mostly not relevant
Low to medium nutrient reserves
SOM content of the surface layer generally low
Biological properties:
Biological activity is medium, but frequently high bioturbation by termites
Rootability medium

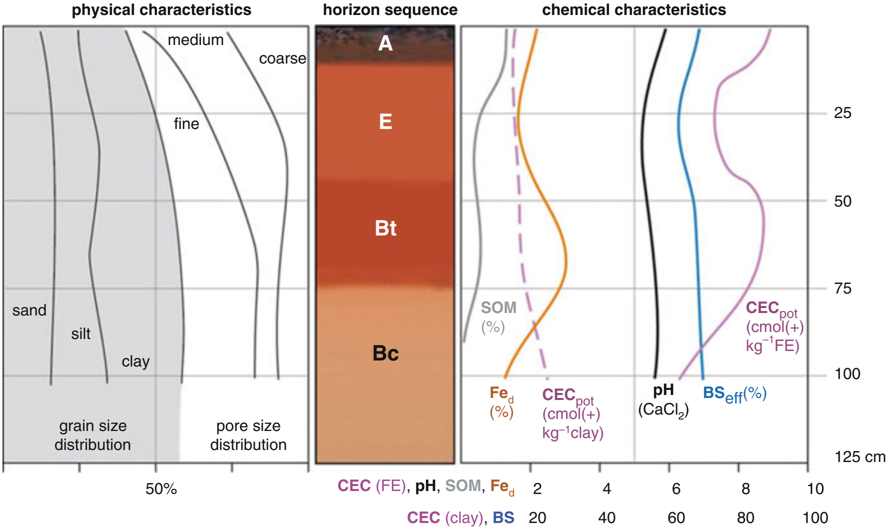


Fig. 32 Depth profiles of selected physical and chemical characteristics of a Chromic* Lixisol derived from loamy clayey colluvium (Zech et al. 2014)

weathered, and unconsolidated materials. Globally Lixisols cover an area of about 435 million ha, especially in southern Sahel, Tanzania, Mosambique, Madagascar, and in addition in Mexico, South America, East India, Southeast Asia, and Northeast Australia. Many Lixisols correlate with Alfisols rich in low-activity clays (US Soil Taxonomy) or with Sols ferralitiques faiblement desaturés appauvris (France).

Forest Management. Lixisols are frequently found under open woodland vegetation and savanna. In regions with hilly topography Lixisols should be preserved for silviculture and agroforestry. On steep slopes selective logging is recommended because clear-cutting operations drastically increase soil erosion and loss of SOM. Since the clay fraction of Lixisols has only a low CEC, the conservation of SOM is of priority for maintaining a high nutrient retention and combating Al toxicity. Oorts et al. (2003), for instance, studied the CEC of Ferric* Lixisols under multipurpose trees. Their results showed that SOM was responsible for 75–85 % of the CEC of these soils. Humus derives not only from the aboveground biomass but also from roots. Root dynamics of fallow trees (e.g., *Albizia* spec., *Leucaena* spec., *Gliricidia sepium*) established in agroforestry systems on Plinthic* Lixisols in the rainforest zone of West Africa were intensively studied by Schroth and Zech (1995) and Schroth et al. (1995). Use of heavy machinery in forests growing on Lixisols will deteriorate the unstable surface soil structure. Reforestation of areas with strongly inclined topography needs erosion control measures, and the establishment of fast-growing tree plantations may be only successful with initial fertilization, especially with *N* and *P*. Also weed control supported survival and reduced tree growth suppression of *Eucalyptus* plantations established on sandy Lixisols in South Africa (Little 2003).

After describing the mature soils of the humid and semihumid tropics, in the following section "Representative Soils of the Semi-Arid and Arid Tropics," representative soils of the semiarid and arid tropics will be discussed.

Representative Soils of the Semiarid and Arid Tropics

Solonchaks (SC)

Definition. Solonchaks show high concentrations of readily water-soluble salts (mainly chlorides, sulfates, carbonates, borates, and nitrates of Na, K, Ca, Mg) at some time of the year. The suffix letter z is used to characterize the pedogenetic accumulation of salts more soluble than gypsum. Generally horizon designation is *A(h)z-Cz or A(h)z-Bz-C(z)*. Diagnostic is the salic** horizon, starting ≤50 cm from the soil surface and having a thickness of ≥15 cm. It may be a surface or a subsurface horizon, consisting of mineral or organic material and resulting from fluvial, aeolian, marine, or ascending salt input. Salt accumulation may be strongest at the soil surface (=external Solonchak, Photo 32) or in deeper layers of the profile (=internal Solonchak). The salic** horizon can be cemented (Petrosalic* Qualifier). Besides calcic**, gypsic**, duric** horizons and gleyic** properties may occur, but thionic** horizons starting ≤50 cm from the soil surface are not accepted.

Properties. Solonchaks are often flooded for a long period and seasonally dry. The salts of inland solonchaks are either washed into the depressions from the surrounding terrain, during the rainy season by surface runoff, where they crystallize during the dry season, or they stem from the saline groundwater ascending during the dry season with the capillary water within the soil profile (section

Photo 32 External Solonchak with Az-Bz-profile and *Tamarix* (Hunger steppe, Uzbekistan)

"Salinization, Calcification, Sodification and Silification" and Fig. 15). Structure of the soil surface may be loose; but also more or less stable crusty phenomena can occur. During the dry season, subsoil horizons generally are strongly structured, if the texture is clayey. High Na-contents increase the danger of peptization correlated with increase of soil density. The chemical properties are characterized by the high concentrations of total soluble soils which show some correlation with ECe and negatively influence crop performance. High salt concentrations in the soil solutions seriously affect plant growth. Also nutrient deficiencies may occur due to antagonistic effects. In Table 16 main properties of Solonchaks are summarized, and Fig. 33 informs about the depth profiles of selected properties.

Regional Distribution. Solonchaks are commonly found along the sea coast and in depressions of semiarid to arid lands where salty groundwater ascends to the surface soil (Photo 33). Their present wide occurrence is partly due to human mismanagement of irrigated areas. The parent material is generally unconsolidated. Worldwide Solonchaks cover some 260 million ha. They are most present in the arid and semiarid regions of Africa (e.g., Sahara, northern Sahel, Somalia, Namib, Kalahari), the near East, Central Asia, Australia, and America. Together with the Solonetz they belong to the halomorphic soils. According to the US Soil Taxonomy many Solonchaks are classified as Aridisols, suborder Salids or as Halomorphic soils (Russia).

Forest Management. Strongly salt-affected soils have little silvicultural value. High salt contents cause water stress and disturb the uptake of nutrients like K, Ca,

Table 16 Properties of Solonchaks

Physical properties:
Periodically water-logged and seasonally dry
Surface soil structure is loose and Puffic* if sulfates dominate, whereas chlorides support the formation of crusts
Plants may suffer from water stress because high salt contents provoke high osmotic pressure
Chemical properties:
Electrical conductivity of the saturation extract (ECe) of the salic** horison is ≥15dS m^{-1} at 25 °C or ≥8 dS m^{-1} if the pH(H_2O) of the saturation extract is ≥8.5
Antagonistic effects (e.g., K/Na, K/Mg, Ca/Na) may cause mineral deficiencies of plants
Contents of water-soluble salts are commonly >0,15 %, and even >1 % in the salic** horizon
High $pH_{(H2O)}$ values of 7–10 are very common, especially in alkaline carbonate soils
Chloride and boron toxicity possible
Thickness (in cm) of the salic** horizon x ECe (in dS m^{-1}, 25 °C) = ≥450
Biological properties:
Soils with salt contents >0.6 % in the topsoil are generally without vegetation cover
Salt-tolerant plants are called halophytes, e.g., *Tamarix*

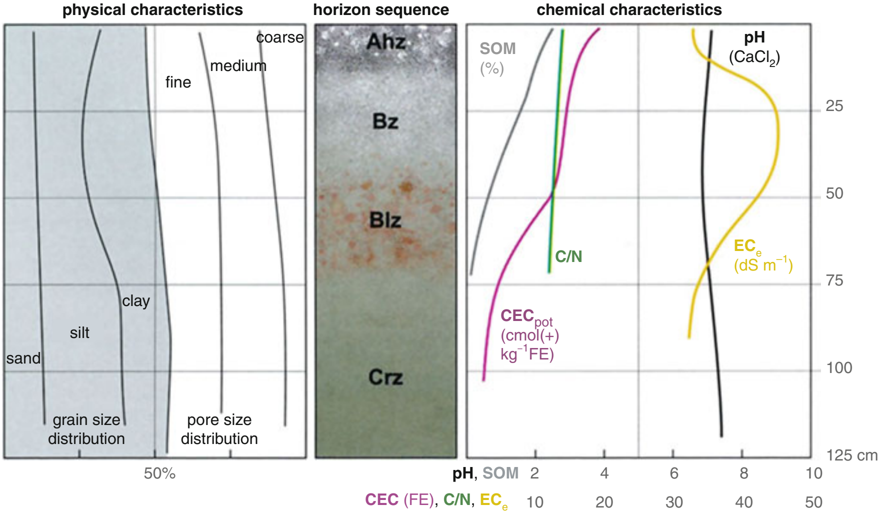


Fig. 33 Depth profiles of selected characteristics of an Endogleyic* Solonchak derived from loamy unconsolidated material (Zech et al. 2014)

and Mg. For instance, on salt-affected soils in Somalia Zech et al. (1991) found chlorotic leaf margins in stands of *Cassia siamea* induced by *K*-deficiencies (K/Ca-antagonism). High foliar Cl and B indicated toxicities responsible for die-back in plantations with *Azadirachta indica* and *Conocarpus lancifolius*. Also the agricultural value is low, and many salt-affected soils are used for extensive grazing. Only few crops survive if the ECe is >15 dS m^{-1} (Table 17).

Photo 33 Salt pan with salt-tolerant *Prosopis juliflora* at its margin (Senegal)

Table 17 Indicative soil salinity classes and the effects of soil salinity on crop performance (Driessen and Dudal 1989)

ECe at 25 °C	Salt concentration		FAO-Unesco	Effect on crops
(dS/m)	Extract (cmol/1)	Soil (percent)	Qualification	
<2.0	<2		–	Mostly negligible
2.0–4.0	2–4	<0.15	–	Some damage to sensitive crops
4.0–8.0	4–8	0.15–0.35	Salic phase (Solonchak)	Serious damage to most crops
8.0–15	8–15	0.35–0.65	Salic phase (Solonchak)	Only tolerant crops succeed
>15	>15	>0.65	Salic phase (Solonchak)	Few crops survive

Tree species tolerant to slightly or moderately saline environments, according to Davidson (1985) and Webb et al. (1980), are *Acacia cyanophylla, Acacia nilotica, Acacia salicina, Casuarina equisetifolia, Conocarpus lancifolius, Cupressus macrocarpa, Elaeagnus angustifolia, Eucalyptus camaldulensis (proc. septent.*), *Melaleuca leucadendron, Parkinsonia aculeata, Prosopis juliflora, Schinus molle, Tamarix articulate, Derris indica, Sesbania bispinosa,* and *Sesbania sesban.* On tropical coastal sites also *Leucaena leucocephala* and *Samanea saman* may grow, if salinity and water table are not too high; also flooding must be prevented. Strongly saline tidal soils should be kept under mangrove vegetation which can be carefully used for charcoal and fuelwood production. *Anacardium occidentale* succeeds on sandy saline coastal soils in West Africa but develops no nuts. Madsen and Mulligan (2006) studied the effects of NaCl on emergence and growth of a range of provenances of *Eucalpytus* species and *Acacia salicina*. They found that *Acacia salicina* performed much better than the eucalypts under study. In another study, Sun and Dickinson (1995) identified *Eucalyptus camaldulensis* to be more preferable than *Casuarina cunninghamiana* for the reclamation of salt-affected land. Amelioration of Solonchaks is expensive. Suitable methods include

– Leaching of salts from the surface layers by excess water
– Drainage to decrease the water table
– Application of gypsum to stabilize soil structure and to reduce negative effects of Na-surplus
– Removal of salts by salt-accumulating plants (bioremediation)

Solonetz (SN)

Definition: Solonetz are soils having a natric** subsurface-horizon starting ≤100 cm from the soil surface. It is dense and has higher clay contents than the overlying coarse-textured horizon. Diagnostic are high contents of exchangeable Na and sometimes also a high content of exchangeable Mg throughout the entire natric** horizon or its upper 40 cm, also a columnar (Photo 34) or prismatic structure if dry. pH values are alkaline due to the dominance of $NaHCO_3$, Na_2CO_3, and Na_2SiO_3. Common horizon designation is *A(h)-Btn-C* or *A(h)-E-Btn-C*. The bleached E-horizon, often with the properties of albic** material, shows a blocky structure if dry, with tongues extending into the Btn-horizon. Alteration between dry and wet conditions results in a swelling/shrinking dynamic of the Na-rich subsoil layer, generating desiccation cracks and columnar, prismatic, and polyhedral structures. Solonetz may exhibit below the natric** horizon a calcic**, gypsic**, duric**, and salic** horizon; especially the subsurface layer

Photo 34 The natric** horizon of Solontz often have a columnar structure. Their upper parts are rounded and became visible after the erosion of the A and E horizons

Table 18 Properties of Solonetz

Physical properties:
A-horizon with stable structure
Subsurface horizon dense, clayey, and strongly structured
Water-logging during the rainy season
Chemical properties:
High Exchangeable Sodium Percentage (ESP) $\geq$15 %, toxic for many plants ("sodicity")
Sometimes also a high content of exchangeable Mg
Disturbances in the uptake of other nutrients such as *K* may occur
High BS
CEC_{pot} 15–30 cmol(+) kg^{-1} FE
Biological properties:
Poor rootability of the Btn

is normally salt affected (section "Salinization, Calcification, Sodification and Silification," Sodification, Fig. 17.)

Properties: Besides Na- also Ca- and Mg-activities are important. To quantify their interactions the sodium adsorption ratio (SAR) of the soil solution (or of the irrigation water) is a suitable tool: SAR $= Na^+ : \left[\left(Ca^{2+} + Mg^{2+}\right) : 2\right]^{0.5}$ [ions in cmol (+)L^{-1} of the soil solution or water irrigation, respectively]. SAR allows to evaluate "sodification hazard" (low: <10; medium: 10–18; high: 18–26; very high: >26). High percentages of exchangeable sodium (ESP) are responsible for alkaline pH values, generally >8.5. Consequences are illuviation (section "Lessivation") and even destruction of the clay minerals in the surface soil layer and clay accumulation in the subsurface horizon. More properties of Solonetz are summarized in Table 18, and in Fig. 34 the depth profiles of selected properties are shown.

Regional Distribution. Solonetz frequently occur in temperate, subtropical, and tropical regions with flat or gently undulated topography, often associated with Solonchaks which may develop to Solonetz due to progressive leaching of salts after lowering of the groundwater level. Also ascendance of Na-rich groundwater related with increased precipitation may lead to the development of Solonetz. Climatic conditions are (semi)arid with hot summers and with mean annual precipitation of 400–500 mm. Parent material is usually fine textured and unconsolidated. According to the US Soil Taxonomy many Solonetz are classified in the Natric Great Groups of Aridisols, Entisols, or Inceptisols; in former times these soils were called sodic soils, alkali soils and Solonetz (Russia). Worldwide they cover approximately 135 million ha, especially in dry areas of South Africa, South America, and Australia. In addition Solonetz occur in flatlands of SE Europe, Russia, Central Asia, China, and USA, mainly covered by steppe.

Forest Management. Most Solonetz are only used for extensive grazing or lie idle. For agricultural and silvicultural use the majority of these soils need preliminary amelioration focusing on dealcalinization. This can be achieved by deep ploughing, thus destroying the natric** horizon and mixing gypsum and lime from the By- and Bk-subsoil horizons into the surface soil. At the same time soil

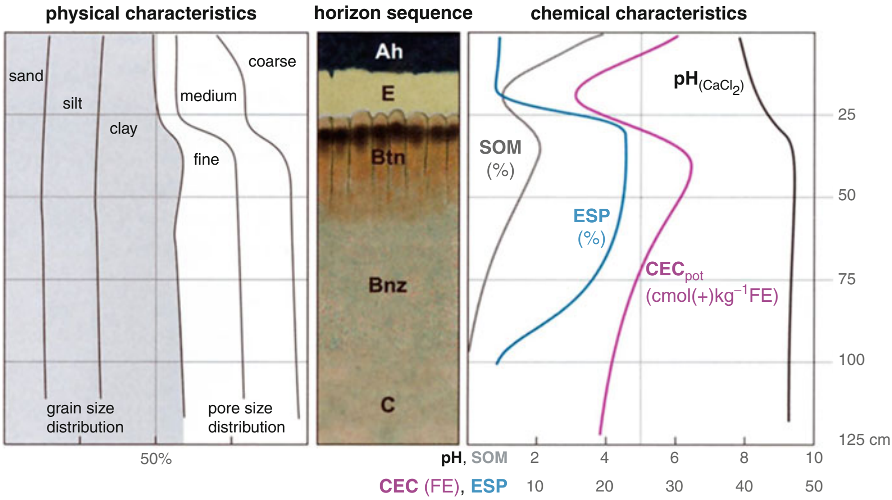


Fig. 34 Depth profiles of selected properties of an Endosalic* Solonetz derived from silty clayey alluvium (Zech et al. 2014)

porosity is increased, improving water permeability and soil aggregation of the surface and subsurface layers. Melioration can also be achieved by flushing with Ca^{2+}–rich water or application of gypsum, sulfur, or pyrite reducing soil pH. Forest management must take into consideration that tree species planted on Solonetz should be drought resistant, tolerant to high pH- and ESP-values, waterlogging, and restricted root development due to subsoil density. Suitable tree species could be *Acacia nilotica, Prosopis juliflora, Melaleuca leucadendron, or Tamarix* spec.

Gypsisols (GY)

Definition. Soils of (semi)arid regions with a significant accumulation of secondary gypsum ($CaSO_4\ 2H_2O$) starting within ≤100 cm from the soil surface. The gypsum accumulation layer may have the properties of a petrogypsic** horizon (suffix letter designation = ym), being more or less hard and continuous, or those of a gypsic** horizon (suffix letter designation = y), being soft. Typical horizon sequences are *A (y)-Cy, A-By-C(y), A-Bym-C, A-(E-)Bty-C(y).* Gypsisols may also have (petro) calcic** and (petro)duric** horizons. If downward movement of water dominates (descendance), then the (petro)gypsic** horizon is below the calcic** horizon; ascendance results in the accumulation of gypsum above the calcic** horizon, due to the higher solubility of gypsum in comparison to calcium carbonate. Argic** horizons above gypsic** horizons are permeated with secondary gypsum or secondary carbonate.

Properties. Table 19 and Fig. 35 inform about selected properties of Gypsisols.

Regional Distribution. Gypsisols are found in (semi)arid regions with 200–450 mm mean annual precipitation. Topography is predominantly level (terraces) to hilly; they are also found in depressions. Gypsisols mostly derive from

Table 19 Properties of Gypsisols

Physical properties:
Light-colored surface horizon
Weakly structured
Low infiltration rate, high erosion hazard
Low available water holding capacity if the solum above a petrogypsic** horizon is thin
Chemical properties:
Poor in SOM (<0.6 % SOC)
$pH_{(H2O)}$ 7–8, BS about 100 %
Availability of P reduced due to high pH values
Reduced availability of K and Mg if gypsum content is >25 % due to K/Ca and Mg/Ca antagonistic reactions
CEC_{pot} between 10 and 20 cmol(+) kg^{-1} FE
Biological properties:
Poor rootability of the petrogypsic** horizon
Biological activity low because of water stress

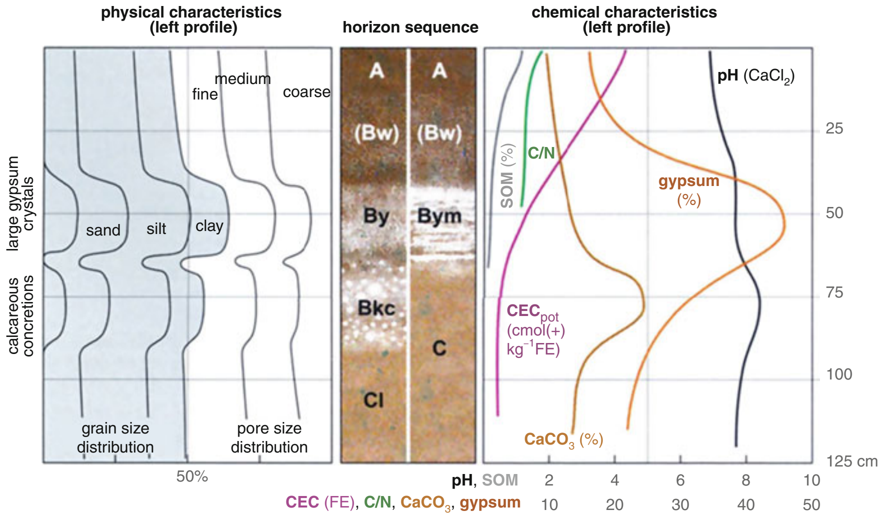


Fig. 35 Depth profiles of selected properties of a Calcic* Gypsisol (*left*) and a Petric* Gypsisol (*right*) derived from a loamy colluvium rich in base cations (Zech et al. 2014)

unconsolidated, base-rich alluvial, colluvial, or aeolian materials. Many of them belong to the Gypsids (US Soil Taxonomy). They cover approximately 100 million ha, especially in the dry regions of North and Southwest Africa, Somalia, Near East, Central Asia, Australia, and southwestern USA.

Forest Management. The natural vegetation is sparse, consisting mainly of ephemeral grasses and xerophytic shrubs and trees. Tree growth is heavily limited due to water stress, especially on Petric* Gypsisols characterized by petrogypsic**

horizons reducing rootability. The establishment of forest plantations on such soils can only be recommended if the indurated horizon exhibits fissures. In addition, planting the saplings in microbasins with deep planting holes improves water supply and significantly increases survival rate of reforestations (Photo 35a, b). Only drought-resistant trees like *Salvadora persica, Prosopis, Artiplex, Acacia tortilis, Azadirachta indica, Balanites aegyptiaca, Ziziphus,* etc. can survive. Reforestation experiments with *Eucalyptus camaldulensis* are not very promising. Using rainwater harvesting methods survival rate can be increased. Main task of forestry is the protection of the natural vegetation cover. Besides from water stress plant growth is limited due to nutrient imbalances (e.g., K/Ca- and Mg/Ca-antagonism) and *N*- and *P*-deficiencies, especially if gypsum contents are higher than 25 % in the surface soil.

Calcisols (CL)

Definition. Soils of (semi)arid regions having a substantial accumulation of secondary carbonates ($CaCO_3$, $MgCO_3$) starting $\leq$100 cm from the soil surface. The carbonate accumulation layer may have the properties of a petrocalcic** horizon (suffix letter designation = km), being more or less hard and continuous, or those of a calcic** horzon being soft (suffix letter designation = k), or rich in carbonate concretions (suffix letter designation = kc). Typical horizon sequences are *A(k)-Ck, A-Bk-C(k), A-Bkc-C, A-Bkm-C, A-(E-)Btk-C(y).* Sometimes several calcic** (petrocalcic**) horizons have developed lying upon each other. Calcisols may also have (petro)gypsic** and (petro)duric** horizons but not in the upper 100 cm of the profile. If an argic** horizon occurs above the calcic** horizon, then it must be permeated with secondary carbonate.

Properties. Table 20 and Fig. 36 inform about main properties of Calcisols.

Regional Distribution: Calcisols are widespread in the (semi)arid tropics and subtropics with level (terraces) to hilly topography. They mostly developed from colluvial, aeolian, lacustrine, and alluvial base-rich sediments. Many Calcisols correlate with the Calcids (US Soil Taxonomy). They cover about 1,000 million ha, especially in North and Southwest Africa, Somalia, Near East, Central Asia, Australia, Southwest USA, North Mexico, and southern South America.

Forest Management. Since Calcisols occur in zones with aridic moisture regimes their silvicultural potential is reduced. Tree growth is limited again by dryness. Special soil preparations like planting holes and microbasins increase water supply. In zones with high erosion hazard, slope terracing is necessary. Tree species susceptible to lime-induced chlorosis are not suited for plantation forestry on Calcisols. For more details on forest tree planting in arid soils see Goor and Barney (1976) (Photos 36 and 37).

