2.3 Soils

2.3.1 Processes of soil formation and soil dynamics in the tropics

It is not possible to describe all tropical soils within the scope of this general account. We will seek to provide some insight into the various nomenclatures for tropical soils, so that those carrying out trials or comparing results across locations will have at least some reference points.

It is possible to develop appropriate cropping systems only if soils are carefully taken into account, with a knowledge of the most important properties determining fertility. Based on a knowledge of soil moisture relations, the proportion of weatherable minerals, the dynamics of humus, the exchange capacity, clay minerals and soil structure (to name only the most important properties), vital decisions can be made as to the choice of crops, tillage, type of fertilizer, and so on.

Soil conditions, together with the climatic and vegetation conditions already discussed, provide the natural resource base for sustainable agriculture, which in turn must be developed in harmony with socio-economic conditions.

The factors determining soil formation are in principle the same in the tropics as in temperate climates (parent material, climate, vegetation, topography, time, gravity, groundwater, human activity, etc). The only differences lie in the intensity and continuity of individual factors (BURINGH 1979; YOUNG 1976). As in temperate zones, the effects of these factors within the tropics vary widely.

There is no such thing as a "tropical soil". There are older, heavily weathered soils (commoner in the tropics because of the absence of Ice Ages) and young, sedimentary or volcanic soils, soils rich or poor in humus, deep or shallow soils, and so on. Soils develop differently and possess different characteristics, depending on how long and intensively they have been affected by soil formation processes. The most important factors influencing soil formation are the climatic ones of temperature and rainfall.

Compared with temperate regions, the higher temperatures of the tropics accelerate the chemical weathering of minerals through the H^+ and OH^- ions in water (hydrolysis). Hydrolysis is the most important process in chemical weathering, and it takes place almost twice as fast at 25°C as at 10°C. The Van't Hoff isotherm, which states that the rate of a chemical reaction increases by a factor of 2 to 3 with every temperature increase of 10° C, gives some idea of the profound impact of temperature on soil dynamics and decomposition processes.[16]