Durisols (DU)

Definition. Strongly weathered **s**oils of (semi)arid regions with accumulation of secondary silica starting $\leq$100 cm from the soil surface. The SiO_2-accumulation may form an indurated layer (duripan) having the properties of a petroduric** horizon (suffix letter = qm) or consisting of nodules (durinodes, suffix letter = qc)

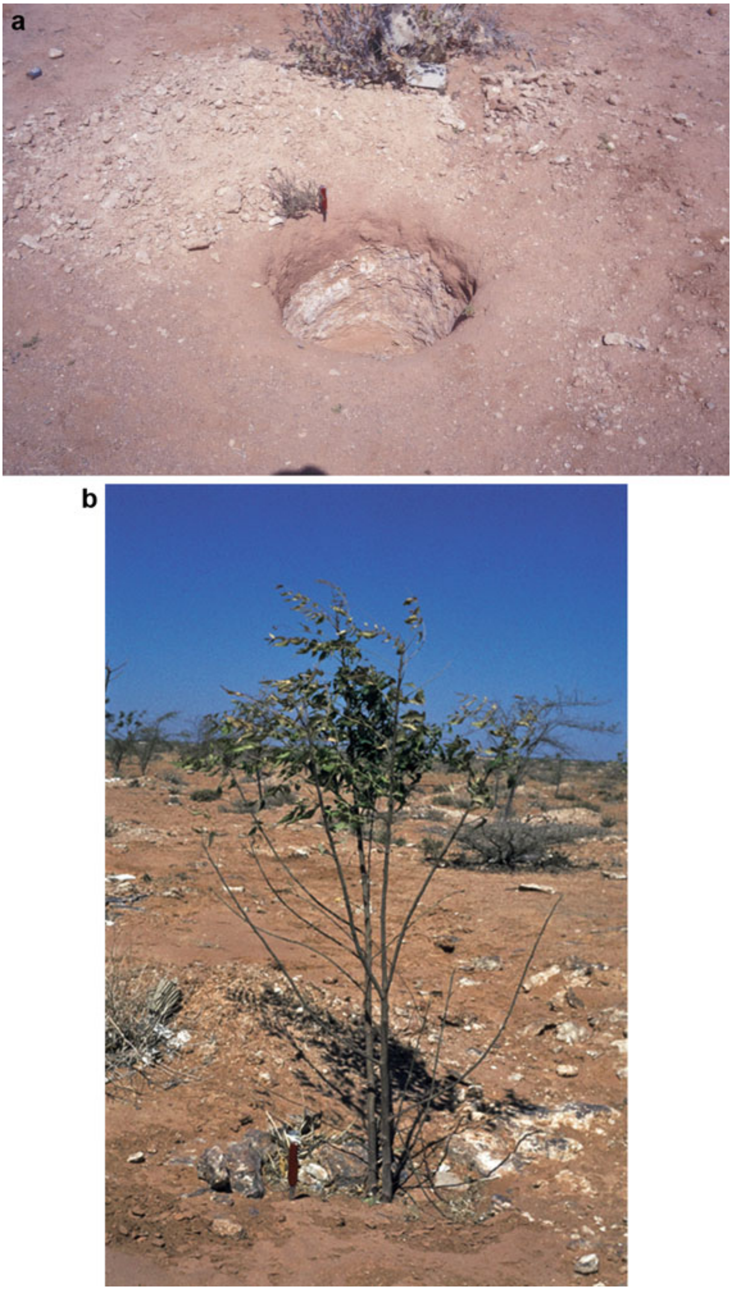


Photo 35 (**a**) The establishment of forest plantations on Petric* Gypsisols, Petric* Calcisols, and Petric* Durisols is only sustainable if the solum above the indurated layer is thick enough to store sufficient water to provide the survival of trees during the long dry season. Planting the saplings in hollow molds (microcatchments) increases the survival rate. (**b**) shows *Cordeauxia edulis*, an economically and ecologically important species (Somalia)

Table 20 Properties of Calcisols

Physical properties:
A-horizon is thin, pale brown to brown, and frequently with platy structures
The B-horizon may have concretions (= Bkc) or clay illuvation (= Btk), with weak blocky structure
Low infiltration rate if the surface soil developed crusts, then high erosion hazard
Medium to fine textured, then with sufficient water-holding capacity
But low water-holding capacity if the petrocalcic** horizon occurs at shallow depth
Chemical properties:
Poor in SOM, C/N <10
$pH_{(H2O)}$ 7–8, BS 100 %, mainly Ca and Mg
CEC_{pot} of the A-horizon 10–25 cmol(+) kg^{-1} FE
Low nutrient availability: *N*-stocks low, P-supply low due to the high pH, K/Ca-antagonism, micronutrient deficiencies (e.g., Fe- and Mn-chlorosis)
Biological properties:
Microbial actitvity reduced due to dryness
Rooting of the petrocalcic** horizon only possible if rich in fissures

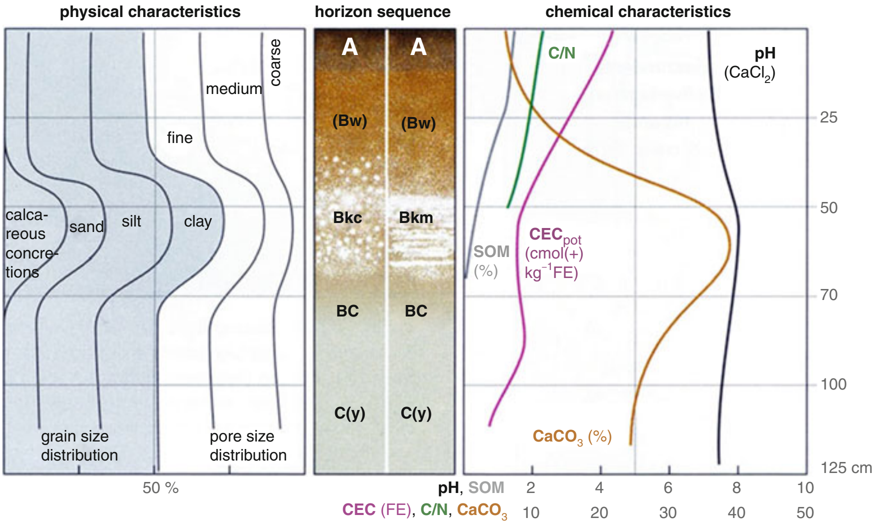


Fig. 36 Depth profiles of selected characteristics of a Haplic* Calcisol (*left*) and a Petric* Calcisol (*right*) derived from carbonate-rich unconsolidated sediments (Zech et al. 2014)

or fragments of secondary silica with the properties of a duric** horizon (suffix letter = q).). Typical horizon sequences are *A-Bw-Bqc-C, A-Bw-Bqm-C, A-(E-)Bt-Bq-C, A-Bk-Bq-C,* indicating that between the A-horizon and the (petro)duric** horizon often cambic**, argic**, and calcic** horizons are intercalated.

Properties. Table 21 and Fig. 37 inform about representative properties of Durisols. See also Fig. 18, Silification.

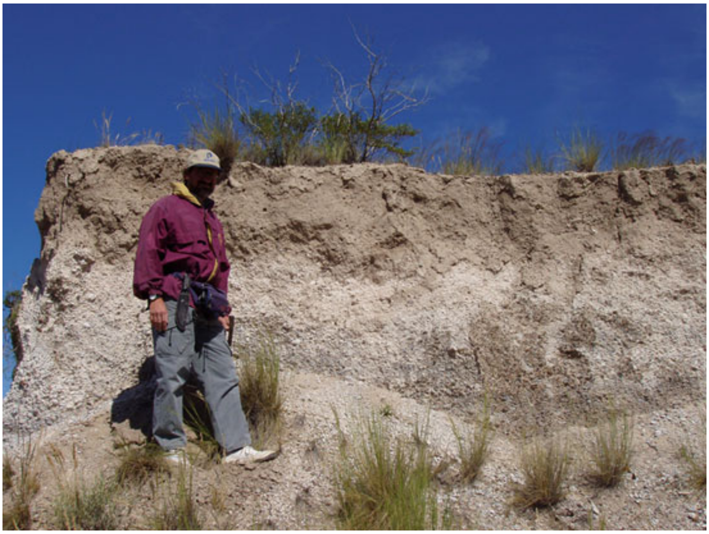


Photo 36 Endopetric* Calcisol (Hyperochric*, Siltic*) developed from gravels west of Puerto Madryn, Argentina. The A-horizon is thin, poor in SOM, with platy structure. The B-horizon is brownish, about 50 cm thick, and silty. Below is the whitish Ckm-horizon

Photo 37 The natural vegetation developed on the Calcisol shown in Photo 36 is dominated by xerophytic shrubs, locally called monte bajo

Table 21 Durisol properties

Physical properties:
SiO_2-concretions may be soft to very hard, having a concentric structure
Thickness of pertroduric** horizons vary between 0.3 and 4 m; their structure is massive or platy to laminar
Water-holding capacity is medium, and low if the petroduric** horizon occurs at shallow depth
High infiltration rate
Chemical properties:
Low in SOM
$pH_{(H2O)}$ 7–8, but weak acidification of the topsoil possible
BS close to 100 %, in the topsoil less
Fe_O-contents often low
CEC_{pot} low
Biological properties:
Rooting of the petroduric** horizon only possible if rich in fissures
Microbial activity during the dry season low

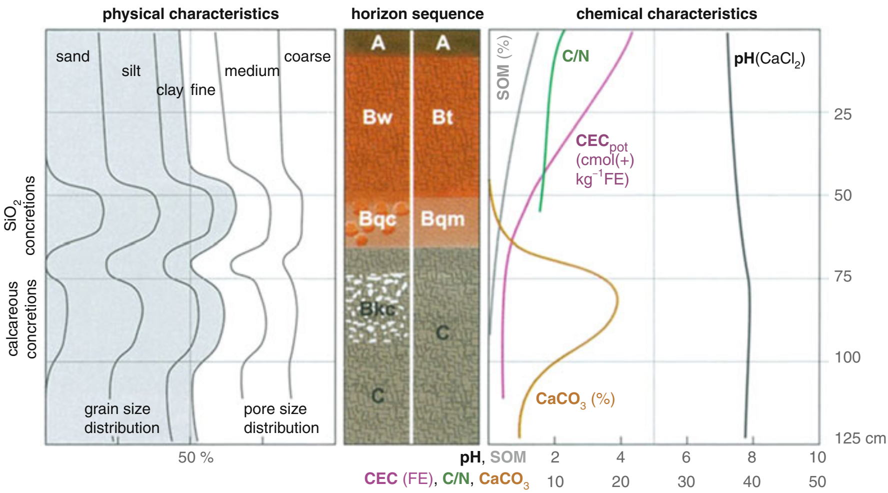
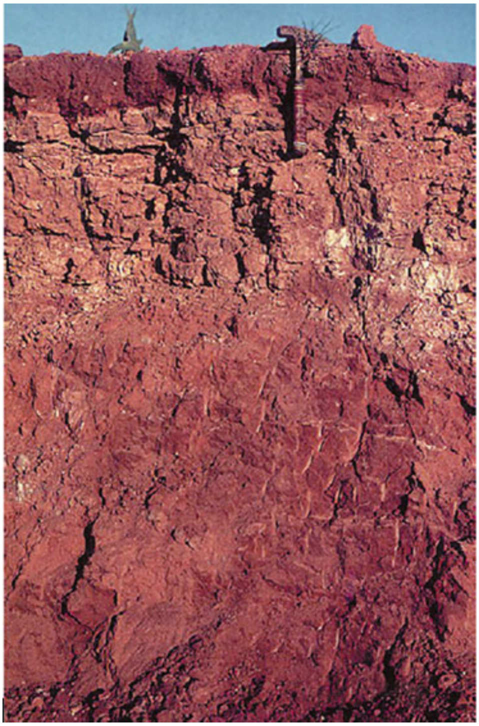


Fig. 37 Depth profiles of selected characteristics of a Calcic*Durisol (*left*) and a Lixic* Petric*Durisol derived from silicate-rich alluvial materials (Zech et al. 2014)

Regional Distribution. Durisols usually derive from alluvial and colluvial, silicate-rich materials, deposited in plains, terraces, and pediment landscapes. They also develop from volcanic ashes succeeding Andosols (section "Andosols (AN)"). Petroduric** horizons are often exposed on old geomorphic surfaces as indurated crests (silcrete) after erosion of the topsoil. Worldwide Durisols cover about 260–340 millon ha, for instance, in South and Southwest Africa, Australia, Southwest USA, and Northwest Mexico. Many Durisols correspond to the Durids in the US Soil Taxonomy.

Photo 38 Epipetric*Durisol (Aridic*, Chromic*), South Afriaca (Photo c F. Ellis)



Forest Management.: The silvicultural use of Durisols is limited as already described for Gypsisols and Calcisols. Main restrictions concern water and nutrient supply. Planting the saplings in microbasins with deep planting holes reduces water stress and increases survival rate. Also the application of *N* and *P* improves tree growth if the Durisols are very poor in SOM (ochric*). Trees growing on sandy Durisols (Arenic*) may need *K*-fertilizer, improving water use efficiency of the trees, and trees planted on Dystric* Durisols may positively react upon the application of lime. Most problematic are silvicultural activities if the petroduric** horizon occurs at shallow depth. A main recommendation must be to carry out a thorough site evaluation to identify the localities where the high costs for silvicultural efforts are justified. If this is not justified, then the task of forestry should be to protect the natural vegetation cover of the Durisols. This holds true also for other soils with marginal carrying capacity for trees, like many Gypsisols, Calcisols, Solonchaks, and Solonetz. Such a site evaluation must focus on proxies related with the water availability for trees depending, for instance, on texture, stone content, rooting depth, SOM content, relief position, shape of the terrain, groundwater level, mean annual precipitation, and mean annual temperature. Nutrient supply is often strongly correlated with nutrient stocks and their availability, depending, for instance, on soil pH, microbial activity, etc. (Photos 38 and 39).

In the following chapter, soils will be described which develop as zonal soils outside the tropics. Their occurrence in the tropics is mainly conditioned by parent material and topography.

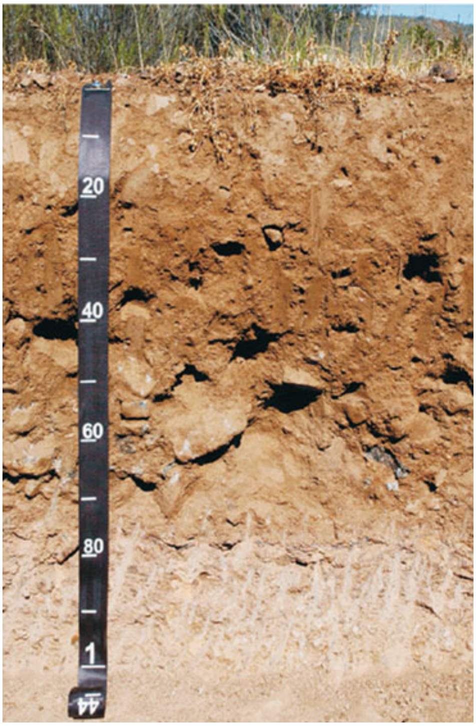


Photo 39 Endopetric* Durisol (Chromic*) with A-Bw-Bqm(80+cm)- profile (Chile; photo P. Schad)

Soils Mainly Conditioned by Parent Material and Topography

Andosols (AN)

Definition: Andosols are typically dark soils with A-C- or A-B-C-profiles derived from glass-rich pyroclastic materials like volcanic ash, tuff, pumice, and cinders of varying chemical composition. They show one or more layers with andic ** properties (Al_o + ½ Fe_o $\geq$ 2 %, P-retention $\geq$85 %, bulk density $\leq$0.9 kg dm^{-3}) or vitric**properties (Al_o + ½ Fe_o $\geq$ 0.4 %, P-retention $\geq$25 %, $\geq$ 5 % counts of volcanic glass, glassy aggregates, and other glass-coated primary minerals in the fraction $\geq$0.02 and $\leq$2 mm) having a cummulative thickness of $\geq$30 cm within $\leq$100 cm of the soil surface, and the uppermost layer is starting within $\leq$25 cm from the soil surface. If continuous** rock, technic hard** material, or a cemented or indurated layer occurs between >25 and $\leq$50 cm from the soil surface, then $\geq$60 % of the total soil thickness must reveal andic** or vitric** properties. Argic**, ferralic**, petroplinthic**, pisoplinthic**, plinthic**, or spodic** horizons may occur as buried layers $\geq$50 cm from the mineral soil surface. (A-)C profiles derived from **fresh** volcanic ash are usually not classified as Andosols but as **Tephric* Regosols**, ($\geq$30 % grain counts volcanic glass, glassy aggregates, and other glass-coated primary minerals in the fraction $\geq$0.02 and $\leq$2 mm) which may develop to **vitric* Andosols** characterized by vitric** properties due to the rapid

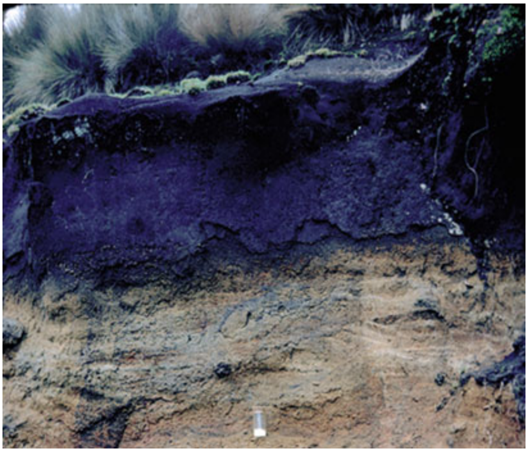


Photo 40 Aluandic* Andosol with Ah-C-profile (Ecuador). Weathering of glass in acid volcanic ejecta results especially in humid environments in the formation of organo-*Al*-complexes and in the accumulation of high humus stocks. Allophane and imogolite contents are low (in contrast to the Silandic*Andosols). The dark A-horizon is characterized by Andic** properties, e.g., by high *P*-fixation

alteration of volcanic glasses. If the alteration of glass continues, andic** properties develop. A-(B-)C soils with andic** properties can be differentiated into **Silandic* Andosols** ($Si_o \geq 0.6$ %, or $Al_{py}/Al_o < 0.5$) and **Aluandic* Andosols** ($Si_o < 0.6$ %, and $Al_{py}/Al_o \geq 0.5$; Photo 40). The latter ones are very rich in humic substances and stable organo-Al-complexes, whereas the first ones have moderate humus contents and in addition short-range-order minerals such as allophane and imogolite. The A-horizon is usually rich in C_{org} (5–25 %), being mollic**, umbric**, folic**, or histic**. Aluandic* Andosols may also develop from glass-free silicates under humid to perhumid conditions, medium temperatures, and good drainage supporting the formation of Al^{3+}-humus chelates. With continuing soil development Andosols may grade into Nitisols, Podzols, Ferralsols, or soils with clay illuvation.

Properties: Dominant physical and chemical properties are summarized in Table 22, and in Fig. 38 depth profiles of selected characteristics of a Silandic*Andosol (above) derived from intermediate to basic volcanic ash and of an Aluandic* Andosol (below) developed from acid volcanic ash are shown.

From the physical point of view, most Andosols are favorable sites for plant growth, permitting good rootability together with a high water storage capacity. The high aggregate stability reduces susceptibility to water erosion, but wind erosion hazards may be high if the cohesion of soil particles is diminished during dry periods. Depending on pH, CEC can be up to 100 cmol (+) kg^{-1} soil, but in humid climates leaching of the base cations is accelerated inducing low pH values and reduction of CEC. Andosols with low pH and low base saturation have high amounts of exchangeable Al, which can be toxic to plants and microorganisms. In this way, parts of SOM are supposed to be protected against biodegradation. In the field, Andosols rich in allophane feel smeary.

Regional Distribution: Andosols develop from glass-rich volcanic parent materials under humid to semiarid climatic conditions in tropical to artic environments. They were also reported to develop under humid to perhumid conditions from

Table 22 Properties of Andosols

Physical properties:
High stability of the microaggregates forming polyaggregates, often with smeary features
Crumby or granular structures in the horizon
Bulk density low, if andic** properties ($\leq$0.9 kg dm^{-3})
High pore volume, especially in the topsoil (50 to >70 %)
High water storage capacity, good internal drainage, high water permeability
Under dry conditions cohesion of soil particles reduced and problems with wind erosion
Chemical properties:
Aluandic* Andosols have low pH-values, Silandic* and Vitric* Andosols may have also high pH-values
But BS usually low, especially under humid conditions due to rapid leaching of base cations
Pronounced variable charge properties
High CEC (up to 100 cmol(+) kg^{-1} soil) if the pH is high, and high AEC if pH is low
If pH is low, high contents of exchangeable Al (Al^{3+} >2 cmol(+) kg^{-1} soil)
High contents of ferrihydrite
High P-retention (if andic** properties $\geq$85 %) due ot high contents of active Al and Fe
Formation of stable organomineral complexes (Aluandic* Qualifier), rich in aromatic C
Biological properties:
Activity of the mesofauna is high
Good rootability

glass-free silicates under pronounced acid weathering (Baeumler and Zech 1994). In tropical countries Andosols cover about 60–70 million hectares, mainly in the volcanic landscapes of South and Central America, Philippines, Madagascar, and East Africa. Also in Europe they occur. Globally, Andosols cover about 110 million ha. Many Andosols correspond to the Andisols (US Soil Taxonomy). In the French soil classification system they are called Vitrisols and Andosols; in Russia they are called Volcanic ash soils.

Forest Management: Most Andosols have a high potential for agricultural production. Major limitations concern topography, *P*-fixation, and perhaps *Al*-toxicity. Thus, in general, steep slopes are preserved for forestry, while flat areas are cultivated by a great variety of crops especially after amelioration by adding *P*-fertilizers, lime, and silica. Since trees developing mycorrhiza are able to better assimilate *P*, natural forest stands growing on Andosols generally do not suffer from P-deficiencies. Only in fast-growing tree plantations have *P* deficiencies been reported, for instance, in the Philippines (Zech 1990). In the semiarid Djebel Marra Region (Darfur Province, Rep. of Sudan) Nettelroth (1992) found that height growth of *Cupressus lusitanica* planted on Andosols mainly correlated with soil water and *N*-supplies. In the perhumid Zona Norte of Costa Rica with mean annual precipitation of about 3,000 mm, growth of *Cordia alliodora*-reforestations established on **Umbric* Andosols** is also restricted due to *N*-deficiency, especially on steep slopes, where after clearing the rainforests, soil erosion occurred, reducing the *N*-reserves of the soils. Trees develop only small and completely chlorotic leaves. Besides *N*-deficiency, also *Mn*-nutrition seems to be disturbed because

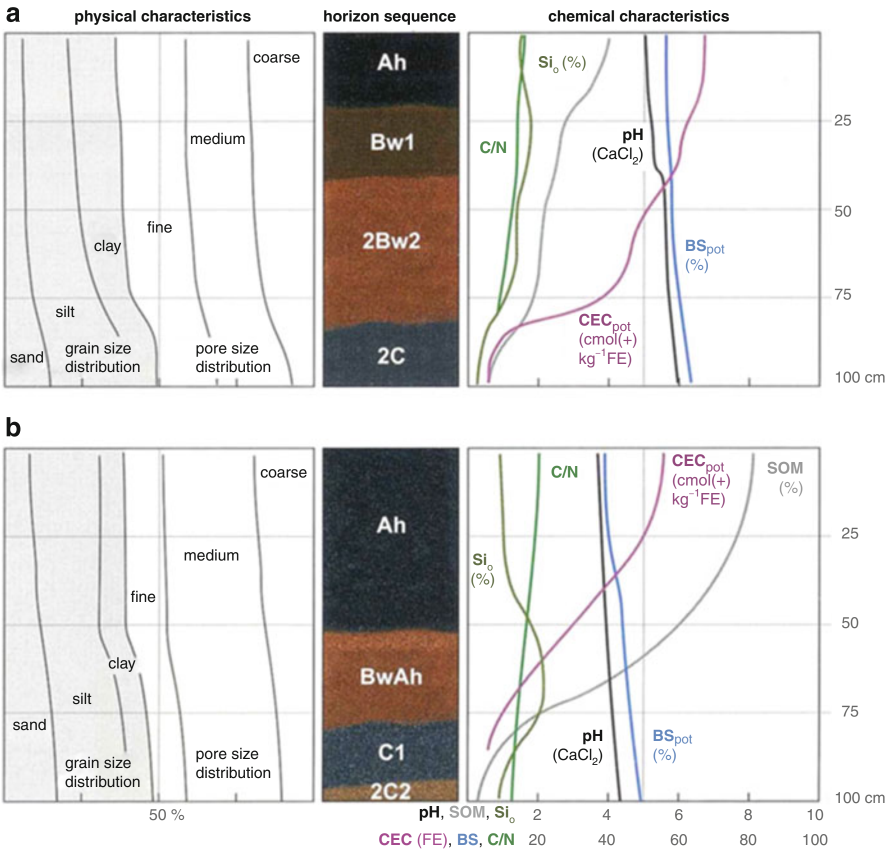


Fig. 38 Depth profiles of representative characteristics of a Silandic*Andosol (*above*) derived from intermediate to basic volcanic ash and of an Aluandic* Andosol (*below*) developed from acid volcanic ash (Zech et al. 2014)

foliar *Mn*-levels in the yellow leaves were only near 20–25 ppm (Zech et al. 1992a). On the other side, fast-growing healthy *Cordia* revealed foliar *Al*-levels of only <60 ppm, whereas the declining ones contained more than 100 ppm Al in their chlorotic leaves. Nearby growing secondary forests revealed no deficiency symptoms due to an inadequate mineral supply. Since the increment of most tree species of economic value in these secondary forests is considerable, the reestablishment of these stands may be of higher economic benefit than planting exigent species in plantations (Fedlmaier, pers. comm.). In the highlands of southern Ethiopia Lemenih et al. (2005) studied the changes of SOC and total *N* following reforestation of previously cultivated Andosols with *Cupressus lusitanica* and *Eucalyptus saligna*. Fifteen years after plantation establishment, clear changes in soil properties could be identified by comparing the sites below *Cupressus lusitanica*, *Eucalyptus saligna*, natural forest, and farmland. SOC and total N contents in the upper

0–20 cm layers differed significantly in the order Natural Forest > *Cupressus* > *Eucalyptus* > Farmland. Also the SOC and N stocks in the upper 80 cm mineral soil varied significantly in the same order. The authors estimated the average annual SOC accruals to 156 and 37 g SOC m^{-2} $year^{-1}$ for *Cupressus* and *Eucalyptus*, respectively. These results are important for evaluating the potential for SOC sequestration of different tree species. Analyzing besides SOC and N other soil properties like CEC, BS, exchangeable K, Ca, and Mg, Lemenih et al. (2004) concluded that the establishment of *Eucalyptus saligna* plantations on Andosols under study might even contribute to soil deterioration. An alternative to the establishment of *Eucalyptus* could be to support the regeneration of native woody species, for instance, by enrichment planting (Girma and Mosandl, 2012; see also Lemenih and Teketay 2005). Becker et al. (2011) studied litterfall in natural forests (Lower Montane Belt, *Ocotea* dominated forest, *Podocarpus* dominated forest) along south exposed slopes of Mt. Kilimanjaro. They found that the annual pattern of litterfall exhibited a large peak toward the end of the dry season. Annual litterfall ranged from 4.6 to 10.7 Mg ha^{-1}, and the annual *N*-deposition by litterfall varied from 38 to 52 kg ha^{-1}. Andosols, without doubt, have high potentials for forest production due to favorable physical and often also chemical properties. On steep slopes erosion hazard may restrict site quality (Photo 41).

Photo 41 In many East African Mountains *Erica arborea* and *Erica trimera* occupy Andosols at the transition between the afromontane and afroalpine belts. They are frequently burnt but resprout rapidly (Harrena Forest, Bale Mts., Ethiopia, 3,200 m a.s.l.)

Arenosols (AR)

Definition: Arenosols are deep sandy soil; in the dry regions they are weakly developed, showing an *A(h)-C*-profile, whereas in humid zones besides *A(h)-C*-profiles also deep *AEC*-profiles and *A(h)-Bw-C*-profiles may occur. Arenosols derive from coarse-textured materials; the weighted average texture class is loamy sand or coarser to a depth of 100 cm from the mineral soil surface. Layers of finer texture may occur, but their combined thickness must be <15 cm. The content of coarse fragments is in all layers within ≤100 cm from the mineral soil surface less than 40 % (vol.). Arenosols may also develop from quarz-rich stones and even from Ferralsols after intensive in situ weathering and destruction of the clay minerals and residual accumulation of coarse sands. They may also evolve from Podzols if the E-horizon becomes so thick that the spodic** horizon occurs >200 cm below the soil surface. Also sand-rich Acrisols and Lixisols are classified as Arenosols where the argic** horizon begins below 200 cm from the soil surface. SOC-content of the A-horizon is generally <0.6 %. Sandy soils with umbric** and mollic** horizons are classified as Umbrisols or, for instance, as Phaeozems, whereas fine-textured *A(h)-C*-profiles belong to the Regosols. The parent materials show no andic** properties and are mostly unconsolidated.

Properties: Dominant physical and chemical properties are summarized in Table 23, and Fig. 39 informs about representative characteristics of a Dystric* Albic* Arensol developed from quarz-rich sands.

Regional Distribution: Arenosols are widespread over the world from arid to humid and from cold to hot climates and cover about 1,300 million ha, corresponding to ~10 % of the land surface They occur in deserts, along beaches and rivers, on unconsolidated sand, or on old peneplains formed from quarz-rich sandstones, granites after intensive in situ weathering, as in Guyana or Madagascar. Well known are the Arenosols in the Kalahari, the Sahel, and also some parts of the Sahara. They also occur in the Near East, Central Asia, and Australia. Most Arenosols correlate with the Psamments (US Soil Taxonomy) and with the Sols minéraux bruts or Sols peu évolués (France). In Russia they are called Psammozems.

Table 23 Properties of Arenosols

Physical properties:
High permeability and low water-holding capacity due to coarse texture and many coarse pores
Good rootability and workability
High sensitivity to erosion due to single grain or weak subangular structures with low coherence
Chemical properties:
Low SOM contents
Low nutrient stocks, low nutrient storage capacity, and generally low nutrient availability
pH-values and BS varying
CEC_{pot} low
Biological properties:
Generally low biological activity

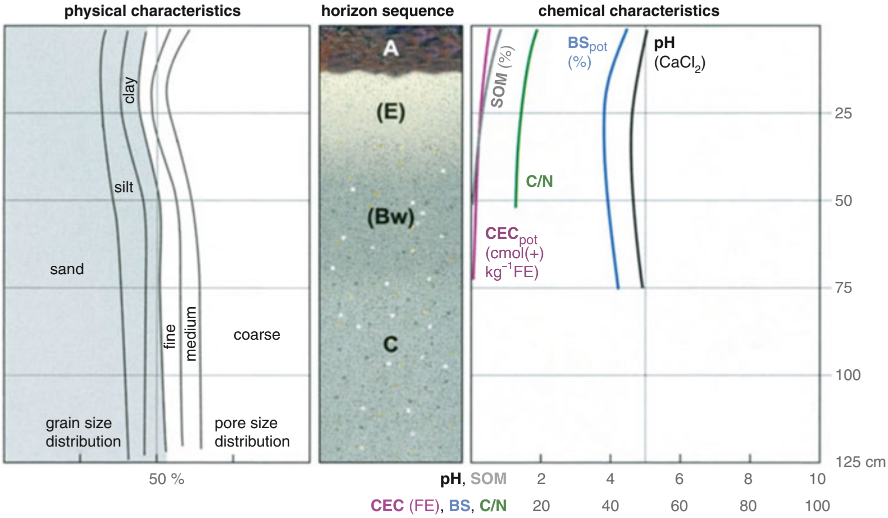


Fig. 39 Selected characteristics of a Dystric* Albic* Arensol developed from quartz-rich sands (Zech et al. 2014)

Forest Management: In the semiarid zones Arenosols are relatively favorable for tree growth because rainfall will easily infiltrate into the solum. Since the surface sandy layers may react as mulch, the lower horizons remain humid for some time and thus supply deep-rooting tree species like *Azadirachta indica, Eucalyptus camaldulensis, Adansonia digitata, or Acacia senegal* with water even during long dry periods. Canopy closure of these light forests is usually not dense. Compacted C-horizons induce shallowness and thus limit the potential for tree growth; in contrast, slightly increasing clay contents in the subsoil improve site quality due to a higher water holding capacity. Arenosols in the Sahelian zone of Senegal are best suited for *Acacia senegal* plantations (Zech 1984), which are of high economic importance because of gum production. Since in dry regions trees and shrubs play an important role for the fodder supply of grazing animals, the establishment of plantations on Arensosols with trees having high fodder values makes sense (Zech 1981). Such plantations not only improve the fodder supply of animals, they are also important for soil conservation by stabilizing the soils and reducing deflation. Water supply of such forest plantations in semiarid regions can be significantly improved if the seedlings are planted in small microcatchments of about 1 m^2 or even by water harvesting methods in hilly landscapes (Lehmann et al. 1999a, b). In Egypt irrigation with waste water significantly contributed to the successful establishment of plantations with *Eucalyptus camaldulensis*, *Eucalyptus citriodora,* and *Khaya senegalensis* (El Kateb 2011; El Kateb and Mosandl 2012)

In contrast to the Arenosols of the semiarid zones, where water stress is the main restricting factor, utilization of Arenosols in the humid tropics is generally limited by low nutrient supplies, especially if they consist of deeply weathered albic**

Photo 42 Dystric* Albic* Arenosol (Areninovic*) with Ah-C-2Ahb-2C-profile, developed on quartz-rich and deep (≥100 cm) alluvial sands of the Rio Negro (Brasil). The light color of the sands is not the result of podzolization in situ; its alluvial sand bleached in the catchment of the river

material. Such soils, e.g., in NE of Madagascar or on the margins of Rio Negro near Manaus, classified as Albic*Arensols (Photo 42), are under thin and light forests of low or even noneconomic value. Clearing such stands will cause rapid SOM mineralization and soil erosion. Reclamation is very expensive if possible at all. Thus, forest stands on these endangered sites must be very carefully managed or should best be protected and remain out of use. More fertile soils like Eutric* Arenosols (Humic*) can be used for timber, pulp, and rubber production. Arenosols along coastal environments are frequenly under coconuts (Photo 43). Other tree species growing well on Arenosols are *Casuarina equisetifolia, Anacardium occidentale,* and pines.

Vertisols (VR)

Definition: Vertisols are deep, clay-rich soils with *Ah-(Bw-)Bi-C*-profiles. They are rich in swelling clays responsible for heavy peloturbation (see section "Turbation," Table 6). Diagnostic is the vertic** horizon, a clayey mineral subsurface layer starting ≤100 cm from the soil surface, containing ≥30 % clay, shiny surfaces (slickensides, suffix letter = i), often wedge-shaped soil aggregates, and having a thickness of ≥25 cm. Also the solum above the vertic** horizon contains ≥30 % clay. Due to the high content of swelling clays (mainly smectites) Vertisols develop

Photo 43 Arenosols on coastal sands in the subhumid and humid tropics are frequently used for coconut production. Even on Arenosols with low nutrient levels cassava can be cultivated whereas groundnut prefers more fertile Arensols (Benin)

during the dry season deep cracks, width often $\geq$1 cm, starting from the soil surface or some cm below, or at the base of an Ap-horizon, and extending to the vertic** horizon. The parent materials of the Vertisols (Photo 13) are fine-textured sediments (marl, clay) rich in swelling clays or swelling clays rich in base cations and originating from deep rock weathering (e.g., basalt) due to neoformation.

Main **properties** of Vertisols are summarized in Table 24 and Fig. 40.

Regional distribution: Vertisols develop in depressions, in lower slope position, on plateaus, or in undulating areas of the semiarid (500–1,000 mm) to (sub) humid (up to 2,000–3,000 mm MAP) tropics and subtropics, with a pronounced dry period up to 9 months. According to FAO, about 335 million hectares are covered with Vertisols globally, especially in India, Australia, Sudan, Ethiopia, South Africa, Texas, SW Brasil, Paraquay, and N Argentina. In the US Soil Taxonomy these heavy clay soils are also classified as Vertisols in Russia as Slitozems or Dark vertic soils.

Forest management: This summary makes clear that Vertisols in general have favorable chemical properties. In contrast, their physical features render soil use more difficult. In the Central Rangelands of Somalia, for instance, Drechsel (1991)

Table 24 Properties of Vertisols

Physical properties:
High density (1.5–1.8 kg dm^{-3})
At the beginning of the rainy season high water infiltration due to preferential flow; surface soil material is washed into the cracks. After swelling of the clays, soil volume extends, causing swelling pressures. They are responsible for the development of intersecting slickensides, stress cutanes like polished aggregate surfaces, reduction of the pore volume, temporary water logging, and low air capacity
During the dry season shrinking of the soil volume and increase of the pore volume as desiccation proceeds with formation of cracks, prismatic, angular blocky, subangular and wedge-shaped soil aggregates
Heavy clayey texture inducing a high water-holding capacity but plant available water contents are low
Sometimes a so-called gilgai relief develops, characterized by microbasins and microknolls (see Photo 13)
During the dry period with pronounced shrinking, the soil surface may be covered by loose granular or crumbly aggregates, called surface mulch
Chemical properties:
Dark color but SOC-contents usually <3 %
The clay fraction is rich in swelling smectites (often >50 %)
pH(H_2O) ~6.5–8 and BS frequently >50 % with dominance of Ca and Mg
CECpot is high (40–80 cmol(+) kg^{-1} FE)
Nutrient stock generally high but nutrient availability may sometimes be reduced
Secondary accumulation of silica (Duric* Vertisol), lime (Calcic* Vertisol), and/or gypsum (Gypsic* Vertisol) may occur
Biological properties:
Medium to high biological activity
Turnover rate of the SOM is low due to the formation of stable organomineral complexes
During water logging denitrification and methanogenesis

described Calcic* Vertisols in the floodplains of the Shebeli River. The natural vegetation includes *Salvadora persica, Commiphora* sp., *Euphorbia* sp., *Indigofera* sp., and *Acacia nilotica*. After destruction of the vegetation cover, reforestation trials with *Prosopis, Acacia nilotica,* and *Parkinsonia* were carried out. The main problem was water stress due to pronounced dry periods and the dominance of fine pores fixing water after periods of inundation. Only the establishment of microcatchments using rainwater harvesting methods improved the situation (Klein et al. 1990). Mineral deficiencies could not be identified. Since the pore volume of the subsoil horizon is only 45 %, planting holes must be prepared to secure root development during initial phases of reforestation. In the surface horizons the amount of stable aggregates is only 7 %, indicating sensitivity to erosion.

In southern Benin (West Africa), with mean annual rainfall of about 1,200 mm, some 1,000 hectares covered with Vertisols have developed from Tertiary clays in the depression of Lama, 60 km northwest of Cotonou. To satisfy the supplies of a

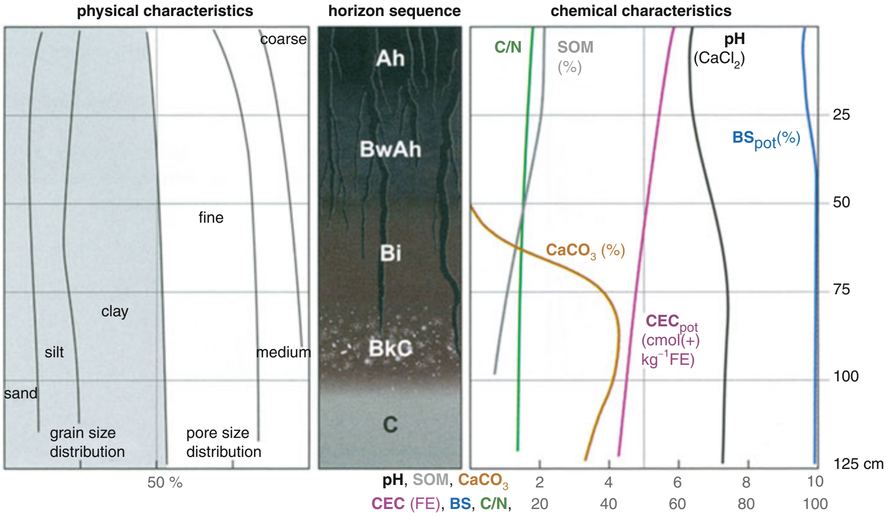


Fig. 40 Selected characteristics of a Pellic* Calcic* Vertisol derived from lime-rich clay (Zech et al. 2014)

nearby established modern saw mill, *Tectona grandis* is planted on a large scale in the depression of Lama. Since this tree species is known to be sensitive to waterlogging, which occurs during the rainy period, small dams have been prepared by pushing surface soil materials together with heavy bulldozers. In this way, the negative effects of temporary waterlogging are supposed to be reduced. Despite this expensive soil preparation, young teak plantations suffer from leaf discoloration due to Mg deficiencies and perhaps root decay (Drechsel et al. 1991b).

Chlorosis was found also in plantations with *Anacardium occidentale,* established on Calcic* Vertisols in Jucatan (mean annual precipitation about 1,200 mm). The leaves revealed chlorosis of the interveinal space, due to *Zn* deficiency, probably induced by high pH-values of the soils. Chlorotic leaves contained only 7–8 ppm Zn (Zech et al. 1992c). The cashew tree is not adapted to Vertisols. This was confirmed by studies in Middle Senegal (mean annual precipitation about 800 mm), concerning the relationship between site factors, mineral nutrients, and growth of *Anarcadium occidentale* (Zech et al. 1992b). We found that tree growth was highest on deep sandy soils (Arenosols) and lowest on Vertisols, occuring in the depressions, despite the fact that nutrient stocks of the Vertisols were much higher than those of the sandy soils. Growth increment correlated significantly with the bulk density in 100 cm soil depth. In the Vertisol profiles this value always was much higher than in the sandy soils, preventing the development of a deep root system. The result is a reduction of photosynthesis and biomass production of cashew on Vertisols during the pronounced dry season due to water stress.

Photo 44 Calcic* Vertisol (Hypereutric*, Stagnic*) with the following horizons: Ah (0–20 cm), BigAh (20–70 cm, = vertic** horizon, wedge-shaped soil aggregates, slickensides, red mottles), Bgk (70 cm +, *red* mottles, secondary carbonates). The deep cracks, which develop during the dry period, may disrupt roots, rendering the sustainable establishment of tree plantation more difficult. The red mottles indicate water logging during the rainy period (Ethiopia)

According to these examples, forest management of Vertisols is difficult. Plantation forestry seems not to be promising because most tree species have difficulties to root the clay-rich subsoils which are periodically dry with wide cracks and then waterlogged. Also less is known about the sustainable management of natural woodland (Photos 44 and 45).

Leptosols (LP)

Definition: Weakly developed shallow soils, conditioned by the parent material, with *(O-)A-(B-)C- or (O-)A-(B-)R*-profiles. Within ≤25 cm from the soil surface, Leptosols are limited in depth by continuous** rock or technic hard** material. According to Fig. 41, also profiles having less than 20 % (by volume) of fine earth averaged over a depth of 75 cm from the soil surface or to continuous** rock or technic hard** material belong to the Leptosols. They have no calcic**, chernic**, duric**, gypsic**, petrocalcic**, petroduric**, petrogypsic**, petroplinthic**, or spodic** horizon. The A-horizon may be mollic** or umbric**; sometimes a thin cambic** B-horizon occurs. The organic surface layers can be folic** or histic** (see Fig. 41).

Properties: Table 25 and Fig. 41 inform about representative properties of Leptosols.

Photo 45 In the semiarid tropics Vertisols are generally used for grazing, and the forests are only extensively used (chopping, charcoal production). Ploughing by hand is difficult due to the special physical properties described in Table 24; but mechanical cultivation increasingly allows to use the agricultural potential of Vertisols. Ploughing is best done at the beginning and at the end of the rainy season (Northern slopes of Mt. Kilimanjaro, Tanzania)

Regional distribution: Leptosols are poorly developed and/or extremely stony soils of mountainous areas occuring particularly on rocky slopes due to soil degradation (removed older soil covers) by erosion. But they also occur on young fluvial terraces rich in coarse gravels, thus comprising thin soils representing initial phases of soil formation. Leptosols extend all over the world (totally 1,655 million ha) and in the tropics and subtropics cover approximately 900 million ha especially in South and Central America, in the Sahara, in the Arabian Peninsula, and SE Asia. Many Leptosols correlate with the Lithic subgroup of the Entisols (US Soil Taxonomy). The qualifier Nudilithic* describes continuous** rock at the surface.

Forest Management. Due to stoniness and shallowness nutrient stocks and water-holding capacity are low and seriously restricting tree growth. pH varies according to the mineral composition of the parent material. On Rendzic* Leptosols trees may suffer from deficiencies in Fe and Mn, showing symptoms of lime-induced chlorosis with yellow recent leaves. Examples have been described from Jucatan, Mexico, where *Manilkara zapota* and *Swietenia macrophylla* growing on Rendzic* Leptosols derived from Tertiary limestones suffered from Mn -deficiencies, with chlorotic leaves containing only 9 and 13 ppm Mn respectively (Zech et al. 1992c). Tree species better adapted to high pH values, like *Tectona grandis* (Photo 46) *and Khaya ivorensis,* may better succeed if the supply with other nutrients and water is secured. Umbric* and Dystric* Leptosols with low pH may be used for planting pines and *Eucalyptus*.

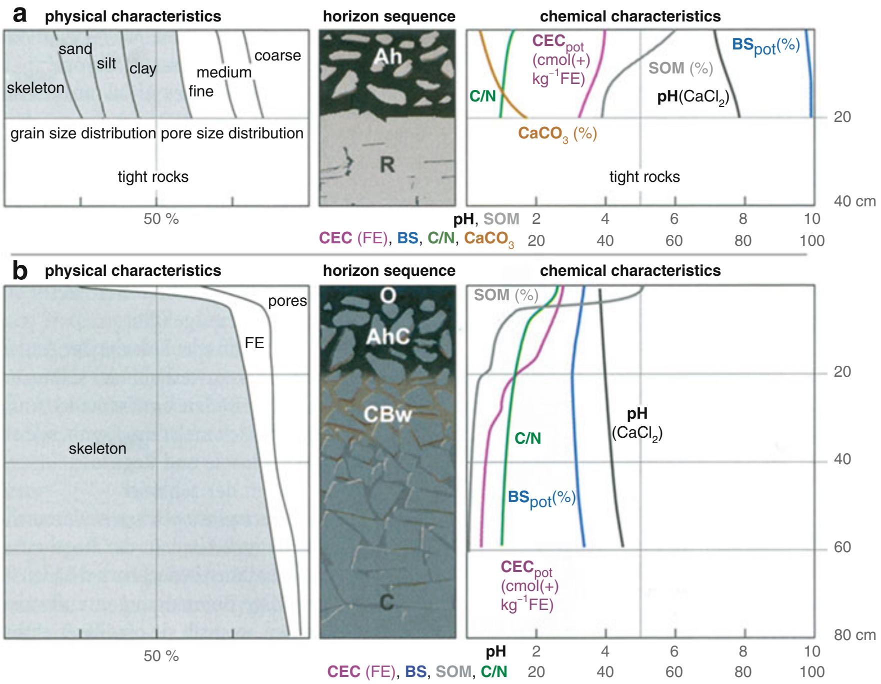


Fig. 41 Depth profiles of selected characteristics of a Rendzic* Leptosol derived from limestone (*above*) and of a Dystric* Hyperskeletic* Leptosol on granite slope debris

Table 25 Properties of Leptosols

Physical properties:
Shallow or/and skeletic
Low water storage capacity
Chemical properties:
Low nutrient stocks
pH varying, according to the chemistry of the parent material
Leptosols rich in limestone may induce chlorosis due to Fe/Mn-deficiency
Biological properties:
Strongly varying according to pH, microclimate, litter quality
Sometimes with rich macrofauna (earthworms, anthropodes)

Lithic* Leptosols especially in arid environments should be protected by preserving the naturally occurring forests and bushes. The destruction of the vegetation cover and overutilization accelerate soil erosion. In some cases, e.g., in Jemen or Bolivia, the establishment of terraces may allow agriculture, partly based on agroforestry or extended fallow periods. Relicts of Polylepis forests are preserved

Photo 46 *Tectona grandis* plantation on Eutric* Cambic* Leptosols and Cambisols (Pacific coast, Costa Rica)

on Leptosols in Bolivia at high altitudes with strongly dissected topography (Photo 47). In summary, these soils generally are not best suited for highly productive natural forests and forest plantations.

Regosols (RC)

Definition. Regosols are young and less developed mineral soils derived from unconsolidated, less altered materials with A-C-profiles. Sometimes they may be very deep. Regosols have no diagnostic features of other Reference Soil Groups. The parent material may be with or without carbonates. It is fine grained and does not contain medium to coarse sand (see section "Arenosols"); it is also not rich in coarse materials (see section "Leptosols"). In addition, the parent material of Regosols is not of fluvial, marine, or lacustrin origin with fine stratified structure (fluvic** material, see section "Fluvisols"). Regosols also differ from the Vertisols which are rich in swelling clays.

Properties: The parent material is highly conditioning the properties of the Regosols. In the surface horizon some SOM accumulation occurs, inducing darker colors. In arid and semiarid regions, accumulation of calcaric** and/or gypsiric** material may occur throughout between 20 and 100 cm from the soil surface or

Photo 47 *Polyleptis* growing on Leptosols in 3,800 m (Bolivia)

Table 26 Properties of Regosols

Physical Properties:
Fine-grained (clay, silt, fine sand)
Varying plant available water-holding capacity
Good rootability
In mountainous regions high erosion hazard
Chemical properties:
Depending on the chemical properties of the parent material
Nutrient stocks and SOM-contents generally low
Varying pH-values (4–7) and BS
Biological properties:
Eutric* Regosols under humid conditions have a high biological activity
Dystric* Regosols under semiarid and arid environments have a low biological activity

between 20 cm and any hard layer. In Table 26 and in Fig. 42 representative properties are summarized.

Regional Distribution: Regosols can be found in all climate zones without permafrost, frequently in regions influenced by wind and water erosion. They are common in the dry tropics (ca. 50 million ha) and in cold mountain regions where unconsolidated, fine-grained sediments dominate. Worldwide Regosols cover about 260 million ha, for instance, in northern and southern Africa, Near East, and Australia. Many Regosols correlate with the Entisols of the US Soil Taxonomy.

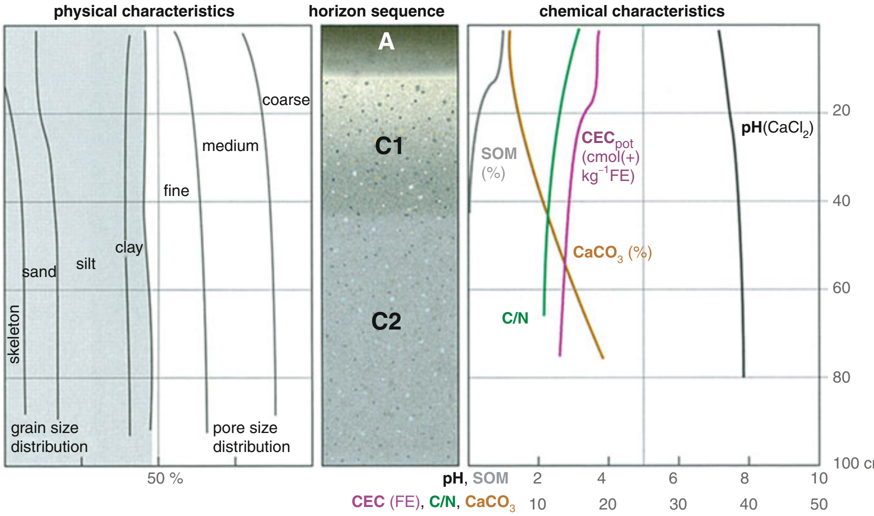


Fig. 42 Representative characteristics of a Calcaric* Regosol derived from loess (Zech et al. 2014)

Forest Management: The establishment of forest plantations is often limited due to low water-holding capacity, low nutrient stocks, but high pH values. In comparison to the Leptisols, root development generally is less restricted because the unconsolidated parent materials permit a deeper and better root penetration. In the Central Rangelands of Somalia with a mean annual rainfall of 250–350 mm, Calcaric* Regosols are used for reforestation with *Conocarpus, Prosopis, Tamarix, Acacia nilotica, Salvadora persica, Parkinsonia aculeata, Balanites aegyptiaca,* and *Acacia tortilis*. Some tree species like *Conocarpus* developed symptoms of *Mn*-deficencies with Mn-foliar levels below 20–25 ppm, but *Prosopis, Acacia* sp., and *Balanites* grew well, especially if their water supply was improved by methods of rainwater harvesting (Drechsel and Zech 1988, 1991; Drechsel et al. 1989; Drechsel 1991). In Central Somalia often soil associations of Regosols and Leptosols occur. Both Reference Soil Groups are sensitive to erosion, especially if overgrazed, and in steep mountainous envirnoments which should be left under forest. Successful reforestation of steep slopes generally requests terracing. In the Sahelian zone the natural vegetation of Regosols near human settlements is heavily destroyed. Temporary fencing has proved to be a more promising method for reestablizing the forest cover than expensive plantation forestry (Klein et al. 1990; Photos 48 and 49).

Cambisols (CM)

Definition: Cambisols are relatively young soils, moderately developed and weathered, with A-Bw-C-profile. They derive from a wide range of rocks. Diagnostic is the cambic** horizon (Bw); it's a brownish, yellowish, or reddish mineral subsoil horizon which is more weathered than the underlying relatively unaltered

Photo 48 Calcaric* Regosol (Clayic*) with O-A-C-profile derived from marl (southern Turkey). These soils are covered by dense *Pinus brutia* stands

C-horizon. It is starting ≤50 cm from the soil surface, has a thickness of ≥15 cm, and the lower limit is ≥25 cm from the soil surface. Other soils having an anthraquic**, hydragric**, irragric**, plaggic**. pretic**, terric** horizon but not fully conforming to the definition (e.g., not thick enough) of the corresponding RSGs are classified as Cambisols; or soils with fragic**, petroplinthic**, pisoplinthic**, plinthic**, salic**, thionic**, or vertic** horizon starting ≤100 cm from the soil surface are also classified as Cambisols even if they have no cambic** horizon. In addition, soils with one or more layers having andic** or vitric** properties with a combined thickness of ≥15 cm within ≤100 cm from the soil surface belong to the Cambisols. On limestone the cambic** horizon is frequently rich in clay and intensive red. If this layer has a Munsell color hue redder than 7.5YR, a chroma of >4 (moist) and is ≥30 cm thick, then the Chromic* qualifier is used; such soils, well known as Terrae rossae, are classified as Chromic* Cambisols (Photo 50).

Properties: Table 27 and Fig. 43 inform about selected properties of Cambisols.

Regional Distribution: In humid tropical and subtropical regions Cambisols are less common; they generally occur in mountainous regions where erosion prevents intensive weathering. Larger areas are described from the Indus, Ganges, and Brahmaputra valley systems. Soils rich in kaolinite may be classified as Cambisols

Photo 49 Eutric* Regosol (Aeolic*, Protocalcic*, Siltic*) with Ah-C-profile derived from loess

if no ferralic** or argic** horizon has developed. In semiarid regions Cambisols are associated with Calcisols, Durisols, Regosols, or Arenosols. The Cromic* Cambisols are well known from the Mediterranean zone. Cambisols generally correlate with Sols brun in the French soil classification with the Inceptisols of the US Soil Taxonomy, and with Burozems in the Russian classification.

Forest Management: If not eroded, Eutric* Cambisols usually are fertile and used in agriculture. Limitations may be due to stoniness (Skeletic*), acidity (Dystric*), or shallowness (Leptic*). Cambisols on steep slopes are generally covered by forests. In the arid to semiarid tropics Salic*, Gypsiric*, Vertic*, Calcaric*, or Eutric* Cambisols occur. High stone contents and cemented layers, typically for Skeletic* and Leptic* Cambisols, preventing deep rootability and reducing the water holding capacity, may limit tree growth. In the humid tropics leaching of nutrients is more pronounced especially in Pisoplinthic*, Plinthic*, Dystric*, and Ferralic* Cambisols; but in comparison to frequently associated Ferralsols, Acrisols, and Plinthosols, the wet-tropical Cambisols are still more fertile due to higher amounts of weatherable minerals like apatite, biotite, and feldspars. In addition, these tropical Cambisols have a higher CEC and thus can better store nutrient cations (Photo 51).

Photo 50 Eutric* Skeletik* Chromic* Cambisol derived from limestone (Croatia) with Ah-Bw-CBw-C-profile. At present the soil is covered by macchie; the former natural forests were clear cut causing severe soil erosion during the heavy winter rains

Table 27 Properties of Cambisols

Physical properties:
Bw-horizon generally more colored than the C-horizon; Chromic* Cambisols have an intensive reddish brown to red Bw rich in hematite
Bw mostly fine textured and generally containing more clay than horizons below
No pronounced lessivation, SOM-illuvation, and podzolization
High aggregate stability, high pore volume, internal drainage good
Generally high water-holding capacity
Chemical properties:
Nutrient stocks and nutrient availability in undisturbed profiles are intermediate to high; after erosion N-deficiency frequent
pH(H_2O) 5–7; in Chromic* Cambisols derived from limestone BS $\geq$50 %
CECpot intermediate to high
The Bw-horizon is slightly to moderately more weathered than the C-horizon (as indicated, for instance, by structure, color, clay and carbonate contents)
In the clay fraction 2:1 minerals dominate, Chromic* Cambisols may already contain kaolinite
Biological properties:
Biological activity intermediate to high; during dry periods reduced
Rootability generally good

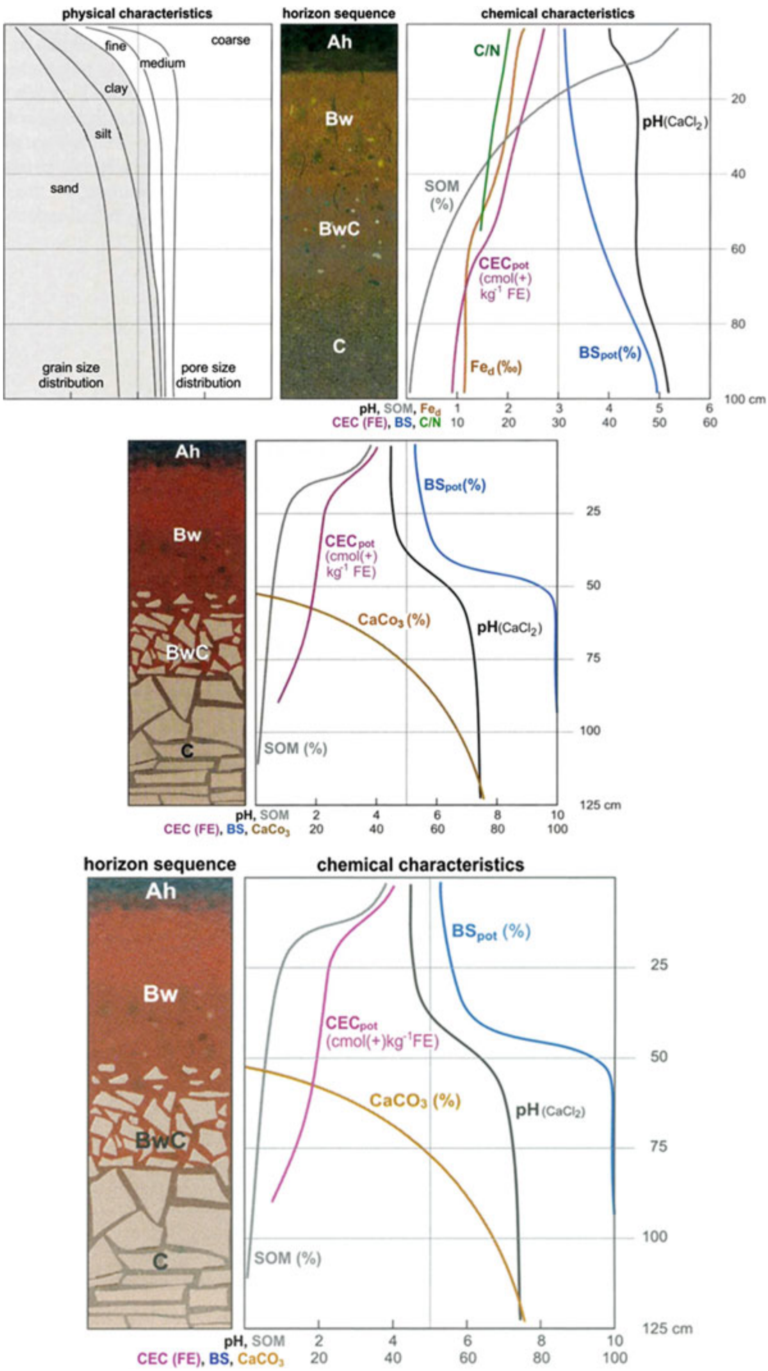


Fig. 43 Depth function of selected properties of a Dystric*Cambisol derived from loamy sand (**a**) and of an Eutric* Chromic*Endoskeletic*Cambisol (**b**) derived from limestone

Photo 51 Eutric* Skeletic* Cambisol (Desa Forest Afar region, Ethiopia). Overgrazing caused deterioration of the forest, and in slope position severe erosion of the fine earth resulted in the accumulation of the skeletic material on the soil surface

Podzols (PZ)

Definition: Acid soils with O-Ah-E-Bhs-Bsh-C-profile, having a spodic** B-horizon. The word "spodic" derives from Greek *spodos* = wood ash. But the spodic horizon comprises the dark to reddish colored Bhs- and Bsh-horizons starting ≤200 cm from the mineral soil surface, and not the ash-colored E-horizon lying above the B-horizon. Parent material is generally sandy and mostly acid. The low pH-values of the topsoils evoke intensive weathering and destruction of the primary and secondary minerals. The fragments are leached in an ionar state or after reaction with low molecular organic compounds as complexes from the surface soil layers to the subsoil where they precipitate, forming the spodic** horizon. The impoverished surface layers become bleached albic** material. For more details about podzolisation see section "Podzolization" (Fig. 20).

Properties: In Table 28 and Fig. 44 properties and selected depth profiles of Podzols are summarized.

Regional Distribution: Podzols cover large areas in the cool, temperate zone; but they also occur locally in the humid tropics especially on acid, quarzitic, deeply weathered sandstones (totally less than ca. 10 million ha). Tropical Podzols occur in S America (along Rio Negro, Guyana), SE Asia (Kalimantan, Sumatra), subtropical

Table 28 Properties of Podzols

Physical properties:
Coarse textured, often high sand contents, mainly quartz; sometimes skeletic; clay contents often <10 %
High water infiltration; if the B-horizons are indurated (ortstein), water-logging may occur and Histosols and/or Stagnosols may develop
Low water-holding capacity
Erosion hazard on slopes
Chemical properties:
Slow decomposition of litter, C/N in the surface soil >25, in the subsoil >20
Downward percolaton of fulvic acid complexes with Fe and Al
Low pH-values of 3–4.5 in the topsoil layers; slightly higher (up to 5.5) in the subsoil
Low BS, Al-toxicity possible
Low plant availability of *N* and *P*, despite moderate to high stocks, due to low pH-values
And phosphates are strongly bonded on sequioxides
Low reserves in base cations (*K*, Mg, *Ca*) and micronutrients, especially in the topsoil
Low CEC_{pot} in the eluvial E due to low SOM-and clay-contents
The clay fraction of the spodic** horizons consists frequently of vermiculite and secondary chlorite
Biological properties:
Low biological activity, reduced litter decomposition, development of thick raw humus
Reduced bioturbation
Reduced rootability if the spodic** horizon is indurated

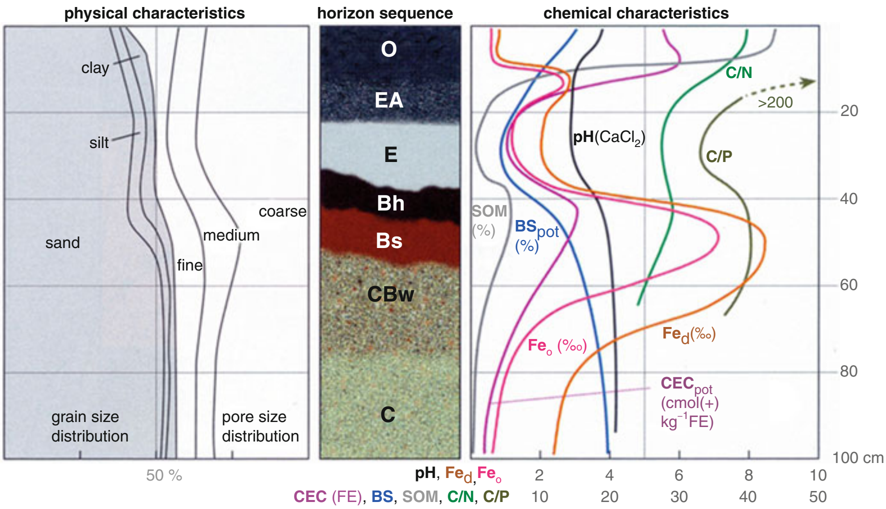


Fig. 44 Depth profiles of selected characteristics of Folic* Albic* Podzol derived from quartz-rich sand (Zech et al. 2014)

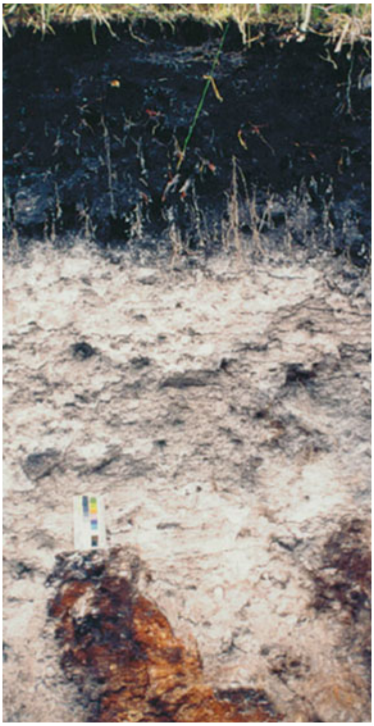


Photo 52 Umbric* Albic* Rustic* Podzol derived from quartz-rich sand (watershed Nile/Congo, 2,500 m asl, Rwanda). In the cool and humid mountainous environment a thick and acid umbric** horizon developed at the soil surface. Below is the bleached E-horizon and the mainly reddish spodic** horizon, rich in sesquioxides

Australia, and S Africa. Sometimes their solum is very deep; such soils are called "giant podzols." If the spodic** horizon is starting $\geq$200 cm below the soil surface, then these soils are classified as Arenosols if the texture is sandy. Most podzols correlate with the Spodosols in the US Soil Taxonomy.

Forest Management: The agricultural value of Podzols is low, mainly due to unfavorable chemical properties. Thus forest use (mainly coniferous forests) dominates. During the dry season trees growing on skeletic or coarse sandy, podzolized soils may suffer from drought, since the water-holding capacity is low. The natural vegetation of tropical Podzols might be a light forest highly sensitive to fire and clearing. These stands should be protected. The establishment of tree plantations on tropical Podzols is supposed to be relatively uneconomic, since heavy inputs are necessary. Besides *N*, also *P* and *K* as well as micronutrients may be limiting tree growth. But in South Africa and especially in Australia the application of mineral fertilizers in pine plantations growing on Podzols gave good results. Application of lime stimulates *N*- and *P*-mineralization and reduces *Al*-toxicity. Erosion hazard in hilly landscapes with Podzols is high (Photos 52 and 53).

Luvisols (LV)

Definition: Undisturbed Luvisols have an A-E-Bt-C-profile; if disturbed, e.g., after erosion, A-Bt-C-profiles are frequent. The subsoil B-horizon has higher clay contents than the overlying horizons, due to pedogenetic processes like clay migration.

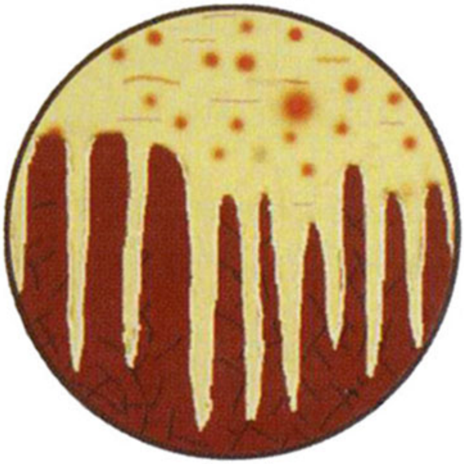


Photo 53 Someriumbric* Albic* Carbic* Podzol (Arenic*) derived from strongly altered and bleached quartz-rich rocks. At present, these soils are covered by light tropical forests in Kalimantan. After forest clearing and burning, SOM-mineralization and erosion drastically reduce the site quality and the regeneration of forest is difficult

Diagnostic is an argic** horizon starting $\leq$100 cm from the soil surface and which has in general a high CEC_{pot} ($\geq$24 cmol(+) kg^{-1} clay) in its upper 50 cm and a high BS_{eff} ($\geq$50 %) between 50 and 100 cm from the soil surface. Texture class is loamy sand or finer; and clay contents (mainly High-Activity Clays = HACs) must be $\geq$ 8 %; sometimes the argic** horizon is intensive red; and if its Munsell color hue is redder than 7.5YR (moist) and $\geq$30 cm thick, then the Chromic* Qualifier is used; such soils are classified as Chromic* Luvisols. The parent material is widely varying and generally consists of unconsolidated sediments like loess, glacial till, colluvial (Photo 54), and alluvial deposits. In section "Lessivation" the process of lessivation is described in more detail (Fig. 19).

Properties: In Table 29 and Fig. 45 representative properties of Luvisols are summarized.

Regional Distribution: Most Luvissols occur in the temperate zone on flat and weakly inclined topography and less in warmer climates with distinct dry and wet periods (e.g., southern Australia). Especially in the Mediterranean zone Chromic* Luvisols (Photo 55) developed. Ferric* Luvisols may occur as young and immature soils in the tropics. They frequently correlate with the Sols lessivés in the French Soil Classification and with the Alfisols in the US Soil Taxonomy.

Forest Management: According to Table 29, Luvisols are fertile and of high agricultural value. The natural vegetation of Luvisols is a deciduous or coniferous forest or grassland. Leptic*, Gleyic*, and Stagnic* Luvisols are less favorable because root growth may be restricted and wind cast frequently occurs especially in monocultures of shallow root trees like *Picea abies*. On Albic* Luvisols nutrient supply of the trees may be a limiting factor. Today, only shallow, eroded Luvisols are available for forestry. In regions with a long dry period water stress could reduce photosynthesis.

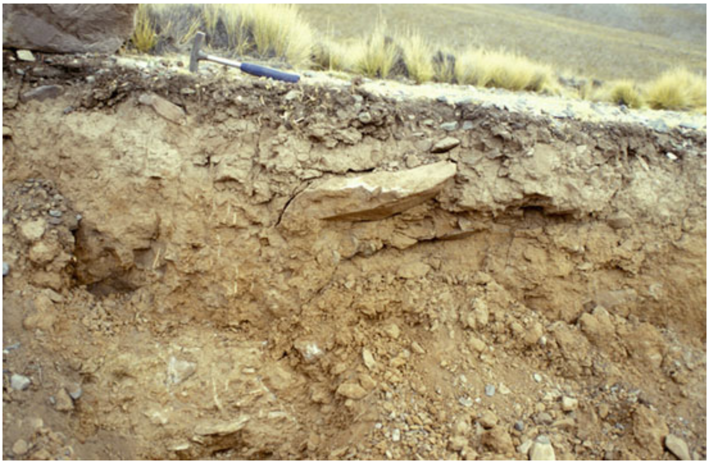


Photo 54 Luvisol derived from unconsolidated slope debris (Equador)

Table 29 Properties of Luvisols

Physical properties
The subsoils have higher clay contents than the surface soil layers mainly due to lessivation
Surface soil layers mostly well drained and porous but a dense argic** horizon may induce stagnic** properties
Soil surface structure is crumb and/or granular, the structure of the B-horizon is often blocky
Due to clay and Fe_d migration the surface layers may be bleached (E-horizon)
Luvisols do not have interfingering of coarse-textured bleached (albic**) material into the finer-textured argic**horizon typically for the Retisols
High soil erosion hazard
Chemical properties
High BS_{eff} in 50–100 cm depth
Surface pH H_2O near 5–6 supporting lessivation, subsoil pH-values near 7 supporting coagulation of the colloids
High nutrient stocks and good nutrient availability
High HAC-contents throughout the argic** horizon
The argic** horizon has higher Fe_d-contents than the surface soil horizons

Umbrisols (UM)

Definition: Soils with *Ah-C-* or *Ah-Bw-C*-profiles mainly derive from siliceous material or from strongly leached basic rock and having a pronounced dark topsoil. Diagnostic is in many cases the umbric** horizon, a significantly thick, dark-colored, humic, and well-structured mineral surface A-horizon with low base saturation. In the subsoils pH-values may vary from acid to neutral. Seldom Umbrisols may have a mollic** surface soil horizon (= Mollic* Umbrisol) with

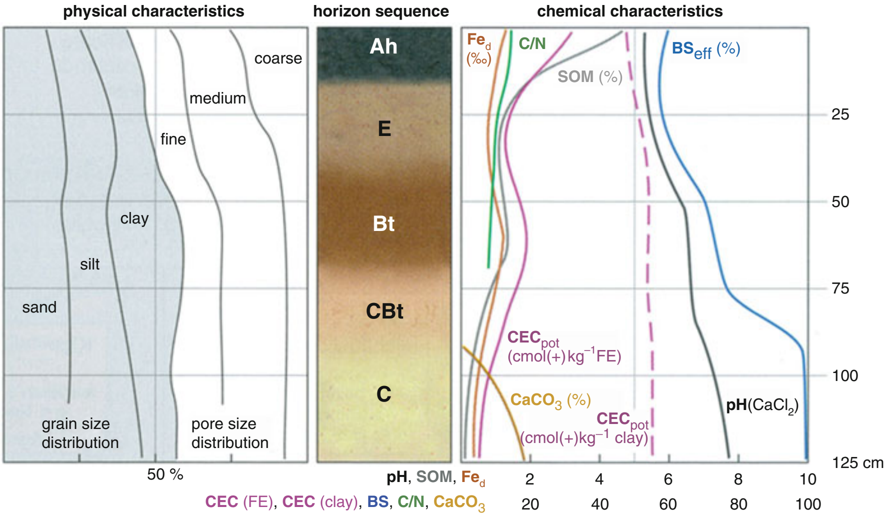


Fig. 45 Depth profiles of a Hablic* Luvisol derived from sandy loess loam (Zech et al. 2014)

Photo 55 Chromic* Luvisol derived from Young Quaternary loess over gravels showing a pocket-like penetration of the argic** horizon into the gravels (Manchuria)

higher BS than the umbric** horizons, e.g., due to anthropogenic application of lime. Umbrisols with a mollic** horizon have always low pH-values in the subsoil. Also hortic** horizons may occur. Sometimes redoximorphic features emerge in the subsoil (=Gleyic* or Stagnic* Umbrisols). In some cases featurres of initial podzolization are obvious.

Properties: In Table 30 and in Fig. 46 representative characteristics of Umbrisols are summarized.

Regional Distribution: Typical for highly humid mountainous regions with little or no moisture deficit (e.g., Galicia, Himalaya, Baikalia, Sumatra, Papua New Guinea, humid part of the South American Andes, Serra do Mar, South and

Table 30 Properties of Umbrisols

Physical Properties
Surface soil layers are frequently wet due to humid climatic conditions
High plant available water-storage capacity, despite high water percolation, no water logging
On steep slopes erosion hazard
Chemical properties
CEC_{pot} between 20 and 30 cmol(+)kg^{-1} FE
Supply with mineral nutrients (e.g., K, Mg) may be problematic
N-stocks high but low plant availability
SOM stocks high
Al-toxicity may be a problem
Biological properties
Reduced biological activity, increased only in Mollic* Umrisols
SOM-turnover low since too acid, too cold, or too humid

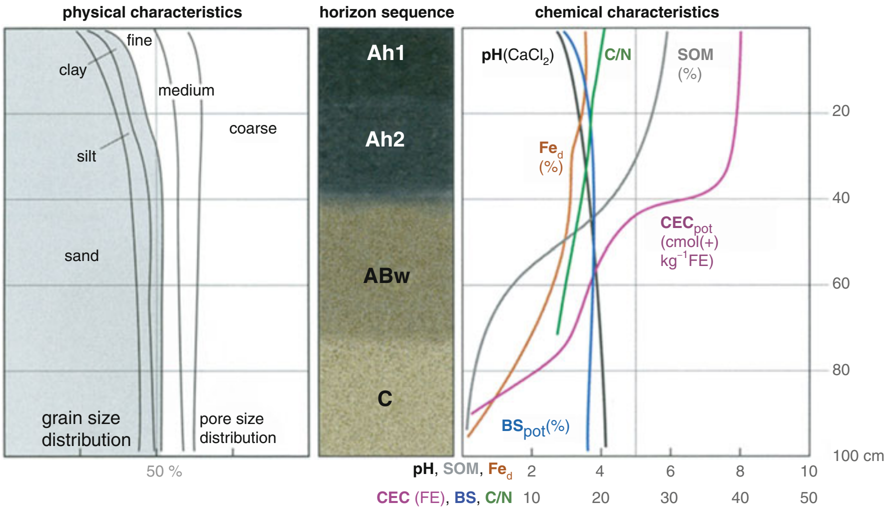


Fig. 46 Selected properties of a Haplic* Umbrisol derived from loamy sand (Zech et al. 2014)

East Africa). Globally they cover about 100 million ha. In the French Soil Classification many Umbrisols are called Sombric Brunisols and Humic Regosols; in the US Soil Taxonomy they belong to the Entisols and Inceptisols.

Forest Management: High erosion hazard after forest clearing. Contour terracing increases the succcess of reforestations. Umbrisols are suitable for the establishment of conferous monocultures (e.g., *Araucaria* spp. in Brazil). Fertilization with *P*, *K*, and Mg and moderate liming (*Al*-toxicity!) increases soil fertility and survival rate of reforestations. Forests growing on very steep slopes should be better protected as ecological reserves (Photos 56 and 57).

Photo 56 Haplic* Umbrisol (Hyperhumic*, Pachic*) derived from weathered gneiss (Burundi, 2,300 m asl). Diagnostic is the thick ($\geq$50 cm = Pachic*), dark-colored umbric**horizon, having $\geq$ 5 % SOC as a weighted average in the FE fraction to a depth of 50 cm from the mineral soil surface (= Hyperhumic*)

Temporarily or Permanently Hydromorphic Soils

In this section we present permanently hydromorphic soils such as Fluvisols, Gleysols, and Histosols. In addition, the periodically hydromorphic Planosols, which are seriously influenced by water-logging during the rainy season, will be described here. Newly introduced are the Stagnosols and Retisols. For intensive forest management these periodically wet soils must at least partly be drained. Methods available are discussed under Forestation within this handbook (see also Chapman and Allan 1978).

Fluvisols (FL)

Definition: The parent materials of the Fluvisols are young fluviatile, marine, or lacustrine deposits. They receive, unless empoldered and/or drawdown of the water table, fresh materials in regular intervals by overflooding. Diagnostic for Fluvisols is the accumulation of fluvic** material (Photo 58) showing obvious stratification, being $\geq$25 cm thick and starting $\leq$25 cm from the mineral soil surface; if it starts from the lower limit of a plough layer that is $\leq$40 cm thick, the fluvic** material must extend to a depth of $\geq$50 cm from the mineral soil surface. Many Fluvisols

Photo 57 Folic* Umbrisol derived from weathered gneiss covered by Afromontane Mountenous Forests (Rwanda)

show an irregular decrease in the SOC-contents depending on the C_{org}-contents of the accumulated material or due to burying of young Ah-horizons. Stratification is documented by SOC-contents $\geq$0.2 % than in the overlying layer. In general, soil profile development of the Fluvisols is weak; only A- and C-horizons can be identified but with different modifications, e.g., due to the accumulation of lime, easily soluble salts, or sulfides.

In the subsoil buried older soils may occur whereas in the upper soil layers no diagnostic horizons like a cambic** horizon or diagnostic properties have developed indicating advanced soil genesis and being diagnostic for other RSGs. But most Fluvisols are in some parts of the profile groundwater influenced and reveal red mottles (gleyic** properties; Gleyic* Fluvisol).

Properties: In Table 31 and Fig. 47 representative properties of Fluvisols are summarized.

Regional Distribution: Worldwide Fluvisols occupy about 350 million ha, and more than half occur in the tropics. Fluvisols with mangrove forests cover about 15 10^6 ha. Subhydrical soils (<2 m water and $\pm$ permanently covered by water) are usually classified as Subaquatic* Fluvisols. Fluvisols occur along rivers (e.g., Mesopotamia, Nile) and lakes, in deltaic zones, and along coastal lowlands which are periodically flooded. Many Fluvisols correlate with the Sols minéraux bruts d'apport alluvial ou colluvial and with the Sols peu évolués non climatiques d'apport alluvial ou colluvial in the French Soil Classification with Fluvents in the US Soil Taxonomy and with Fluvial soils according to the Russian Soils Classification.

Photo 58 Fluvic** material is diagnostic for Fluvisols. It is a stratified material of fluviatile, marine, or lacustrine origin showing obvious stratification reflected by alternating layers of different color (e.g., due to varying SOC-contents) or variation in texture or skeletic material (Rio Oriente, Argentina)

Table 31 Properties of Fluvisols

Physical properties:
Fluvisols are characterized by an obvious stratification due to the repeated accumulation of differently textured or differently colored fluvial, marine, or lacustrine material
According to the grain size distribution, water permeability varies
Low carrying capacity for heavy machinery
Land use may be restricted due to the alternation between flooding and dry falling
Usually deep profiles with week horizon differentiation but a distinct topsoil horizon may have developed
Chemical properties:
Strongly varying according to the chemical properties of the accumulated material
Mostly favorable nutrient supply
The SOM may be accumulated or developed in situ
Water-saturated Fluvisols with sulfidic** material become very acid (pH H_2O <4) after drying out and oxidation due to the formation of the thionic** horizon
Biological properties:
Root development partly restricted due to high groundwater level, increased salt and sulfide contents

Forest Management. Natural fertility of Fluvisols varies considerably according to the origin of the sediments, the chemical properties of the groundwater, and its fluctuations. Many Fluvisols have been under intensive use for very long

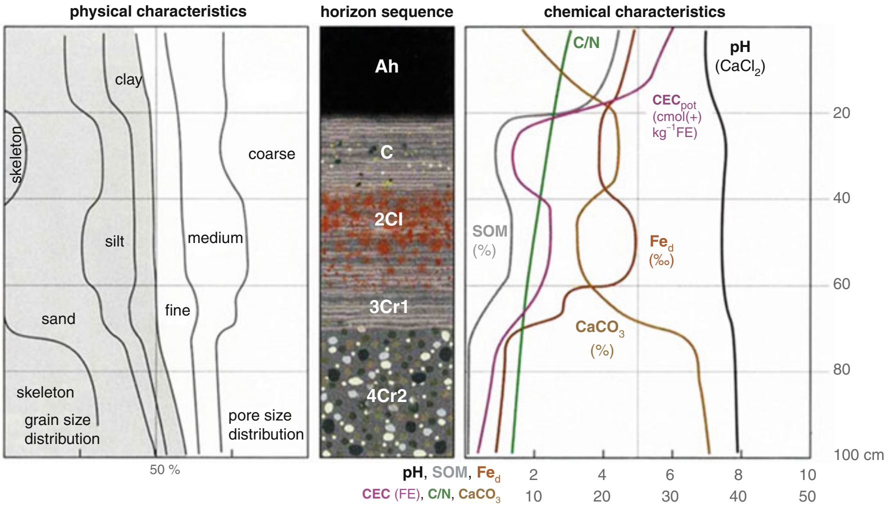


Fig. 47 Depth profiles of selected properties of a Calcaric* Gleyic* Fluvisol derived from fluvial deposits (Zech et al. 2014)

times, e.g., for planting paddy rice. Thus, less possibility for forestry remains especially when Fluvisols are used by gardening and food production for the local markets. Sometimes agroforestry seems acceptable. For instance, on Calcaric* and Gypsiric* Fluvisols near the Shebeli river south of Belet Uen (Somalia), gardening was combined with planting *Ziziphus, Acacia seyal, Acacia nilotica, Cassia siamea, Conocarpus lancifolius,* and *Prosopis* (Drechsel 1991). Due to the availability of irrigation water during the dry season, the survival rate of the planted trees was high; but sensitive tree species like *Cassia siamea, Conocarpus,* and *Azadirachta indica* some years later developed decline phenomena due to boron and chloride toxicity (Zech et al. 1991). Only proper water management with removal of salts by flooding during the rainy periods can prevent increasing salinization and toxicity phenomena.

In tropical lowland along many coasts influenced by tide, mangrove forests with *Rhizophora racemosa, Rhizophora harrisonii, Rhizophora mangle,* and *Avicennia africana* have developed on Tidalic* Fluvisols. Carefully managed, they can serve as a long-lasting source for firewood and charcoal. If Fluvisols with thionic** horizons are drained, oxidation of the sulfides starts, pH will drastically decrease, and Al-toxicity may totally prevent utilization. The rehabilitaion of such Fluvisols with thionic** horizons is difficult. Thus, proper water management is obligatory. According to site evaluation studies in semiarid Gambia (mean annual rainfall 800–1,000 mm), Fluvisols of colluvial and alluvial origin have developed in drainage depressions or near the floodplain border of the Gambia River (Zech 1984). Under these site conditions the following tree species seem to be promising: *Chlorophora regian, Khaya senegalensis, Borassus aethiopum, Elaeis guineensis, Acacia seyal, Acacia sieberiana, Acacia nilotica* var. *tomentosa,* and *Gmelina arborea.* Also coconut is adapted to periodic

Photo 59 The Amazon River regularly overfloods large areas, called Varzea, during the rainy season, thereby accumulating nutrient-rich stratified fluvic** material, from which Eutric* Fluvisols (Siltic*) develop. Higher located areas, which are no more inundated, are called Terra firme, generally covered by tropical rainforests growing on Ferralsols

flooding and survives on Gleyic* Fluvisols if the salt contents are not too high. Many ecosystems developed on Fluvisols reveal a high biodiversity and are worth to be protected as a refugium for fauna and flora (Photo 59).

Gleysols (GL)

Definition: Gleysols are mineral soils influenced by groundwater, tidal water, and underwater. They have gleyic** properties throughout in a layer $\geq$25 cm thick and starting $\leq$40 cm from the mineral soil surface, and reducing** conditions in some parts of every sublayer. Subsoils are more or less permanently water saturated, whereas the surface soils experience water influence only periodically. This results in the development of reddish to yellowish mottles especially at the aggregate surfaces in the periodically aerated upper soil layers (Al or Bl = oxydation horizon); in contrast, the low redox potential in the interior of the aggregates and mainly in the permanently water-saturated subsoil causes greyish-bluish to greyish-blackish colors typically for the so-called reduction horizon (Br, Cr). Horizon differentiations are frequently *Ah-Cr* (see Photo 60), *Ah-Bl-Cr, Ahl-Br-Cr, H-Cr or H-Bl-Cr.*

Also soils with a mollic** or umbric** horizon >40 cm thick having reducing** conditions in some parts between 40 cm below the mineral soil surface and the lower limit of the mollic** or umbric** horizon are classified as Gleysols. Also soils without permanent groundwater saturation but with gleyic** properties and

Photo 60 Dystric*Gleysol with *O-Ah-Cr*-profile derived from metamorphic rocks. The *Cr*-horizon is very dense and nearly saturated with groundwater all the year round and thus developed reducing** conditions in the *Cr*-horizon. Rootability is difficult, and frequent windbreaks at sites with such properties are the consequence

reducing** conditions due to ascending CO_2 and CH_4 are classified as Gleysols applying the Reductic* qualifier.

Properties: In Table 32 and in Fig. 48 selected properties of Gleysols are summarized and in Fig. 21 the process of Gleyization is visualized.

Regional Distribution: Gleysols occur nearly in all climates, also in arid regions, mainly located in valleys, depressions, or in (lower) slope position with high groundwater table. They also occur in shallow lakes, in low positions along the shore of seas and lakes, and in tidal areas. Parent materials generally are alluvial unconsolidated fine textured sediments of fluvial, lacustrine, marine, or glacial origin. If they show fine stratification (see fluvic** material) soils are not classified as Gleysols but as Fluvisols. Worldwide Gleysols cover about 720 million ha; in the tropics and subtopics about 200 million ha are found, for instance, along the alluvial fans of big rivers (Amazonia, Nile, Congo, Ganges, Indus, etc.). Acid Sulfate Soils with thionic** horizon or hypersulfidic** material are far spread in the coastal lowlands of West Africa, Southeast Asia, and in the northeastern shores of South America. In the US Soil Taxonomy Gleysols may belong to the Aqualfs, Aquents, Aquepts, Aquolls, or to the Wassents.

Table 32 Properties of Gleysols

Physical properties:
Gleysols rich in clay have a massive structure when wet, after desiccation polyhedral and/or prismatic structures develop; sandy Gleysols exhibit single grain structures
Layers with high redox potential (e.g., *Ahl, Bl*) may be reddish brown (due to ferrihydrite), yellowish brown (due to goethite), orange (due to lepidocrocite), or yellow (due to jarosite).
Layers with low redox potential (e.g., Br, Cr) may be white to light gray (if sandy), blue to green (if loamy and clayey), or dark gray to black (if sulfides). In underwater soils reduction processes dominate documented by reduction colors.
Carrying capacity often low
Chemical properties:
rH <20 in the layer with low redox potential due to oxygen deficiency
pH may strongly vary between 2.5 in Thionic* Gleysols and 9.5 in Sodic* Gleysols
Also BS_{pot} can strongly vary, e.g., from 10 % in Dystric* Gleysols to 100 % in Calcaric* Gleysols
Biological properties:
A high water table restricts the establishment of most tree species
Also the biological activity and the soil fauna are reduced if the water saturation lasts long

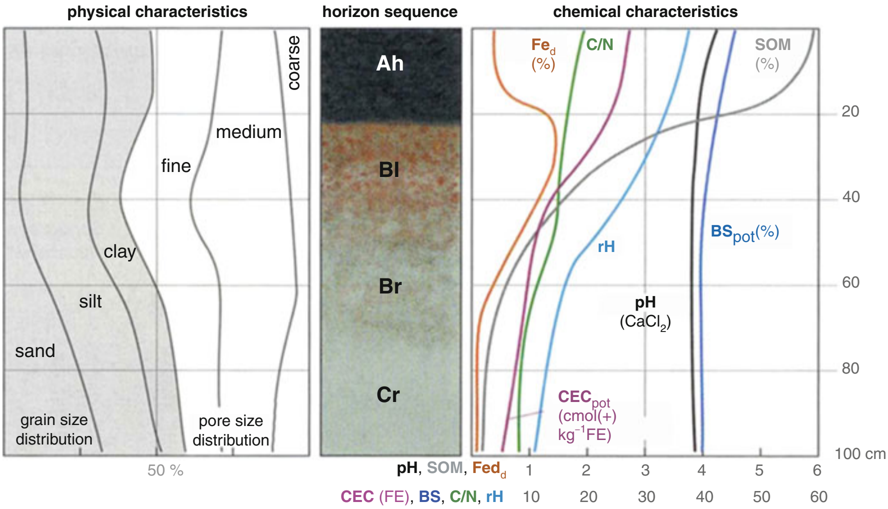


Fig. 48 Depth profiles of selected characteristics of a Dystric* Gleysol derived from silty loamy sand (Zech et al. 2014)

Forest Management. In comparison to the soils of the surrounding landscape, Gleysols often are more fertile due to higher contents in SOC and nutrients, but the main problem is the regulation of the groundwater level. In the tropics and subtropics Gleysols are frequently used for rice cultivation (Hydragric* Gleysol). According to the origin of the parent materials pH-values may be strongly varying (Dystric* and

Eutric* Gleysols), and in Thionic* Gleysols even severe acidification and Al-toxicity occurs (=Acid Sulfate Soils). These soils are suitable for sylviculture, if at all, only after application of high amounts of lime and regulation of the groundwater level by installing a drainage system. More favorable are generally Histic*, Chernic*, Mollic*, Umbric*, and Eutric* Gleysols. Their main limitation is a high water table existing generally throughout the whole year. This induces low redox potentials in the water-saturated horizon. Thus, only trees adapted to a lack in aeration can grow. Also root development is restricted. For this reason it should be discussed whether Gleysol areas are better put under nature protection covered, e.g., by swamp forests, and serve as groundwater and nature reserves. In the tropical rainforests of Liberia (West Africa) the following tree species adapted to Gleysols could be identified: *Heritiera utilis, Calpocalyx aubrevillei, Strephonema pseudocola, Protomegabaria staphiana, Stachothyrsus staphiana, Scytopetalum tieghemii* (Zech 1989). With regard to plantation forestry, most fast-growing tree species are not adapted to Gleysols. In addition, the carrying capacity of these soils is generally low, restricting the use of heavy machinery. If soils too wet are ploughed, then the structure becomes compact and massive. In the semihumid Ivory Coast *Tectona grandis* rapidly dies if planted in water-logged depressions. Similar results have been reported for *Anacardium occidentale* in Middle and Southern Senegal. On Gleysols in Gambia the following tree species have been reported to grow satisfactorily: *Chlorophora regina, Khaya senegalensis, Borassus aethiopum, Mitragyna inermis, Acacia seyal, Acacia sieberiana,* and *Acacia nilotica* var. *tomentosa.*

For intensive forest management Gleysols must be drained and limed if pH is too low. The result is an increased mineralization of the SOM. In contrast, inundation favors methanogenesis. Forest plantations on Histic* Gleysols will profit from the application of P- and K-fertilizers. Also agroforestry (Photo 61) is an interesting approach comprising the establishment of trees on parallel ridges and cultivating rice in the furrows between the forested ridges. In such systems, trees contribute to the reduction of the water table due to increased transpiration. Mangrove forests frequently covering Tidalic* Gleysols can be used for firewood production but should be managed carefully.

Histosols (HS)

Definition: Histosols (organic soils, peats, bocks, mucks) usually have *H-Cr*-profiles; if influenced by permafrost and with cryoturbations *H@-Hf-Cf*-profiles dominate. The H-horizon consists of organic** material, derived from incompletely decomposed plant remains, poor in sand, silt, or clay. It contains ≥20 % SOC (by mass) in the FE-fraction, generally accumlated under wet conditions as groundwater peat (fen), rainwater peat (raised bog), mangrove peat, etc. Also in cool mountainous areas organic** material frequently accumulates. Diagnostic features are

(a) ≥10 cm if starting from the soil surface and directly overlying ice, or continuous** rock or technic hard** material, or coarse skeletic fragments if in its interstices organic** material is accumulated

Photo 61 Agroforestry on Gleysol: cultivation of paddy rice below palm trees (southern Senegal)

(b) A combined thickness of ≥60 cm between ≤40 cm to ≤100 cm of the soil surface if ≥75 % (by vol.) of the organic** material consists of moss fibers
(c) ≥40 cm in other cases between ≤40 cm to ≤100 cm of the soil surface

(b) and (c) refer to the situation that mineral** materials ≤40 cm like slope debris, volcanic ash, or aeolian deposits are overlying the organic** material. Below the organic**material often strongly reduced mineral layers (e.g., Cr) follow.

Diagnostic is a histic** horizon consisting of organic** material being continuously water saturated ≥1 month in most years. Rheic* Histosols are influenced by groundwater, Ombric* Histosols by rainwater. If water saturation of the organic** material is <1 month per year, then soils are classified as Folic* Histisols with *O-(Bw-)C- or O-(Bw-)R*-profiles, characterized by the folic** O-hoirzon.

Properties: In Table 33 and Fig. 49 characteristic properties of Histosols are summarized.

Regional Distribution: Histosols occur at all altitudes but are mostly found in lowlands (marsh lands, coastal plains, lagoons) with high groundwater levels or in highlands with high precipitation exceeding evapotranspiration. Worldwide Histosols cover about 350 million ha especially in boreal to arctic regions of Eurasia and Canada. They also occur in the tropics (ca. 35 million ha), e.g., along border of shelfs, in poorly drained alluvial basins and river deltas (Mekong, Orinoco) where biomass production is higher than biomass decomposition. Well known are the Histosols in the higher cooler belts of tropical mountains, e.g., in East

Table 33 Properties of Histosols

Physical properties:
Low bulk density of 0.05–0.2 kg dm^{-3}
Pore volume up to 90 %
Permanently wet and water table often close to the surface
Saturated hydraulic conductivity usually high (up to 30 m d^{-1})
High water storage capacity (~40 mm dm^{-1})
Air deficient when water table is high
Chemical properties:
Rich in SOM, slow *C*- and *N*-mineralization
N-stocks moderate to high but low plant availability
P-, *K*-, and *S*- stocks low
Supply of *N*, *P*, and *S* deficient, also micronutrients like *Cu* may become deficient
Especially Ombric* Histosols are deficient in P, K, Mg, and micronutrients
pH-values strongly varying: Ombric* and Dystric* Histosols 2.5–4; Eutric* Histosols ~ 7; Histosols (Alcalic*) $\geq$ 8.5
Even in Dystric* Histosols with low pH no *Al*-toxicity since low contents in Al-containing minerals
CEC generally high and pH dependent
Lowering the water table contributes to the emission of the greenhouse gas CO_2
Renaturation by ascending the water level supports denitrification and methanogenesis (emission of N_2O and CH_4)
Biological properties:
Generally reduced biological activity due to high water saturation, oxygen deficiency, low pH-values
Low nutrient contents of the litter reduce its decomposition

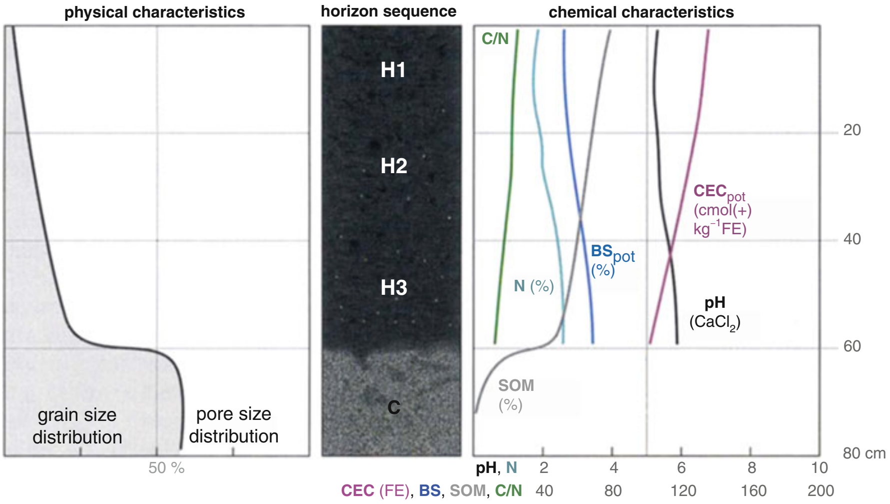


Fig. 49 Selected characteristics of an Eutric* Rheic* Hemic* Histosol derived from the litter of alder, dwarf-shrubs, and moss fibers (Zech et al. 2014)

Africa (Mt. Kenia, Mt. Kilimanjaro, etc.) at the transition between the afromontane to the afroalpine belts. Many Histosols belong to the Histosol order according to the US Soil Taxonomy.

Forest Management. Folic* Histosols are mostly under forest. In the tropics lowland Histosols often consist of acid forest peats, but in the highlands peats may be derived from *Papyrus* (Rwanda), grasses (Mt. Kenia), or *Erica* species. Histosols develop if on a certain site more biomass is produced than mineralized. Maximum of biomass production is near 25 °C, and the maximum of mineralization varies between 30 °C and 35 °C.

According to the water regime, which is usually responsible for the reduced mineralization rates, two prototypes of peat can be distinguished: **topogenous peats** are groundwater influenced; the water table is close to the surface. **Ombrogenous peats** are rain dependent with precipitation surplus and dome shaped; they have no mineral materials despite dust.

The properties of Histosols influence the suitability for tropical forestry considerably. According to water quality and water regime, productive mixed swampy forests occur or only stunted forests or no forests at all. Forest management is mostly only possible after drainage has been achieved. At present, in Sumatra and other tropical countries large areas with Histosols are drained for the establishment of oil palm and pulp wood plantations (*Eucalyptus* spp., *Acacia mangium*, *Acacia crassicarpa*). Thereby high amounts of CO_2 are produced. Also the use of heavy machinery is problematic due to the low carrying capacity of the soils. Drainage is accompanied by a drastic increase of humus and nutrient losses. Burning increases only short-term nutrient availability. Successful reforestation of ombrogenous peats needs, besides drainage, liming and fertilization with N, P, S, K, Mg, and micronutrients. The stability of forest stands growing on Histosols is often low; in consequence in areas with frequent storm events, wind throw is likely to occur. The high costs and environmental risks involved with forestry utilization suggest that especially deep tropical Histosols should be assigned as much as possible as protected areas (Photos 62 and 63).

Planosols (PL)

Definition: Soils with *Ah-Eg-2Bwg-2C*- or *Ah-Bg-2Bwg-2C*- or *Ah-Eg-(2)Btg-2C*-profiles which have periodic water stagnation. Diagnostic is the abrupt** textural difference within ≤100 cm from the mineral soil surface, signifying that the upper parts of the soil profiles (*Ah-, Eg-, Bg*-horizons) are more coarse textured, sandy and silty, and often enriched in stable minerals like zircon, overlying abruptly dense clay-rich, slowly permeable subsoil layers (*2Bwg*-, (*2*)*Btg*-, *2C*-horizons). Such abrupt** textural differences may be provoked by vertical (see lessivation, section "Lessivation") and lateral clay migration; also the chemical clay destruction in the topsoil layers is in discussion. In addition, sedimentation of coarse textured material (e.g., sand) above fine textured substrates (e.g., clay) is possible (geologic stratification).

The dense, clay-rich subsoil induces water stagnation during rainy periods initiating reducing** conditions during some time of the year and stagnic** properties, both in a layer ≥5 cm directly above and below the abrupt** textural

Photo 62 Dystric* Rheic* Sapric* Cryic* Histosol (Pamir, 4,100 m a.s.l.). The light colors in ca. 90 cm below the soil surface indicate massive perennial ice (cryic** horizon)

difference. The layer above (Eg-horizon) is mostly light colored with features of albic** material (Albic* Planosol) due to the lateral removal of sesquioxides and/or due to their accumulation in concretions directly above the abrupt** textural difference. Penetration of clay- and sesquioxide-depleted material into the clay-rich *2Bwg*- or *(2)Btg*-horizons forming vertically continuous tongues, called albeluvic** glossae, is not typical for Planosols (see section "Retisols").

Properties. Planosols have unfavorable physical and chemical properties. These are summarized in Table 34 and in Fig. 50.

Regional Distribution: Planosols have mainly developed in semiarid to subhumid temperate and subtropical regimes; but small areas are also found in tropical environments. They occur preferentially in plains, depressions, and flat slopes with periodical or seasonal water logging. Parent materials mostly consist of unconsolidated, clayey alluvial, and colluvial sediments. Worldwide Planosols cover about 130 million ha, for instance, in NE and SW of Brazil, Paraquay, and NE Argentina. In Africa they can be found in the S and E but also in the Sahelian Zone. They also occur in SW and E Australia. According to the US Soil Taxonomy

Photo 63 A partly Subaquatic* Histosol in the lowlands north of the Pare Mountains, Tanzania. Without drainage such sites cannot be put under forest use and are better protected as nature conservation area

Table 34 Properties of Planosols

Physical properties
Coarse-textured surface soil
Dense clayey subsoil (2Bwg, (2)Btg) with water-logging during the rainy season provoking reducing** conditions
Varying redox potentials: high when dry, low when water-logged
Water stress during the dry season, oxygen deficiency during water-logging
Low structural stability of the surface layers
Often very hard when dry
Chemical properties
Surface horizons: low pH, low CEC, low BS, poor in macronutrients (N, P, K, Mg, S)
Deficiencies in micronutrients
CEC in the subsoil low if rich in kaolinite, high by dominance of smectite and vermiculite
Varying pH-values: from acid with Al-toxicity to alkaline if contents of exchangeable Na are high
Biological properties
Low biological activity during the culmination of the dry and the wet period
Reduced rootability of the dense clayey subsoil

Fig. 50 Selected depth profiles of a Dystric* Albic* Planosol derived from loamy clayey colluvium (Zech et al. 2014)

most Planosols belong to the Great Soil Groups of the Albaqualfs, Albaquults, and Argialbolls.

Forest Management: Root growth is heavily restricted due to compactness of the *2Bwg*- or *2Btg*-horizons. Tree species must be adapted to waterlogging during the rainy season and water stress during the dry season. Due to the shallow root systems wind casts are limiting besides *Al*-toxicity and paucity in nutrients. Most Planosols are used for extensive grazing because their silvicultural potential is generally low. The actual vegetation is mostly a more or less open grass savanna with scattered shrubs and trees (light forest) like *Pinus caribaea, Byrsonima crassifolia* L., *Quercus oleoides,* and *Paurotis wrightii,* as described from Belize, Central America (Baillie 1989). Heavy inputs are necessary for amelioration including drainage, application of lime, macro- and micronutrients. The establishment of forest plantations might be more successful, if surface modification is carried out and saplings are planted on ridges some dm high, whereas the furrows between such ridges can be used for cultivating paddy rice (Photos 64 and 65).

Stagnosols

Definition: Soils which are periodically influenced by stagnating water. Under wet conditions the redox potential is low, causing reducing** conditions. Fe^{3+} is

Photo 64 Dystric* Alic* Albic* Planosol (Endoclayic*, Endogleyic*, Epiarenic*) with the following horizons: Ah (0–15 cm), EgAh (15–30 cm, stagnic** properties), Eg (30–40 cm, albic** material with some red mottles), Btg (40–80 cm, argic** horizon, stagnic** properties, clayey), Cl (80+ cm, gleyic** properties). Diagnostic is the abrupt** textural difference between the upper three more sandy horizons and the clay-rich subsoil. The red mottles and the bleached horizon document water-logging during the rainy period (Ethiopia)

reduced to mobile Fe^{2+} which can be removed, for instance, laterally, resulting in the development of a bleached Eg-horizon consisting of albic** material. This mobile Fe may be transported over larger distances and then accumulate in other parts of the landscape. During desiccation air penetrates into the solum and some Fe^{2+} can precipitate in the form of concretions at the basis of the Eg-horizon. Reduced Fe may also move from aggregate surfaces into the interior of aggregates where still included air leads to oxidation and precipitation of reddish Fe-oxides, causing strong mottling. Thus stagnic** properties develop, in which areas of reductimorphic plus oximorphic colors occupy $\geq$50 % of the total area. Stagnic** properties and reducing** conditions are characteristic features of Stagnosols within $\leq$50 cm from the mineral soil surface or to continuous rock** or technic** hard material, whichever is shallower.

Due to the processes induced by periocically perched water (stagnization, s. section "Hydromorphic Features" and Fig. 22) Stagnosols develop *Ah-Bg-C-* or *Ah-Eg-Btg-C-*profiles. Texture may be silty to fine sandy throughout the solum or stratified with coarser material in the surface soil and more clayey in the subsoil. Such grain-size differentiation may result from lessivation (section "Lessivation," Fig. 19) or from sedimentation of coarser over finer materials, leading to *Ah-Eg-2Bg-2C*-profiles.

Photo 65 Dystric* Albic* Planosol (Epiarenic*, Endoclayic*, Endogleyic*): Soils with such a thick bleached E-horizon (albic** material) are less fertile and should be used for extensive grazing or left untouched. Silvicultural management seems costly and wood production might remain low (South Africa)

But Stagnosols do not have an abrupt**textural difference as Planosols no albeluvic** glossae like the Retisols.

Properties: In Table 35 and Fig. 51 representative properties of Stagnosols are summarized.

Regional Distribution: Only in 2006 Stagnosols were introduced in the WRB classification system. They cover worldwide 150–200 million ha mainly in climates with periodically dry and humid to perhumid periods, for instance, in subtropical regions associated with Acrisols and Planosols (SE Australia, Argentina). The parent materials are mostly unconsolidated, like alluvial, colluvial, aeolian deposits, and glacial till deposited in flat and gently sloping terrain.

Forest Management: Long-lasting perched water reduces drastically rootability of most trees, and wind cast damages are frequent phenomena. But if the dry period is not too long, short-term stagnating water may be even favorable for tree growth. Forest plantations established on Dystric* Alic* Stagnosols may suffer from Al-toxicity, and liming may be required besides the application of basic P-fertilizers. Deep rooting and stagnic water-tolerant trees like *Eucalyptus* and

Table 35 Properties of Stagnosols

Physical properties
Grain-size distribution may be silty to fine sandy throughout the whole solum and thus being poor in coarse pores or alternatively coarse textured in the surface soil (e.g., sand, rich in coarse pores) and fine textured (e.g., clayey and poor in coarse pores when wet) in the subsoil
Perched water during the rainy season with oxygen deficiency
Water stress during the dry season
Surface horizons may be bleached, subsoils are mottled
Chemical properties
pH-value and BS varying
Reduced litter decomposition
Deficient in plant available *N* and *P*
Plants growing on Dystric* Albic* Stagnosols also often suffer from low Ca- and Mn-supply
K-deficiency possible on Dystric* Albic* Stagnosols (Arenic*)
If rich in concretions, then P may become deficient
Biological properties:
Oxygen deficiency, denitrification and methanogenesis during the wet period
The fluctuation between wet and dry periods stongly influences the soil fauna
Poor rootability especially of the dense, clay-rich subsoil; high wind waste hazard

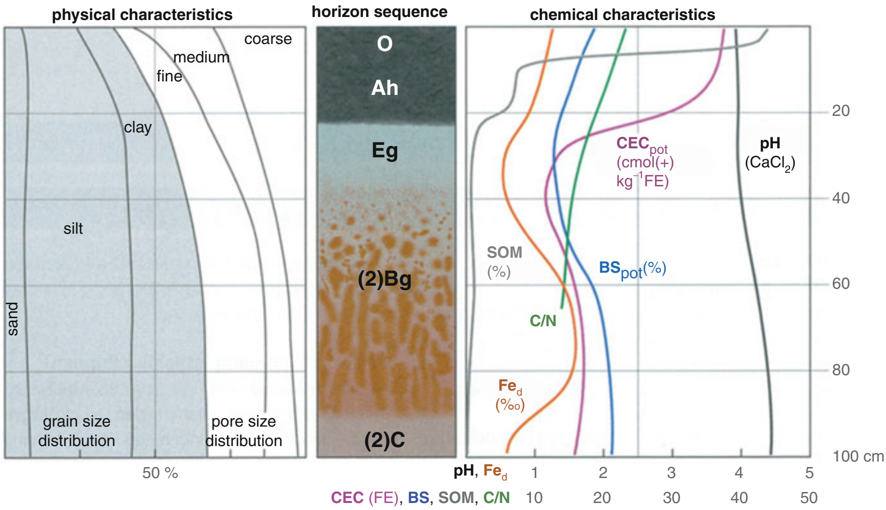


Fig. 51 Selected properties of a Dystric* Albic* Stagnosol derived from silty clay (Zech et al. 2014)

Casuarina spp. could be recommended for some Stagnosols. Supporting drainage by deep loosening or deep ploughing, improvement of the soil structure by liming can contribute to ameliorate site quality. Also agroforestry systems with paddy rice in furrows and trees along the ridges seem promising. Clear-cutting forest stands on

Photo 66 Dystric* Albic* Folic* Stagnosol (Siltic*) with an *O-Ah-Eg-Bg*-profile derived from metamorphic, silty material. Trees with shallow root systems are endangered by wind cast

Stagnosols may cause rise of the perched water table due to the absence of the transpiration by trees impeding reforestation (Photos 66 and 67).

Retisols

Definition: Soils, mostly with *Ah-E-Bt-C-* or *Ah-Eg-Btg-C*-profiles, having a bleached eluvial E-horizon overlying a brownish clay-rich argic** horizon that starts $\leq$ 100 cm from the soil surface. Diagnostic are retic** properties at the upper boundary of the Bt-horizon, indicated by the interfingering (partly forming tongues, albeluvic** glossae: see Fig. 52) of bleached, coarser-textured albic** material into the finer-textured argic** horizon. Partial removal of clay and of free Fe-oxides may be responsible for the interfingering of bleached coarser-textured albic** material; besides, this phenomenon may also be caused by falling of coarser-textured material from overlying layers into cracks of argic** horizons. If the soils are aggregated, the bleached tongues primarily develop on aggregate surfaces. Many Retisols are strongly influenced by stagnating water.

Properties: In Table 36 and Fig. 53 main properties of Retisols are summarized.

Photo 67 Acric* Umbric* Folic* Stagnosol planted with pines (South Africa)

Regional Distribution: Retisols are representative to flat and undulating plains along the southern border of boreal forests (taiga) in Europe and Canada. They also develop in the (sub)humid midlatitudes of Europe and USA. In subtropical and tropical lowlands Retisols only occur sporadically (S Vietnam). The parent material is mostly unconsolidated and of fluvial, aeolian, lacustrine, or glacial origin. Many Retisols correlate with the Albeluvisols according to WRB 2006, and with Glossaqualfs, Glossocryalfs, and Glossudalfs of the US Soil Taxonomy. They cover approximately 320 million ha.

Forest Management: Usually these soils are under forest (conifers or mixed forests); their limiting factors being low nutrient supplies and low nutrient availability (especially *N, P*), acidity, and probably waterlogging. Careful liming, drainage, and the application of basic P-fertilizers may increase site quality, survival rate, and growth of forest plantations (preferentially conifers and eucalyptus). Less experience is available about the establishment and management of forests on tropical Retisols. In Estonia, the estabishment of short rotation plantations with *Betula pendula* on Retisols resulted after 13 years in a significant

Fig. 52 Albeluvic** glossae are characterized by the interfingering of bleached, coarser-textured, partly mottled material into the brownish, clay-rich argic** horizon (See Photos 68 and 69)

Table 36 Properties of Retisols

Physical properties:
The eluvial E-horizon is poor in clay and its structure is less stabile
If the Bt-horizon is dense, periodic water stagnation occurs
Chemical properties:
Low nutrient stocks if the eluvial horizon is thick and often low nutrient availability
In the topsoil layers low pH($CaCl_2$) and low BS; generally higher in the Bt-horizons
In Retisols (Dystric*) contents of exchangeable Al may be high
CEC_{pot} shows minimum values in the E-horizons
Clay minerals display inclusion of Al
Low redox potential during water stagnation produces temporarily reducing** conditions
Biological properties:
Low biological activity, low litter decomposition, low bioturbation
Denitrification and methanogenesis during water stagnation
Poor rootability if the Bt-horizon is very dense (Fragic* Retisol)

decrease of available *K* and pH, while topsoil total *N* and available *P* remained at the same level (Lutter et al. 2015). Under tropical site conditions forest plantations on Retisols most likely will profit from improving the P supply (Photos 68 and 69).

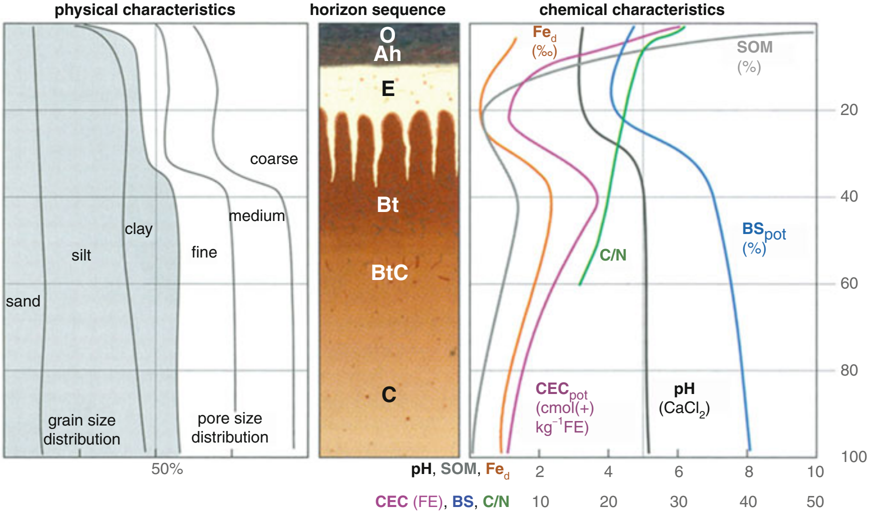


Fig. 53 Depth profiles of selected properties of a Dystric* Retisol derived from silty loam (Zech et al. 2014)

Photo 68 Whitish intercalations (albeluvic** glossae) penetrate from the silt-rich surface layer along the faces of soil aggregates into the dark brown clay-rich subsoil, developed on light brown sandy gravels

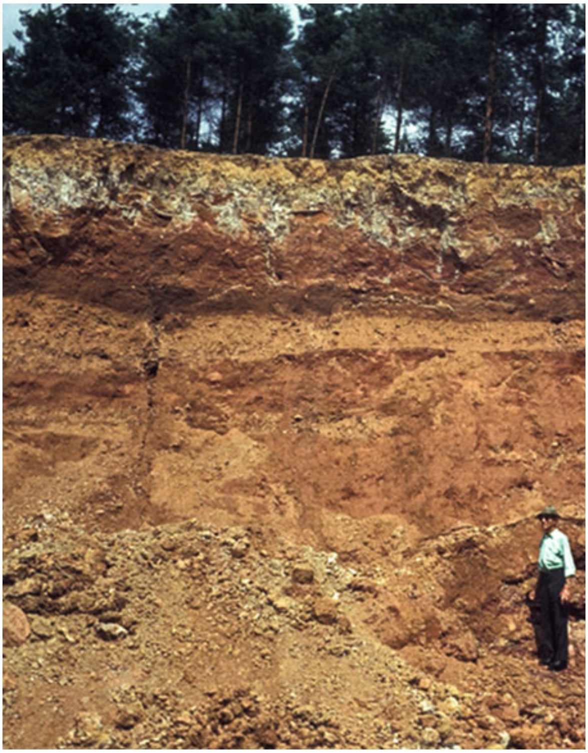


Photo 69 The Bt-horizons of Retisols are often very dense impeding rooting. Therefore roots preferentially penetrate into the subsoil along the coarser-textured tongues. The bleached material interfingers as a net into the underlying dark brown argic** horizon

Soils of the Steppes

These soils develop under steppic conditions with a mean annual precipitation between ~300 and 600 mm. They are not representative for the tropical lowlands but may occur in montane areas of the tropics (e.g., Chernozems in Bolivia, Phaeozems in East Africa) or in subtropical zones (e.g., pampas of Argentina and Uruguay). In general, major distributon of steppic soils is found in the semiarid temperate regions. For this reason in this chapter the steppic soils are only summarized in Table 37. But it should be mentioned that especially the Phaeozems have some silvicultural potential and according to Ghersa et al. (2002) woody species (*Gleditsia triacanthos* L., *Morus alba* L, *Melia azedarach*) are at present invading in the Rolling Pampa grassland soils of Argentina.

Tropical Soils Conditioned by Human Influence

Anthrosols (AT)

Definition: These soils are deeply influenced by human activities, resulting in profound modification or burial of the original soil horizons. Well known are the Hydragric* Anthrosols developed due to long-term cultivation of paddy rice. All other Anthrosols are generated by the additions of organic materials (Hortic* Anthrosols), mineral materials (Terric* Anthrosols), sods enriched by livestock excrements (Plaggic* Anthrosols), charcoal and household wastes (Pretic* Anthrosols), or fluvial, often nutrient-rich sediments (Irragric* Anthrosols) due to long-continued irrigation. The relevant diagnostic horizons (hydragric** together

Table 37 Soils of the steppes with a mean annual precipitation ca. 300–600 mm

	Kastanozems	Chernozems	Phaeozems
Definition	Brown humus-rich soils with a mollic** horizon, and a calcic** horizon or a layer with protocalcic** properties starting ≤50 cm below the lower limit of the mollic** horizon, and a BS_{pot} of ≥50 % from the soil surface to the calcic‘‘ horizon or to the layer with protocalcic** properties, throughout. Derived from unconsolidated material, mainly loess	Black soils having a chernic** horizon, and a calcic** horizon or a layer with protocalcic** properties starting ≤50 cm below the lower limit of the mollic** horizon, and a BS_{pot} of ≥50 % from the soil surface to the Calcic** horizon or to the layer with protocalcic** properties, throughout. Derived from unconsolidated material, mainly loess	Gray-brown soils with a mollic** horizon, and a BS_{pot} of ≥50 % to a depth of 100 cm from the soil surface or to a cemented or indurated layer being shallower. No secondary carbonates ≤50 cm below the lower limit of the mollic** horizon. Derived from unconsolidated predominantly basic material, mainly of aeolian or glacial origin
Profile	*Ah-Ck, Ah-Bw-Ck, Ah-Bk-Ck or Ah-(E-)Bt-Ck*	*Ah-Ck, Ah-Bw-Ck, Ah-Bk-Ck or Ah-(E-)Bt-Ck*	*Ah-C, Ah-Bw-C, Ah-(E-)Bt-C*
Natural vegetation	Short-grass steppe	Tall-grass steppe	Tall-grass steppe and/or deciduous forests, as in tropical highlands with a short rainy season permitting leaching, but with a long dry period
Properties	Medium to good physical properties Wind erosion hazard after ploughing Medium water-holding capacity Chemical properties favorable: High BS CEC_{pot} = 20–30 cmol(+) kg^{-1} FE pH 7–8 High biological activity if not too dry	Good physical properties: High PV (50–60 %) in the Ah High water-holding capacity Stable soil aggregates Chemical properties: pH 6.5–7.5 in the Ah Nutrient-rich High SOM-contents BS ca. 95 %	Good water storage capacity High porosity Stable soil structure Medium to high SOM contents High bioturbation pH 5–7 CEC = 25–30 cmol(+) kg^{-1} FEl BS up to 100 %
Forest management	By nature, steppic soils are rich in nutrients, water stress may be limiting. Main use as range land or crop land	Steppic soils of high agricultural value, no large-scale availability for tropical silviculture, yields limited by water stress, high erosion hazard may be reduced by shelter belts	Soils of high agricultural value; in East Africa covered by a light forest with Acacia species. Drought is a limiting factor. If available for forestry, high potential for drought-resistant tree species. Suitable for wood and fuel production

with the anthraquic**, hortic**, terric**, plaggic**, pretic**, and irragric** horizons) must have a thickness varying between ≥ 10 to ≥ 20 cm.

Properties: Anthrosols vary widely in their properties, depending mainly on the physical, chemical, and biological characteristics of the material applied. But in general, Anthrosols have favorable properties (Fig. 54). For instance, the Pretic* Anthrosols occurring along the river terraces in the Amazon basin differ distinctly in their surface soil properties as compared to the surrounding Ferralsols (Table 38), having higher pH-values, higher SOC-and *N*-stocks; also CEC, BS, and especially P-supplies are more favorable. Most Anthrosols permit sustainable agriculture and are more or less exclusively used for food production. Of interest is the relatively low mineralization rate of the soil organic matter in Pretic* Anthrosols, which is often rich in stabile aromatic humus *C* (black carbon) indicating high SOC sequestration (Zech et al. 1990).

Regional Distribution: Anthrosols have developed in many regions of the world where people practiced long-continued agriculture or where mineral and organic materials, charcoal, kitchen refuse, plaggen, and so on were added. Examples are the Paddy Soils extending over fast areas in (sub)tropical countries, the irrigated lands in arid regions, and the Terra Preta do Indio in the Amazon Basin.

Forest Management: Anthrosols play no important role in tropical forest management. In irrigation areas with Irragric* Anthrosols, the man-made walls between the temporary flooded basins are often planted with tree species tolerant to flooding or high water tables like *Casuarina equisetifolia, Eucalyptus camaldulensis, Sesbania bispinos, Sesbania sesban, and* palm trees. Such soils are less or not suited for *Cajanus cajan, Leucaena leucocephala,* and *Azadirachta indica.* In subtropical countries poplar and willow species are quite well adapted to the site conditions of Irragric* Anthrosols. Sometimes tree nursery soils belong to Anthrosols due to heavy organic inputs (Photos 70 and 71).

Technosols (TC)

Definition: Technosols are strongly influenced by human-made material. They have ≥20 % (by volume, weighted average) artifacts** in the upper 100 cm, a constructed geomembrane in the upper 100 cm, or technic** hard material starting ≤5 cm from the soil surface. Artifacts** comprise rubble and refuse of human settlements (Urbic* Technosol; horizon symbols = Au, Bu, Cu), organic waste material (Garbic*; Technosol; horizon symbol = Ou), industrial waste like mine spoil, slag, ash, etc. (Spolic* Technosol; horizon symbols = Au, Bu, Cu). Buried constructed geomembranes are slowly permeable to impermeable (Linic* Technosol), and soils containing technic** hard material (e.g., asphalt, concrete) are classified as Ekranic* Technosols (horizon symbol = Ru).

Properties: Technosols have strongly varying properties depending on the materials deposited. In Table 39 and in Fig. 55 some properties are summarized.

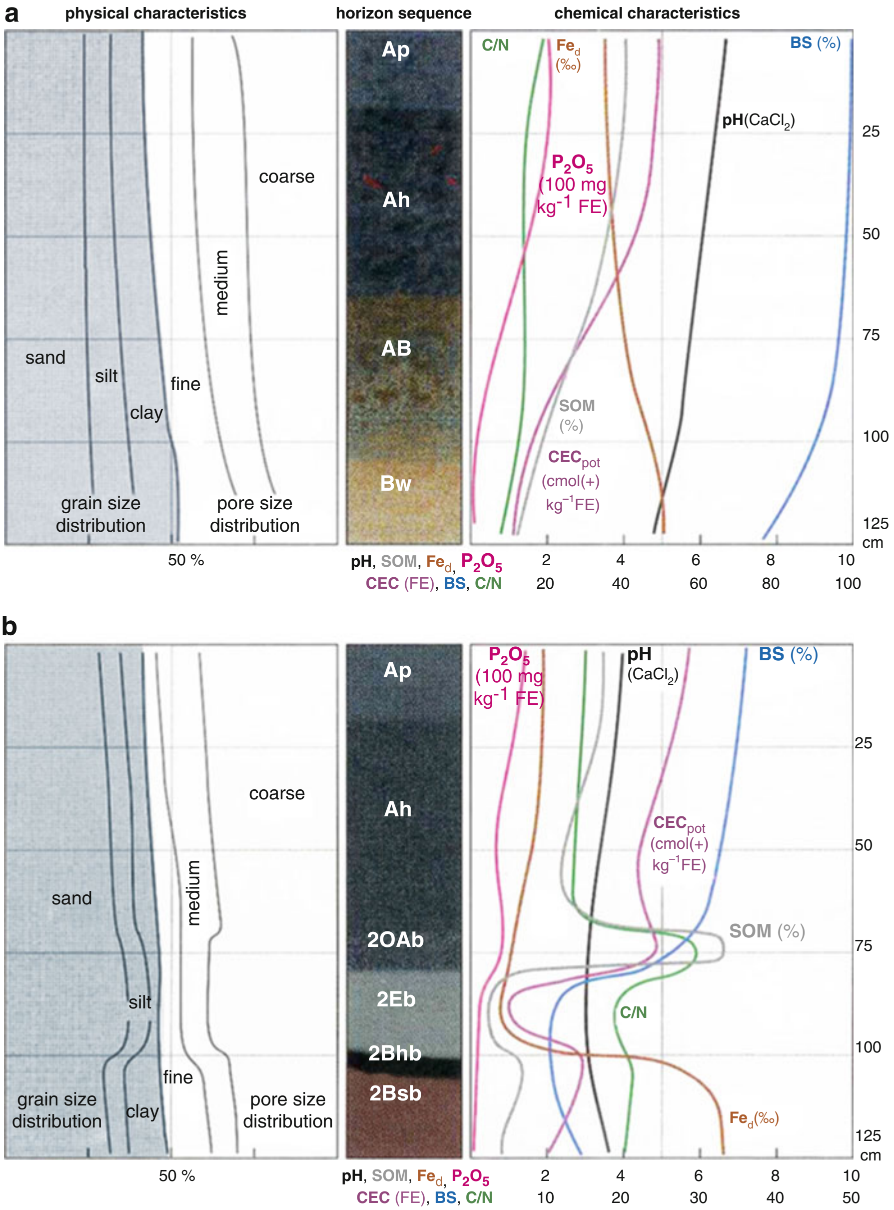
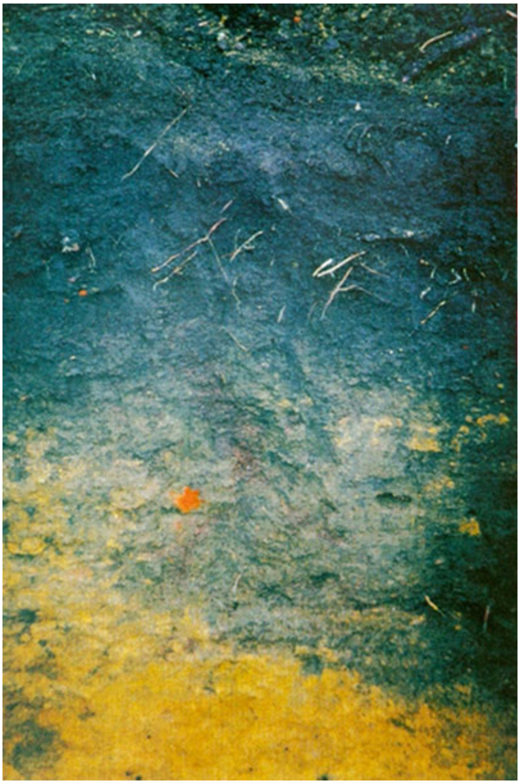


Fig. 54 Depth profiles of selected properties of a Hortic* Anthrosol (**a**) developed above a Cambisol and a Plaggic* Anthrosol (**b**) generated by the application of plaggen on a Podzol (Zech et al. 2014)

Table 38 Some characteristics of the surface soil layers of a Pretic* Anthrosol and a Ferralsol near Santarem, Brazil (Zech et al. 1990)

	Pretic* Anthrosol	Ferralsol
pH ($CaCl_2$)	5.1–6.3	3.7–4.1
% C_{org}	2.8–9.2	0.6–3.0
% N	0.16–0.68	0.06–0.27
C/N	13.5–17.9	10–11.1
CEC [cmol(+)kg^{-1} soil]	22–44	7–15
Exchangeable Ca [cmol(+)kg^{-1} soil]	5–39	Traces

Photo 70 Pretic* Anthrosol (Endoclayic*, Eutric*, Ferralic*) with Ah (0–50 cm)-2AhBo (50–100 cm)-3Bo (100+ cm). The abundant SOM-accumulation is related with land use and housing of former indio tribes on the terra firme, Amazonia. These soils are rich in pyrolized carbon, *N*, *P* and base cations



Regional Distribution: Technosols are found all over the world, especially in and around cities, along roads, near mines, refuse dumps, industrial and military areas, etc. Areas covered by Technosols are increasing globally.

Forest Management: Most Technosols are not suitable for agricultural use. After covering with natural soil material reforestation and revegetation is mostly possible. Spolic* Technosols derived from mine spoils in Liberia resist reforestation

Photo 71 Irragric* Anthrosol (Eutric*, Siltic*) regularly flooded by the Nile, depositing thick layers of silty material eroded in the catchments of Ethiopia. These soils are very fertile and used by establishing trees (palms) in combination with crops (agroforestry)

Table 39 Properties of Technosols

Physical properties:
Texture and stone contents strongly varying
Rubble and refuse of human settlements induce high water permeability
Geomembranes and technic** hard material may provoke waterlogging and sealing of natural soils
Chemical properties:
SOC and available nutrient contents vary from low (deposition of asphalt and concrete) to high (deposition of organic waste)
If waterlogged low redox potential, methanogenesis and denitrification possible
pH and BS generally high
Frequently rich in inorganic and organic pollutants
Biological properties:
Microbial activity and bioturbation varying from low (for instance, if Toxic*, Urbic*. Ekranic*) to high (if Garbic*)
Some Technosols are difficult to revegetate (e.g., if containing technic** hard material)

with pines and other plantation species. Only *Musanga cecropiodis,* a pioneer species, settles in these soils during the first decade after the accumulation of the mine wastes. Often the leaves show chlorosis, due to deficiencies in *N, P,* and *Zn* (Drechsel and Zech 1991; see Table 40). Mine soils (mostly Spolic* Technosols) in

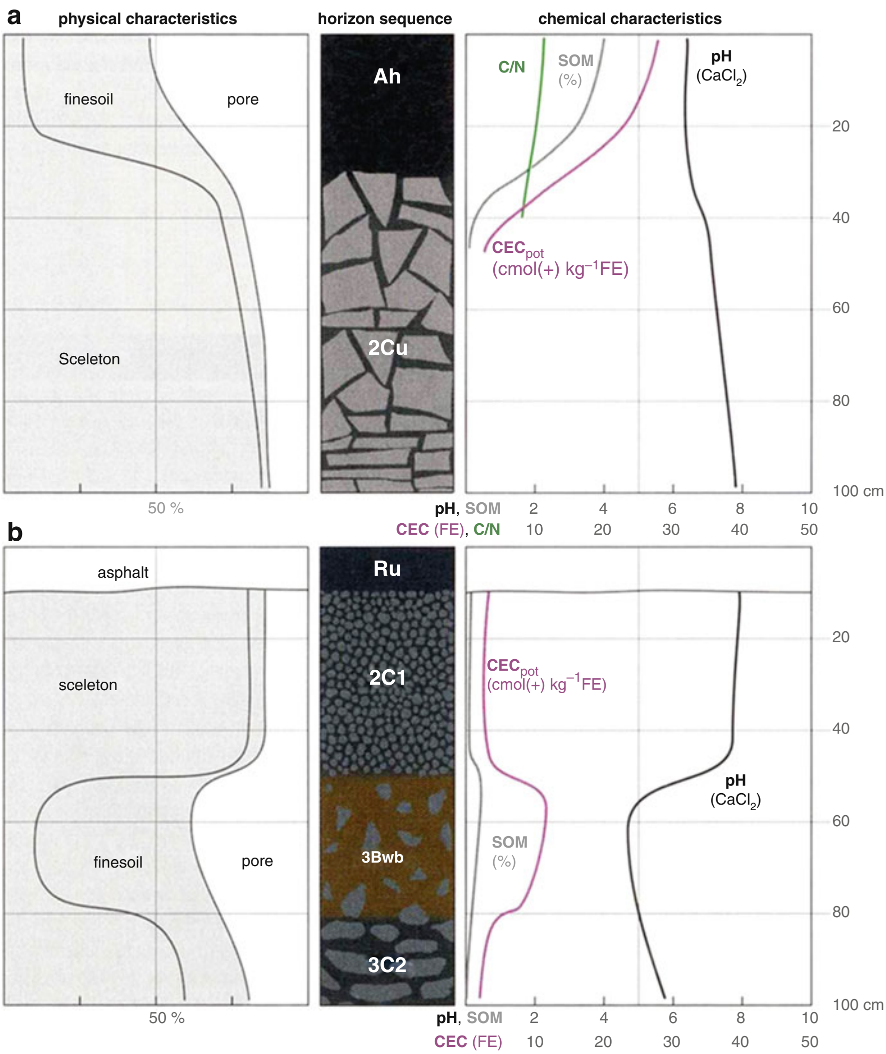


Fig. 55 Depth profiles of selected characteristics (**a**) of an Urbic* Technosol derived from building waste and (**b**) of an Ekranic* Technosol derived from asphalt and gravel, deposited above the buried cambic** horizon of a Cambisol

Table 40 Elemental composition of leaves of *Musanga cecropioides*, 8 years old, growing on Spolic* Technosol derived from mine spoils in the region of Bomi Hills, Liberia

	% dm					mg kg^{-1} dm			
	N	P	K	Ca	Mg	Al	Mn	Cu	Zn
Yellow leaves	1.17	0.065	1.22	0.22	0.16	307	112	8	7
Green leaves	1.28	0.073	0.66	0.23	0.11	219	91	7	36

Photo 72 Spolic* Technosol (Eutric*, Mollic*, Siltic*) with Ahu-Cu profile, derived from brown coal mine waste

NW Spain polluted by heavy metals were vegetated with *Pinus pinaster* or *Eucalyptus globulus*, amended with sewage slude, or received both treatments. According to Asensio et al. (2013a) only the application of sludge improved the biological soil properties. For future remediation of mine soils the authors recommend a repeated addition of sludge and planting of native legumes. At the same locality the effects of reforestation and sludge amendments on heavy metal fractionation were studied. It was found that below pine and eucalyptus the retention of *Ni, Pb,* and *Zn* in the nonmobile soil fractions increased, thus reducing the hazard from being leached into surrounding compartments (Asensio et al. 2013b) (Photos 72 and 73).

The Field Survey

Purpose-Oriented Survey Design

According to the purpose of a soil survey, different types can be distinguished (Landon 1984):

Photo 73 Garbic* Technosols have within the upper 100 cm from the soil surface a layer ≥20 cm thick, with ≥20 % (by volume, weighted average) artifacts** which contain ≥35 % (by volume) organic waste material (horizon symbol Ou)

- **Exploratory survey:** General overview and summarizing inventory of the soil, water, and plant resources including identification of the main physiographic structures; suited for prefeasibility studies; presentation of the results at map scales of 1:200,000–1:1 million or smaller.
- **Reconnaissance survey:** Identification of areas on which activities in the field of forestry, agriculture, grazing, and other types of land use should be focused, as a base for regional operation planning and prefeasibility objectives; preferred map scale 1:50,000; intensive use of aerial photo and satellite image interpretation together with check-line transects across the larger mapped units, which consist of physiographic areas and their representative soil associations and land use patterns.
- **Semidetailed survey:** Identification of the soils within major physiographic units and evaluation of appropriate forest management techniques in relation to the mapping units; contribution to the implementation of a project; for feasibility objectives; preferred map scale 1: 10,000–1: 25,000; maps established using airborne remote sensing together with intensive field work.
- **Detailed survey:** Map scale often l:5,000 or larger; field work on a grid system predominantly in comparison with aerial photographic interpretation; detailed characterization of the chemical and physical soil properties for development objectives and a base for decision making on the field of forest management in view of reducing the risks, increasing yields, and optimizing the utilization of resources; identification of "management units" which need similar management techniques (see section "Soil Management Techniques Influencing Tree Growth," Table 41), have similar risks and similar yields.

Table 41 Tree growth-limiting factors on tropical sites and possibilities for amelioration by soil management techniques

Growth-limiting factors	Causes	Management techniques for amelioration
Water deficiency	Climatic constraints (low annual rainfall, short rainy season) Extreme topographic situation Low water-holding capacity High runoff due to sealing of the surface soil High clay contents (reducing water availability) Wrong tree species selection High stocking level inducing competition Soil compaction and soil erosion render root growth difficult Toxicities reducing root vitality	Irrigation (flood basin, furrow, and drip irrigation): often in connection with agriculture and horticulture; relatively expensive, problems of salinization Rainwater harvesting, tree planting in microcatchments Selection of drought-resistant, site-adapted tree species Surface soil preparation to increase infiltration rate, reduce evaporation and sealing Establishment of water and soil retaining structures (terraces, contour steps and banks, ditches) Increase of spacings (stocking control) Deep subsoiling with a heavy rooter, to improve rainwater absorption, facilitate root growth, remove competition of existing vegetation Avoid compaction by heavy machinery Mulching to reduce evaporation Application of lime, gypsum, and fertilizers to improve root vitality
Water-logging/ oxygen deficiency	Climatic constraints Unfavorable topographic situation Restricted drainage due to high clay contents, compaction, low porosity	Provide drainage (for details see Chapman and Allan 1978) If topography permits, prevention against additional water inputs (dams, channels from the surrounding landscape) Avoid compaction by heavy machinery, especially if soils are wet "pump" to reduce soil water contents before plantation of economic valuable but susceptible species Improve soil structure by application of lime
Salinization Sodification	Irrigation with unsuited water Lack of flooding Lack of drainage High water table, saline water Na-rich irrigation water	Improve drainage to remove salts Flooding with sweet water to remove salts Application of gypsum to exchange Na by Ca Rainwater harvesting for removal of salts
Nutrient deficiencies	Low nutrient reserves Low nutrient availability Nutrient inbalances Soil erosion Reduced nutrient uptake by roots Disturbed microbial activity Drought or wetness Nutrient losses due to fire Competition and (Al)-toxicities	Application of mineral fertilizers Fire control, erosion control Optimize stand density Optimal species selection Irrigation or drainage Application of lime to stimulate microorganisms and to improve nutrient availability and root growth

Before starting the field work, the surveyor must identify what kind of survey is necessary, because the purpose of the survey largely determines the survey logistics and planning.

Preparation of the Fieldwork

Check Lists

Check lists may help in the preparation and performance of the field work; they include (for detailed check lists see Landon 1984 see also FAO 1984)

– Collection of background data (e.g., satellite images and aerial photographs, Google map interpretation, geologic and topographic maps, publications, and reports on the fields of geology, soils, climate, vegetation, land use systems, etc.)
– Working permission, export permission for soil and plant samples based on a Memorandum of Agreement
– Equipment (e.g., auger, infiltration rings, field laboratory, aluminum cylinders for collecting undisturbed soil samples, soil drying facilities, balance, sieves, mobile phone, satellite communication, GPS, laptop, photo, video, etc.)
– Field support staff (depending on the estimated labor intensity, e.g., two trace cutters, two men for auger assistance, two men for digging the soil pits, driver, guards, etc.)
– Transportation facilities (number and type of vehicles required)
– Timing of the fieldwork (taking into consideration restrictions due to climatic pecularities, access to the terrain, availability of the field staff, possibilities for sampling and sample treatments, like drying, sieving, etc.)
– Accommodation during the field work and length of trips
– Sanitary/health conditions (malaria, fevers, other diseases)

Map Scale and Accuracy; Survey Intensity

Depending on the purpose of the soil survey, map scale varies from "very detailed" at scales of 1:5,000 (or even larger) to "very general" 1:500,000 (or smaller). A map scale of 1:5,000, for instance, allows the reliable presentation of a soil/mapping unit of about 20–30 m^2, necessary for intense forest management activities, whereas at map scales of 1:500,000 (or smaller) only large soil/mapping units with a dimension of about 20–30 ha can be drawn. Their use is limited for generalizing planning activities but less for the practical silvicultural tasks. Large-scale surveys are based on a grid system: In tropical rain forests it may be necessary to auger even in a 10×10 m distance or 20×20 m, depending on the intensity of the vegetation and topography. In general, a 100×100 m up to 500×500 m grid is sufficient. If soil distribution is correlated with the geomorphological pattern, a flexible grid system and/or transect survey are mostly sufficient. It is not necessary to mention that accuracy depends on survey intensity, and survey intensity on survey purpose, field assessibility, and other items mentioned in the check lists (section "Check Lists"). Low-intensity surveys are mainly based on the interpretation of aerial photographs and satellite images, which allow the identification of more or less large physiographic units. Such interpretation should always be combined with a low-intensity field survey to verify the boundaries of the identified units. Medium-intensity surveys also use aerial photographs and satellite images, but in addition intensive field work has to be carried out for identifying the mapping units and their soil associations. High-intensity surveys are mainly based on field surveys using flexible or rigid grid patterns with narrow distance of the auger points.

Depending on the scale of a soil map, WRB 2014 recommends for naming of a map unit to refer to RSGs and qualifiers according to the following rules: For very small map scales only the name of a RSG is used (e.g., Ferralsol). At the next larger map scale level the first applicable principal qualifier is added (e.g., Rhodic* Ferralsol); at the next large map scales the first two applicable principal qualifiers are used (e.g.,Folic* Rhodic* Ferralsol), and for the next larger map scales the first three principal qualifiers are used (e.g., Skeletic* Folic* Rhodic* Ferralsol). But at any scale level, further qualifiers may be applied optionally according to the rules for principal and supplementary qualifiers (see WRB 2014).

In addition, WRB 2014 distinguishes between map units consisting of

– A **dominant** soil only (representing ≥50 % of the soil cover)
– A dominant soil plus a **codominant** soil (representing ≥25 and <50 % of the soil cover)
– Oone or more **associated** soils (representing ≥5 and <25 % of the soil cover)
– Two or three codominant soils
– Two or three codominant soils plus one or more associated soils

If codominant and associated soils are identified, then the words “dominant,” “codominant,” and “associated” must be written in front of the RSG name. For example (WRB 2014),

At the first map scale level:	Dominant: Regosols
	Associated: Leptosols
At the second map scale level:	Dominant: Leptic* Regosols
	Associated: Hyperskeletic* Leptosols
At the third map scale level:	Dominant: Calcaric* Leptic* Regosol
	Associated: Hyperskeletic* Leptosol

Besides qualifiers also subqualifiers can be used for naming map units. They refer, for instance, to soil depth requirements and result from the combination of qualifiers with subqualifiers (for details see WRB 2014).

Fieldwork – Practical Indications

Fieldwork starts with an initial reconnaissance to become familiar with the area of investigation concerning the large physiographical units and their geological, geomorphological, hydrological, and pedological equipment, including vegetation. At the same time, it should be examined whether soils, landform, and vegetation are correlated or not. The identification of such relationships is of basic importance for the main part of the survey, concerning the identification and distribution of the mapping units. For this purpose soil exposures and soil pits are studied, and soil profile properties have to be recorded using a standard data sheet (see "Annex 3"; FAO 1977; Ad-hoc-AG Boden 2005). In contrast to agricultural surveys, forest soil evaluation has to check soil profiles to a depth of about 1 m or more. For the quantitative characterization of the soils of the major mapping areas, disturbed and undisturbed samples were taken and analyzed in the laboratory for physical and chemical properties. The laboratory results are synthesized with those from the field work in establishing the final mapping units. These units can be more "genetically oriented" (e.g., Podzols, Ferralsols; see WRB 2014, section "Map Scale and Accuracy; Survey Intensity" above) or more "substrate oriented" (e.g., deep coarse sand over clay; often used in forest soil evaluation). Not more than about 20–25 mapping units should be identified for a given project area. Often the distribution pattern of the natural vegetation is correlated with soil distribution. Also "indicator plants" may help to identify the borders of soil units.

Survey Performance

A "minimum" survey staff unit consists of a soil surveyor, a surveyor assistant, and two men for handling the auger. When the vegetation cover is very dense, additional field staff is obligatory for layout and cutting the transect lines. The soil surveyor examines the soil profiles and describes the properties; the assistant is responsible for recording the results using the data sheets. For preparing the soil pits, two workers can achieve at least one or two profiles (150 cm deep, 150 cm long, 100 cm broad, two steps of 50 and 100 cm depth in 50 or 100 cm distance from the profile front) per day. Usually not more than two or four profiles can be examined per day by the professional staff, including sampling. We have the feeling that it makes no sense to report about productive days, etc. because such information is too theoretical; it depends on the survey intensity, walkability of the terrain, fitness of the staff, etc. For surveying large areas, the establishment of different survey staff units is recommendable. They have to use the same methods and be in close contact for exchanging their experiences achieved during field work.

Presentation of Results

The Report

It is well accepted that a survey report refers to the following disposition:

– Title page
– Table of contents
– Lists of tables, figures, and abbreviations

- Acknowledgments
- Summary (purpose of the study, study area and methods, main results; not more than 5–8 pages, with cross-references to the relevant chapters)
- Part 1: Introduction (TOR, purpose of the study)
- Part 2: The study area (location, topography, geology, climate, vegetation, hydrology, land use, socioeconomy)
- Part 3: Methods (for field work, for physical and chemical analyses, statistical analyses)
- Part 4: Soils and mapping units (description of associations, description of soil genesis and ecology, if possible establishment of relations between properties of mapping units and topographic as well as vegetation patterns, etc.)
- Part 5: Recommendations concerning soil/land management (soil water constraints, soil fertility problems, tree species selection, stand density, site preparation, establishment of nurseries, etc.)

Much information can be presented in the annexes, allowing the preparation of a short, concise text, with an adequate summary.

The Maps

The results of a soil survey are usually presented, besides in reports, also in maps. Most explanatory notes with reference to a map should be written in the accompanying report; but each map has to contain so much information by itself that the report is not obligatorily necessary for the interpretation of the results. For this reason, each map should enclose the following information: title, subject, country, scale, sources and authors, latitude and longitude, north point, and a comprehensive legend explaining the mapping units and their major limitations, risks, and possibilities, e.g., suitability for different tree species. Also management inputs, e.g., necessary for increasing yields, should be identified on the map. Maps should have a convenient size for easy utilization during field work.

Soil Management Techniques Influencing Tree Growth

Describing the major Reference Soil Groups in section "Reference Soil Groups and their Use in Forestry," tree growth-limiting factors were already mentioned, also some soil management techniques improving tree growth. Principally, these factors may be "internal" ones, e.g., the genetically determined growth potential, or "external" ones, conditioned by climate (e.g., temperature, precipitation, radiation), topography, soils (e.g., water, nutrients), pests, and management. In contrast to tree species of the temperate zones, relatively less is known about the influence of these "external" factors on growth of tropical trees. In the (semi)arid tropics water deficiency is the primary growth-restricting factor. In the (sub)humid tropics nutrient deficiencies, especially lack of *N* and *P*, are significant. Drechsel and Zech (1991) reviewed foliar deficiency levels of broad-leaved tropical trees, showing that in addition to N- and P-, also K- and Mg-, as well as micronutrient deficiencies are well known in tropical forests. In the humid tropics water stress during the dry season may also be a limiting factor. Table 41 informs about the main constraints for tree growth on tropical sites and management techniques for amelioration.

Acknowledgment Chapter "**Geology and Soils**" in the second edition of **Tropical Forest Handbook** is significantly based on two publications. That is firstly the **World reference base for soil resources 2014, an international soil classification system for naming and creating legends for soil maps, published by the Food and Agriculture Organization of the United Nations (Rome) as World Soil Resources Reports No. 106**. More information about the soils such as the definition of soils, their properties, their regional distribution, the diagnostic features, and the definition of the qualifiers rely on this publication.

Secondly, many figures and many photos in chapter 1 of the Tropical Forest Handbook are taken with permission of the Springer Spektrum Publishing House from the book "**Böden der Welt**" published in 2014 by W. Zech, P Schad, and G. Hintermaier-Erhard.

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Annex 1

General Description of Diagnostic Horizons

Anthraquic horizon

An anthraquic** horizon (from Greek *anthropos*, human, and Latin *aqua*, water) is a surface horizon modified by human activity (wet cultivation) that comprises a *puddled layer* and a *plough pan*.

Argic horizon

An argic** horizon (from Latin *argilla*, white clay) is a subsurface horizon with distinctly higher clay content than the overlying horizon. The textural differentiation may be caused by:

- An illuvial accumulation of clay
- Predominant pedogenetic formation of clay in the subsoil
- Destruction of clay in the surface horizon
- Selective surface erosion of clay
- Upward movement of coarser particles due to swelling and shrinking
- Biological activity or
- A combination of two or more of these different processes

The following annexes 1, 2, and 3 give only the general description of selected diagnostic horizons, diagnostic properties, and diagnostic materials according the WRB (2014) and are referred to as ** in the text. For the detailed description of the diagnostic features, the interested reader is referred to WRB (2014).

Sedimentation of surface materials that are coarser than the subsurface horizon may enhance a pedogenetic textural differentiation. However, textural difference due only to a lithic** discontinuity, such as may occur in alluvial deposits, does not qualify as an argic** horizon.

Soils with argic** horizons often have a specific set of morphological, physico-chemical, and mineralogical properties other than a mere clay increase. These properties allow various types of argic** horizons to be distinguished and their pathways of development to be traced (Sombroek 1986).

Calcic horizon

A calcic** horizon (from Latin *calx*, lime) is a horizon in which secondary calcium carbonate ($CaCO_3$) has accumulated in a diffuse form (calcium carbonate occurs as impregnation of the matrix or in the form of fine calcite particles of <1 mm, dispersed in the matrix) or as discontinuous concentrations (veins, pseudomycelia, coatings, soft, and/or hard nodules). The accumulation usually occurs in a subsurface horizon, in the parent material, or more rarely, in surface horizons. The calcic** horizon may contain primary carbonates as well.

Cambic horizon

A cambic** horizon (from Late Latin *cambiare*, to change) is a subsurface horizon showing evidence of pedogenetic alteration that ranges from weak to relatively strong. The cambic** horizon has lost, at least in half of the volume of the fine earth fraction, its original rock structure. If the underlying layer has the same parent material, the cambic** horizon usually shows higher oxide and/or clay contents than this underlying layer and/or evidence of removal of carbonates and/or gypsum. The pedogenetic alteration of a cambic** horizon can also be established by contrast with one of the overlying mineral horizons that are generally richer in organic matter and therefore have a darker and/or less intense color. In this case, some soil structure development is needed to prove pedogenetic alteration.

Chernic horizon

A chernic** horizon (from Russian *chorniy*, black) is a relatively thick, well-structured, very dark-colored surface horizon, with a high base saturation, a high biological activity, and a moderate to high content of organic matter.

Cryic horizon

A cryic** horizon (from Greek *kryos*, cold, ice) is a perennially frozen soil horizon in *mineral*** or *organic*** materials.

Duric horizon

A duric** horizon (from Latin *durus*, hard) is a subsurface horizon showing weakly cemented to indurated nodules or concretions cemented by silica (SiO_2), presumably in the form of opal and microcrystalline silica (*durinodes*). Durinodes often have carbonate coatings that have to be removed with HCl before slaking the durinodes with potassium hydroxide (KOH).

Ferralic horizon

A ferralic** horizon (from Latin *ferrum*, iron, and *alumen*, alum) is a subsurface horizon resulting from long and intense weathering. The clay fraction is dominated by low-activity clays and contains various amounts of resistant minerals such as (hydr-) oxides of Fe, Al, Mn, and titanium (Ti). There may be a marked residual accumulation of quartz in silt and sand size particles. Ferralic** horizons normally have $<10\,\%$ water-dispersible clay. Occasionally they may have more water-dispersible clay, but at the same time will display *geric*** properties or a relatively high content of organic carbon.

Ferric horizon

A ferric** horizon (from Latin *ferrum*, iron) is one in which segregation of Fe (or Fe and Mn) has taken place to such an extent that large mottles or discrete concretions or nodules have formed and the matrix between mottles, concretions, or nodules is largely depleted of Fe and Mn. They do not necessarily have enhanced Fe (or Fe and Mn) contents, but Fe (or Fe and Mn) are concentrated in mottles or concretions or nodules. Generally, such segregation leads to poor aggregation of the soil particles in Fe- and Mn-depleted zones and compaction of the horizon. The segregation is the result of redox processes that may be active or relict.

Folic horizon

A folic** horizon (from Latin *folium*, leaf) is a surface horizon, or a subsurface horizon occurring at a shallow depth, that consists of well-aerated *organic*** material. They predominantly occur in cool climate or at high elevation.

Fragic horizon

A fragic** horizon (from Latin *fragilis*, fragile) is a natural noncemented subsurface horizon with a structure and a porosity pattern such that roots and percolating water penetrate the soil only along interped faces and streaks. The natural character excludes plough pans and surface traffic pans.

Fulvic horizon

A fulvic** horizon (from Latin *fulvus*, dark yellow) is a thick, dark-colored horizon at or near the soil surface that is typically associated with short-range-order minerals (commonly allophane) or with organo-aluminum complexes. It has a low bulk density and contains highly humified organic matter that shows a lower ratio of humic acids to fulvic acids compared with the *melanic*** horizon.

Gypsic horizon

A gypsic** horizon (from Greek *gypsos*, gypsum) is a noncemented horizon containing accumulations of secondary gypsum ($CaSO_4 \cdot 2H_2O$) in various forms. It may be a surface or a subsurface horizon.

Histic horizon

A histic** horizon (from Greek *histos*, tissue) is a surface horizon, or a subsurface horizon occurring at a shallow depth, that consists of poorly aerated *organic*** material.

Hortic horizon

A hortic** horizon (from Latin *hortus*, garden) is a mineral surface horizon created by the human activities of deep cultivation, intensive fertilization, and/or long-continued application of human and animal wastes and other organic residues (e.g., manures, kitchen refuse, compost, and night soil).

Hydragric horizon

A hydragric** horizon (from Greek *hydor*, water, and Latin *ager*, field) is a subsurface horizon that results from human activity associated with wet cultivation.

Irragric horizon

An irragric** horizon (from Latin *irrigare*, to irrigate, and *ager*, field) is a mineral surface horizon that results from human activity and that builds up gradually through continuous application of irrigation water with substantial amounts of sediments, which may include fertilizers, soluble salts, organic matter, etc.

Melanic horizon

A melanic** horizon (from Greek *melas*, black) is a thick, black horizon at or near the soil surface, which is typically associated with short-range-order minerals (commonly allophane) or with organo-aluminium complexes. It has a low bulk density and contains highly humified organic matter that shows a lower ratio of fulvic acids to humic acids compared with the *fulvic*** horizon.

Mollic horizon

A mollic** horizon (from Latin *mollis*, soft) is a relatively thick, dark-colored surface horizon with a high base saturation and moderate to high content of organic matter.

Natric horizon

A natric** horizon (from Arabic *natroon*, salt) is a dense subsurface horizon with a distinctly higher clay content than in the overlying horizon(s). It has a high content of exchangeable Na and in some cases, a relatively high content of exchangeable Mg.

Nitic horizon

A nitic** horizon (from Latin *nitidus*, shiny) is a clay-rich subsurface horizon. It has moderately to strongly developed blocky structure breaking to polyhedral, flat-edged or nutty elements with many shiny soil aggregate faces, which cannot or can only partially be attributed to clay illuviation.

Petrocalcic horizon

A petrocalcic** horizon (from Greek *petros*, rock, and Latin *calx*, lime) is an indurated horizon that is cemented by calcium carbonate and in some places by magnesium carbonate as well. It is either massive or platy in nature and extremely hard.

Petroduric horizon

A petroduric** horizon (from Greek *petros*, rock, and Latin *durus*, hard), also known as duripan or dorbank (South Africa), is a subsurface horizon, usually reddish or reddish brown in color, that is cemented mainly by secondary silica (SiO_2, presumably opal and microcrystalline forms of silica). Air-dry fragments of petroduric** horizons do not slake in water, even after prolonged wetting. Calcium carbonate may be present as a supplementary cementing agent.

Petrogypsic horizon

A petrogypsic** horizon (from Greek *petros*, rock, and *gypsos*. gypsum) is a cemented horizon containing accumulations of secondary gypsum ($CaSO_4 \cdot 2H_2O$).

Petroplinthic horizon

A petroplinthic** horizon (from Greek *petros*, rock, and *plinthos*, brick) is a continuous, fractured, or broken layer of indurated material, in which Fe (and in cases also Mn) (hydr-)oxides are an important cement and in which organic matter is either absent or present only in traces.

Pisoplinthic horizon

A pisoplinthic** horizon (from Latin *pisum*, pea, and Greek *plinthos*, brick) contains concretions or nodules that are strongly cemented to indurated with Fe (and in some cases also with Mn) (hydr-)oxides.

Plaggic horizon

A plaggic** horizon (from Low German *plaggen*, sod) is a black or brown mineral surface horizon that results from human activity. Mostly in nutrient-poor soils in the north-western part of Central Europe from Medieval times until the introduction of mineral fertilizers at the beginning of the twentie20th century, sod and other topsoil materials were commonly used for bedding livestock. The sods consist of grassy, herbaceous, or dwarf-shrub vegetation, its root mats and soil material sticking to them. The mixture of sods and excrements was later spread on fields. The material brought in eventually produced an appreciably thickened horizon (in places >100 cm thick) that is rich in *soil*** *organic carbon*. Base saturation is typically low.

Plinthic horizon

A plinthic** horizon (from Greek *plinthos*, brick) is a subsurface horizon that is rich in Fe (in some cases also Mn) (hydr-)oxides and poor in humus. The clay is mostly kaolinitic, with the presence of other products of strong weathering, such as gibbsite. The plinthic** horizon usually changes irreversibly to a layer of hard concretions or nodules or a hardpan on exposure to repeated wetting and drying with free access to oxygen.

Pretic horizon

A pretic** horizon (from Portuguese preto, black) is a mineral surface horizon that results from human activities including the addition of charcoal. It is characterized by its dark color, the presence of artifacts (ceramic fragments, lithic instruments, bone, or shell tools, etc.), and high contents of organic carbon, phosphorus, calcium, magnesium, and micronutrients (mainly zinc and manganese), usually contrasting with natural soils in the surrounding area. It typically contains visible remnants of charcoal.

Pretic** horizons are, for example, widespread in the Amazon Basin, where they are the result of pre-Columbian activities and have persisted over many centuries despite the prevailing humid tropical conditions and high organic matter mineralization rates. These soils with a pretic** horizon are known as "Terra Preta de Indio" or "Amazonian Dark Earths." They generally have high organic carbon stocks. Many of them are dominated by low-activity clays.

Protovertic horizon

A protovertic** horizon (from Greek *protou*, before, and Latin *vertere,* to turn) has swelling and shrinking clays.

Salic horizon

A salic** horizon (from Latin *sal*, salt) is a surface horizon or a subsurface horizon at a shallow depth that contains high amounts of readily soluble salts, that is, salts more soluble than gypsum ($CaSO_4 \cdot 2H_2O$; log Ks = −4.85 at 25 °C).

Sombric horizon

A sombric** horizon (from French *sombre*, dark) is a dark-colored subsurface horizon containing illuvial humus that is neither associated with Al nor dispersed by Na.

Spodic horizon

A spodic** horizon (from Greek *spodos*, wood ash) is a subsurface horizon that contains illuvial substances composed of organic matter and Al, or of illuvial Fe.

The illuvial materials are characterized by a high pH-dependent charge, a relatively large surface area and high water retention.

Terric horizon

A terric** horizon (from Latin *terra*, earth) is a mineral surface horizon that develops through addition of, for example, earthy manures, compost, beach sands, loess, or mud. It may contain stones, randomly sorted and distributed. In most cases, it is built up gradually over a long period of time. Occasionally, terric** horizons are created by single additions of material. Normally the added material is mixed with the original topsoil.

Thionic horizon

A thionic** horizon (from Greek *theion*, sulfur) is an extremely acid subsurface horizon in which sulfuric acid is formed through oxidation of sulfides.

Umbric horizon

An umbric horizon (from Latin *umbra*, shade) is a relatively thick, dark-colored surface horizon with a low base saturation and a moderate to high content of organic matter.**

Vertic horizon

A vertic** horizon (from Latin *vertere*, to turn) is a clayey subsurface horizon that, as a result of shrinking and swelling, has slickensides and wedge-shaped soil aggregates.

Annex 2

General Description of Diagnostic Properties

Abrupt textural difference

An abrupt** textural difference (from Latin *abruptus*, abrupt) is a very sharp increase in clay content within a limited depth range.

Albeluvic glossae

The term albeluvic** glossae (from Latin *albus*, white, and *eluere*, to wash out, and Greek *glossa*, tongue) is connotative of penetrations of clay- and Fe-depleted material into an *argic*** horizon. Albeluvic** glossae occur along soil aggregate surfaces forming vertically continuous tongues. In horizontal sections, they exhibit a polygonal pattern.

Andic properties

Andic** properties (from Japanese *an*, dark, and *do*, soil) result from moderate weathering of mainly pyroclastic deposits. The presence of short-range-order minerals and/or organo-metallic complexes is characteristic for andic properties. These minerals and complexes are commonly part of the weathering sequence in pyroclastic deposits (*tephric*** soil material > *vitric*** properties > andic** properties). However, andic** properties with organo-metallic complexes may also form in nonpyroclastic silicate-rich materials in cool-temperate and humid climates.

Andic** properties may be found at the soil surface or in the subsurface, commonly occurring as layers. Many surface layers with andic** properties contain a high amount of organic matter ($\geq$5 %), are commonly very dark colored (Munsell color value and chroma of $\leq$3, moist), have a fluffy macrostructure and in some places have a smeary consistence. They have a low bulk density and commonly have a silt loam or finer texture. Andic surface layers rich in organic matter may be very thick, having a thickness of $\geq$50 cm in some soils. Andic subsurface layers are generally somewhat lighter colored.

Andic layers may have different characteristics, depending on the type of the dominant weathering process acting upon the soil material. They may exhibit thixotropy, that is, the soil material changes, under pressure or by rubbing, from a plastic solid into a liquefied stage and back into the solid condition. In perhumid climates, humus-rich andic layers may contain more than twice the water content of samples that have been oven-dried and rewetted (hydric characteristic).

Two major types of andic** properties are recognized: one in which allophane, imogolite, and similar minerals are predominant (the *silandic* type) and one in which Al complexed by organic acids prevails (the *aluandic* type). The silandic property typically gives a strongly acid to neutral soil reaction and is a bit lighter colored, while the aluandic property gives an extremely acid to acid reaction and a blackish color.

Anthric properties

Anthric** properties (from Greek *anthropos*, human) apply to some cultivated soils with *mollic*** or *umbric*** horizons. Some of them are altered natural *mollic*** or *umbric*** horizons. But some of the *mollic*** horizons with anthric** properties are natural *umbric*** horizons transformed into *mollic*** horizons by liming and fertilization. Even thin, light-colored or humus-poor mineral topsoil horizons may be transformed into *umbric*** or even *mollic*** horizons by long-term cultivation (ploughing, liming, fertilization, etc.). In this case, the soil has very little biological activity, which is especially uncommon for soils with *mollic*** horizons.

Aridic properties

The term aridic** properties (from Latin *aridus*, dry) combines a number of properties that are common in surface horizons of soils under arid conditions, which can occur under any temperature regime from very hot to very cold, and where pedogenesis exceeds new accumulation at the soil surface by aeolian or alluvial activity.

Continuous rock

Continuous** rock is consolidated material underlying the soil, exclusive of cemented or indurated pedogenetic horizons such as *petrocalcic***, *petroduric***, *petrogypsic***, and *petroplinthic*** horizons. Continuous rock is sufficiently consolidated to remain intact when an air-dried specimen, 25–30 mm on one side, is submerged in water for 1 h. The material is considered continuous only if cracks into which roots can enter are on average $\geq$10 cm apart and occupy $<$20 % (by volume) of the continuous** rock, with no significant displacement of the rock having taken place.

Geric properties

Geric** properties (from Greek *geraios*, old) refer to mineral soil material that has a very low sum of exchangeable bases plus exchangeable Al or even acts as an anion exchanger.

Gleyic properties

Soil materials develop gleyic** properties (from Russian *gley*, mucky soil mass) if they are saturated with groundwater (or were saturated in the past, if now drained) for a period that allows *reducing*** *conditions* to occur (this may range from a few days in the tropics to a few weeks in other areas). However, there may be gleyic** properties in a clayic layer over a sandy layer, even without the influence of groundwater. In some soils with gleyic** properties, the *reducing*** *conditions* are caused by upmoving gases such as methane or carbon dioxide.

Lithic discontinuity

Lithic** discontinuities (from Greek *lithos*, stone, and Latin *continuare*, to continue) are significant differences in particle-size distribution or mineralogy that represent differences in parent material within a soil. A lithic** discontinuity can also denote an age difference. The different strata may have the same or a different mineralogy.

Protocalcic properties

Protocalcic** properties (from Greek *protou*, before, and Latin *calx*, lime) refer to carbonates that are derived from the soil solution and precipitated in the soil. They do not belong to the soil parent material or to other sources such as dust. These carbonates are called secondary carbonates. For protocalcic** properties, they should be permanent and be present in significant quantities.

Reducing conditions

Reducing** conditions show one or more of the following: 1. a negative logarithm of the hydrogen partial pressure of <20, 2. the presence of free Fe^{2+}, 3. the presence of ion sulfide, or 4. the presence of methane.

Retic properties

Retic** properties (from Latin *rete*, net) describe the interfingering of coarser-textured *albic*** material into a finer-textured *argic*** or *natric*** horizon. The interfingering coarser-textured *albic*** material is characterized by a partial removal of clay and free iron oxides. There may be also coarser-textured *albic*** material falling from the overlying horizon into cracks in the *argic*** or *natric*** horizon. The interfingering coarser-textured *albic*** material is found as vertical and horizontal whitish intercalations on the faces and edges of soil aggregates.

Shrink-swell cracks**

Shrink**-swell cracks open and close due to shrinking and swelling of clay minerals with changing water content of the soil. They may be evident only when the soil is dry. They control the infiltration and percolation of water, even if they are filled with material from the surface.

Sideralic properties

Sideralic** properties (from Greek *sideros*, iron, and Latin *alumen*, alum) refer to mineral soil material that has a relatively low CEC.

Stagnic properties

Soil materials develop stagnic** properties (from Latin *stagnare*, to stagnate) if they are, at least temporarily, saturated with surface water (or were saturated in the past, if now drained) for a period long enough that allows *reducing*** *conditions* to occur (this may range from a few days in the tropics to a few weeks in other areas). In some soils with stagnic** properties, the *reducing*** *conditions* are caused by the intrusion of other liquids such as gasoline.

Takyric properties

Takyric** properties (from Turkic languages *takyr*, barren land) are related to a heavy-textured surface layer comprising a surface crust and a platy or massive structure. It occurs under arid conditions in periodically flooded soils.

Vitric properties

Vitric** properties (from Latin *vitrum*, glass) apply to layers with volcanic glass and other primary minerals derived from volcanic ejecta and which contain a limited amount of short-range-order minerals or organo-metallic complexes.

Yermic Properties

Yermic** properties (from Spanish *yermo*, desert) are found in a surface horizon that usually, but not always, consists of surface accumulations of rock fragments (*desert pavement*), embedded in a loamy vesicular layer that may be covered by a thin aeolian sand or loess layer.

Annex 3

General Description of Diagnostic Materials

Albic material

Albic** material (from Latin *albus*, white) is predominantly light-colored fine earth, from which organic matter and/or free iron oxides have been removed, or in which the oxides have been segregated to the extent that the color of the horizon is determined by the color of the sand and silt particles rather than by coatings on these particles. It generally has a weakly expressed soil structure or lacks structural development altogether.

Artifacts

These are solid or liquid substances that are

1. One or both of the following: (a) created or substantially modified by humans as part of an industrial or artisanal manufacturing process; or (b) brought to the surface by human activity from a depth, where they were not influenced by surface processes and deposited in an environment, where they do not commonly occur, with properties substantially different from the environment where they are placed.
2. Have substantially the same chemical and mineralogical properties as when first manufactured, modified, or excavated.

Calcaric material

Calcaric** material (from Latin *calcarius*, containing lime) refers to material that contains ≥ 2 % calcium carbonate equivalent. The carbonates are inherited from the parent material.

Colluvic material

Colluvic** material (from Latin *colluvio*, mixture) is a heterogeneous mixture of material that, by gravitational action, has moved down a slope. It has been transported as a result of erosional wash or soil creep, and the transport may have been accelerated by land-use practices (e.g., deforestation, ploughing, downhill tillage, structure degradation). It has been formed in relatively recent times (mostly Holocene). It normally accumulates in slope positions, in depressions, or above a barrier on a low-grade slope (natural or human-made, e.g., hedge walls).

Dolomitic material

Dolomitic** material (named after the French geoscientist *Déodat de Dolomieu*) effervesces strongly with heated 1 *M* HCl in most of the fine earth fraction. It applies to material that contains ≥ 2 % of a mineral that has a ratio $CaCO_3/MgCO_3 < 1.5$. With nonheated HCl, it gives only a retarded and weak effervescence.

Fluvic material

Fluvic** material (from Latin *fluvius*, river) refers to fluviatile, marine, and lacustrine sediments that receive fresh material or have received it in the past and still show stratification.

Gypsiric material

Gypsiric** material (from Greek *gypsos*, gypsum) is mineral material that contains ≥ 5 % gypsum (by volume) in those parts of the fine earth that do not contain secondary gypsum.

Hypersulfidic material

Hypersulfidic** material is capable of severe acidification as a result of the oxidation of inorganic sulfidic compounds contained within it. It has a positive net acidity using acid-base accounting approaches. Hypersulfidic** material is conceptually the same as defined in WRB 2006 as *sulfidic*** material is also known as "potential acid sulfate soil."

Hyposulfidic material

Hyposulfidic** material is *sulfidic*** material that is not capable of severe acidification resulting from the oxidation of inorganic sulfidic compounds contained within it. Although oxidation does not lead to the formation of acid sulfate soils, hyposulfidic** material is an important environmental hazard due to processes related to inorganic sulfides. Hyposulfidic** material has a self-neutralizing capacity, usually due to the presence of calcium carbonate, that is, it has a zero or negative net acidity using acid-base accounting approaches.

Limnic material

Limnic material (from Greek *limnae*, pool) includes both *organic*** and *mineral*** materials that are

1. Deposited in water by precipitation or through action of aquatic organisms, such as diatoms and other algae **or**
2. Derived from underwater and floating aquatic plants and subsequently modified by aquatic animals

Mineral material

In mineral** material (from Celtic *mine*, mineral), the soil properties are dominated by mineral components.

Organic material

Organic** material (from Greek *organon*, tool) consists of a large amount of organic debris that accumulates under either wet or dry conditions and in which the mineral component does not significantly influence the soil properties.

Ornithogenic material

Ornithogenic** material (from Greek *ornithos*, bird, and *genesis*, origin) is material with strong influence of bird excrement. It often has a high content of gravel that has been transported by birds.

Soil organic carbon

Soil** organic carbon is organic carbon that does not meet the diagnostic criteria of *artifacts***.

Sulfidic material

Sulfidic** material (from Latin *sulpur*, sulfur) is a deposit containing detectable inorganic sulfides. Sulfidic** material accommodates a diverse range of seasonally or permanently waterlogged materials, including artifacts** such as mine spoil. Sulfidic** material often becomes extremely acid when drained (if so, it is termed *hypersulfidic*** material).

Technic hard material

Technic** hard material (from Greek *technikos*, skillfully made or constructed):

1. Is consolidated material resulting from an industrial process
2. Has properties substantially different from those of natural materials
3. Is continuous **or** has free space covering <5 % of its horizontal extension

Tephric material

Tephric** material (from Greek *tephra*, pile ash) consists either of tephra, that is, unconsolidated, non- or only slightly weathered pyroclastic products of volcanic eruptions (including ash, cinders, lapilli, pumice, pumice-like vesicular pyroclastics, blocks and volcanic bombs), or of tephric deposits, that is, tephra that has been reworked and mixed with material from other sources. This includes tephric loess, tephric blown sand, and volcanogenic alluvium.

Annex 4

Simplified Description of selected Qualifiers and Subqualifiers (according to WRB 2014)

Short description of selected qualifiers and subqualifiers (according to WRB 2014) and referred to as * in the text (** characterizes the diagnostic features described in Annexes 1, 2, and 3)

For the detailed description of the qualifiers, the interested reader is referred to WRB 2014.

Abruptic: with abrupt** textural difference within ≤100 cm of the mineral soil surface

Acric: with argic** horizon starting $\leq$100 cm from the soil surface, having a CEC_{pot} of $\leq$24 cmol(+) kg^{-1} clay in some part $\leq$50 cm below its upper limit, a $BS_{eff} < 50$ % in half or more of the part between 50 and 100 cm from the mineral surface

Aeolic: layer at the soil surface $\geq$10 cm thick, deposited by wind, with <0.6 % SOC

Albic: a layer of albic** material $\geq$1 cm thick, and starting $\leq$100 cm from the mineral soil surface

Alcalic: $pH(H_2O) \geq 8.5$ throughout $\leq$50 cm of the mineral soil surface, or to continuous** rock, technic** hard material or a cemented or indurated layer, $BS_{eff} \geq 50$ %

Alic: arig** horizon starting $\leq$50 cm from the soil surface, $CEC_{pot} \geq 24$ cmol (+) kg^{-1} clay throughout or to a depth of 50 cm of its upper limit, $BS_{eff} < 50$ % in half or more between 50 and 100 cm from the mineral soil surface

Aluandic: within $\leq$100 cm of the soil surface one or more layers with a combined thickness of $\geq$15 cm with andic** properties, Si $<$ 0.6 % $Al_{py}/Al_o \geq 0.5$

Andic: within $\leq$100 cm of the soil surface, one or more layers with andic** or vitric** properties with a combined thickness of $\geq$30 cm (Cambisols $\geq$ 15 cm) of which $\geq$15 cm (Cambisols $\geq$ 7.5 cm) have andic** properties

Arenic: sand or loamy sand in a layer $\geq$30 cm, within $\leq$100 cm of the mineral soil surface

Areninovic: young sandy materials overlying a RSG

Aric: ploughed to a depth $\geq$20 cm from the soil surface

Aridic: aridic** properties without takyric** or yermic** properties

Calcaric: with calcaric** material throughout between 20 and 100 cm from the soil surface, or between 20 cm and continuous** rock, technic** hard material or a cemented or indurated layer, whichever is shallower and not having a calcic** or a petrocalcic** horizon starting $\leq$100 cm from the soil surface

Calcic: having a calcic** horizon starting $\leq$100 cm from the surface

Cambic: having a cambic** horizon not consisting of albic** material and starting $\geq$50 cm from the soil surface

Carbic: having a spodic** horizon that does not turn redder on ignition throughout

Chernic: having a chernic** horizon

Chromic: having between 25 and 150 cm of the soil surface a layer, $\geq$30 cm thick, that has, in $\geq$90 % of its exposed area, a Munsell color hue redder than 7.5 YR and a chroma of >4, both moist

Clayic: having a texture like class of clay, sandy clay, or silty clay, in a layer $\geq$30 cm thick, within $\leq$100 cm of the mineral soil surface

Cryic: having a cryic** horizon starting $\leq$100 cm from the soil surface, or having a cryic** horizon starting $\leq$200 cm from the soil surface with evidence of cryoturbation in some layer $\leq$100 cm from the soil surface

Duric: having a duric** horizon starting $\leq$100 cm from the soil surface

Dystric: BS_{eff} <50 % in half or more of the part between 20 and 100 cm from the mineral soil surface, or in half or more of the part between 20 cm from the mineral soil surface and continuous** rock, technic** hard material or a cemented or indurated layer starting >25 cm from the mineral soil surface, or in a layer ≥5 cm thick, directly above continuous** rock, technic** hard material or a cemented or indurated layer starting ≤25 cm from the mineral soil surface

Ekranic: having technic** hard material starting ≤5 cm from the soil surface (in Technosols only)

Endogleyic: a layer ≥25 cm thick somewhere between >50 cm and ≤100 cm from the (mineral) soil surface with gleyic** properties and reducing** conditions in some parts of every sublayer

Endopetric: having a cemented or indurated layer somewhere between >50 cm and ≤100 cm from the (mineral) soil surface

Endosalic: having a salic** horizon somewhere between >50 cm and ≤100 cm from the (mineral) soil surface

Endoskeletic: having ≥40 % (by volume) coarse fragments somewhere between >50 cm and ≤100 cm from the (mineral) soil surface

Epiarenic: having a texture class of sand or loamy sand in a layer ≥30 cm somewhere ≤50 cm from the (mineral) soil surface

Epipetric: having a cemented or indurated layer somewhere ≤50 cm from the (mineral) soil surface

Eutric: having a BS_{eff} of ≥50 % in the major part between 20 and 100 cm from the mineral soil surface, or in the major part between 20 cm from the mineral soil surface and continuous** rock, technic** hard material or a cemented or indurated layer starting >25 cm from the mineral soil surface, or a layer ≥5 cm thick, directly above continuous** rock, technic** hard material or a cemented or indurated layer starting ≤25 cm from the mineral soil surface

Ferralic: having a ferralic** horizon starting ≤150 cm of the soil surface

Ferric: having a ferric** horizon starting ≤100 cm of the soil surface

Fluvic: having fluvic** material ≥25 cm thick and starting ≤75 cm from the mineral soil surface

Folic: having a folic** horizon starting at the soil surface

Garbic: having a layer ≥20 cm thick, within ≤100 cm of the soil surface, with ≥20 % (by volume, weighted average) artifacts** containing ≥35 % (by volume) organic waste (in Technosols only)

Gleyic: having a layer ≥25 cm thick, and starting ≤75 cm from the mineral soil surface that has gleyic** properties throughout and reducing** conditions in some parts of every sublayer

Gypsic: having a gypsic** horizon starting ≤100 cm from the soil surface

Gypsiric: having gypsiric** material throughout between 20 and 100 cm from the soil surface or between 20 cm and continuous** rock, technic** hard material or a cemented or indurated layer, whichever is shallower, and not having a gypsic** or petrogypsic** horizon starting ≤100 cm from the soil surface

Haplic: having a typical expression of certain features; only used if none of the preceding qualifiers applies

Hemic: having, after rubbing, less than two-thirds and one-sixth or more (by volume) of the organic** material consisting of recognizable plant tissue within 100 cm of the soil surface (histosols only)

Histic: having a histic** horizon starting at the soil surface

Hortic: having a hortic** horizon

Humic: having >1 % soil** organic carbon in the fine earth fraction as a weighted average to a depth of 50 cm from the mineral soil surface

Hydragric: having an anthraquic** horizon and a directly underlying hydragric** horizon, the latter starting ≤100 cm from the soil surface

Hypereutric: having a $BS_{eff} \geq 50$ % throughout between 20 and 100 cm from the mineral soil surface, and ≥80 % in some layer between 20 and 100 cm from the mineral soil surface

Hyperhumic: having ≥5 % soil** organic carbon in the fine earth fraction as a weighted average to a depth of 100 cm from the mineral soil surface

Hyperochric:

Hyperskeletic: having <20 % (by volume) fine earth, averaged over a depth of 75 cm from the soil surface or to continuous** rock, technic** hard material or a cemented or indurated layer starting >25 cm from the soil surface, whichever is shallower

Irragric: having an irragric** horizon

Leptic: having continuous** rock or technic** hard material starting ≤100 cm from the soil surface

Linic: having a continuous, very slowly permeable to impermeable constructed geomembrane of any thickness starting ≤100 cm from the soil surface

Lithic: having continuous** rock or technic** hard material starting ≤10 cm from the soil surface (in leptosols only)

Lixic: having an argic** horizon starting ≤100 cm from the soil surface and having a CEC_{pot} < 24 cmol(+) kg-1 clay in some part ≤50 cm below its upper limit; BS_{eff} is ≥50 % in the major part between 50 and 100 cm from the mineral soil surface or in the lower half of the mineral soil above continuous** rock, technic** hard material or a cemented or indurated layer starting ≤100 cm from the mineral soil surface, whichever is shallower

Mollic: having a mollic** horizon

Nudilithic: having a continuous rock at the surface (in leptosols only)

Ochric: having ≥0.02 % soil organic carbon (weighted average) in the layer from the mineral surface to a depth of 10 cm from the mineral soil surface; and not having a mollic** or umbric** horizon and not fulfilling the set of criteria of the Humic* qualifier

Ombric: having a histic** horizon saturated predominantly with rainwater (in histosols only)

Pachic: having a mollic** or umbric** horizon ≥50 cm thick

Pellic: having in the upper 30 cm of the soil a Munsell color value of ≤3 and a chroma of ≤2, both moist (in vertisols only)

Petric: having a cemented or indurated layer starting ≤100 cm from the soil surface

Petrocalcic: having a petrocalcic** horizon starting ≤100 cm from the soil surface

Petrosalic: having a layer ≥10 cm thick, within ≤100 cm of the soil surface, which is cemented by salts more soluble than gypsum

Pisoplinthic: having a petroplinthic** horizon starting ≤100 cm from the soil surface

Plaggic: having a plaggic** horizon

Plinthic: having a plinthic** horizon starting ≤100 cm from the soil surface

Pretic: having a pretic** horizon

Puffic: having a crust pushed up by salt crystals (in solonchaks only)

Reductic: having reducing** conditions in ≥25 % of the volume of the fine earth within 100 cm of the soil surface, caused by gaseous emissions, e.g., methane or carbon dioxide, or caused by liquid intrusions other than water, e.g., gasoline

Rendzic: having a mollic** horizon that contains or directly overlies calcaric** material containing ≥40 % calcium carbonate equivalent or that directly overlies calcareous rock containing ≥40 % calcium carbonate equivalent

Rheic: having a histic** horizon saturated predominantly with groundwater or flowing water (in histosols only)

Rhodic: having between 25 and 150 cm of the soil surface, a layer ≥30 cm thick, that has, in ≥90 % of its exposed area, a Munsell color hue redder than 5 YR moist, a value of <4 moist, and a value dry, no more than one unit higher than the moist value

Rustic: having a spodic** horizon in which the ratio of the percentage of Fe_o to the percentage of soil** organic carbon is ≥6 throughout (in podzols only)

Salic: having a salic** horizon starting ≤100 cm from the soil surface

Sapric: having, after rubbing, less than one-sixth (by volume) of the organic** material consisting of recognizable plant tissue within 100 cm of the soil surface (in histosols only)

Silandic: having within ≤100 cm of the soil surface one or more layers with a combined thickness ≥15 cm with andic** properties and a Si_o content of ≥0.6 % or an Al_{py}/Al_o of <0.5 (in Andosols only)

Siltic: having a texture class of silt or silty loam in a layer ≥30 cm thick, within ≤100 cm of the mineral soil surface or in the major part between the mineral soil surface and continuous** rock, or technic** hard material or a cemented or indurated layer starting <60 cm from the mineral soil surface

Skeletic: having ≥40 % (by volume) coarse fragments averaged over a depth of 100 cm from the soil surface or to continuous** rock, technic** hard material or a cemented or indurated layer, whichever is shallower

Sodic: having a layer ≥20 cm thick, and starting ≤100 cm from the soil surface, that has ≥15 % Na plus Mg and ≥6 % Na on the exchange complex; and not having a natric** horizon starting ≤100 cm from the soil surface

Someriumbric: having an umbric** horizon <20 cm thick

Spodic: having a spodic** horizon starting ≤200 cm from the mineral soil surface

Spolic: having a layer ≥20 cm thick, within ≤100 cm of the soil surface, with ≥20 % (by volume, weighted average) artifacts** containing ≥35 % (by volume) industrial waste (mine spoil, dredgings, slag, ash, rubble, etc.) (in technosols only)

Stagnic: having a layer ≥25 cm thick, and starting ≤75 cm from the mineral soil surface, that does not form part of a hydragric** horizon and that has stagnic**

properties in which the area of reductimorphic colors plus the year in the major part of the layer's volume that has the reductimorphic colors

Subaquatic: being permanently submerged by water not deeper than 200 cm

Tephric: having tephric** material, starting ≤50 cm from the soil surface, that is ≥30 cm thick, or ≥10 cm thick and directly overlying continuous** rock, technic** hard material or a cemented or indurated layer

Terric: having a terric** horizon

Thionic: having a thionic** horizon starting ≤100 cm from the soil surface

Tidalic: affected by tidal water, i.e., located between the line of mean high water springs and the line of mean low water springs

Toxic: having in some layer ≤50 cm of the soil surface, toxic concentrations of organic or inorganic substances other than ions of Al, Fe, Na, Ca, and Mg, or having radioactivity dangerous to humans

Umbric: having an umbric** horizon

Urbic: having a layer ≥20 cm thick, within ≤100 cm of the soil surface, with ≥20 % (by volume, weighted average) artifacts** containing ≥35 % (by volume) rubble and refuse of human settlements (in Technosols only)

Vertic: having a vertic** horizon starting ≤100 cm from the soil surface

Vitric: having within ≤100 cm of the soil surface, one or more layers with andic** or vitric** properties with a combined thickness of ≥30 cm (in Cambisols ≥15 cm), of which ≥15 cm (in Cambisols ≥7.5 cm) have vitric** properties

Xanthic: having a ferralic** horizon that has in a subhorizon ≥30 cm thick, and starting ≤75 cm of the upper limit of the ferralic** horizon, in ≥90 % of its exposed area, a Munsell color hue of 7.5 YR or yellower, a value of ≥4 and a chroma of ≥5, all moist

Annex 5

Standard Data Sheet for Soil Profile Description

<table>
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<tr><td colspan="4">m.a.s.l.:</td><td colspan="7">Topography:</td></tr>
<tr><td colspan="4">Slope:</td><td colspan="7">Parent material:</td></tr>
<tr><td rowspan="2">Horizon</td><td rowspan="2">Depth cm</td><td colspan="2">Munsell colour</td><td rowspan="2">Texture</td><td rowspan="2">Structure</td><td rowspan="2">Density</td><td rowspan="2">Stoniness Vol %</td><td rowspan="2">Organic matter</td><td rowspan="2">Rooting intensity</td><td rowspan="2">Lime test (10% HCl)</td></tr>
<tr><td>dry</td><td>moist</td></tr>
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<tr><td>Soil fauna:</td><td colspan="5"></td><td colspan="5" rowspan="2">Mapping unit:</td></tr>
<tr><td>Understorey:</td><td colspan="5"></td></tr>
<tr><td>Forest floor:</td><td colspan="5"></td><td colspan="5">Recommendations:</td></tr>
</table>

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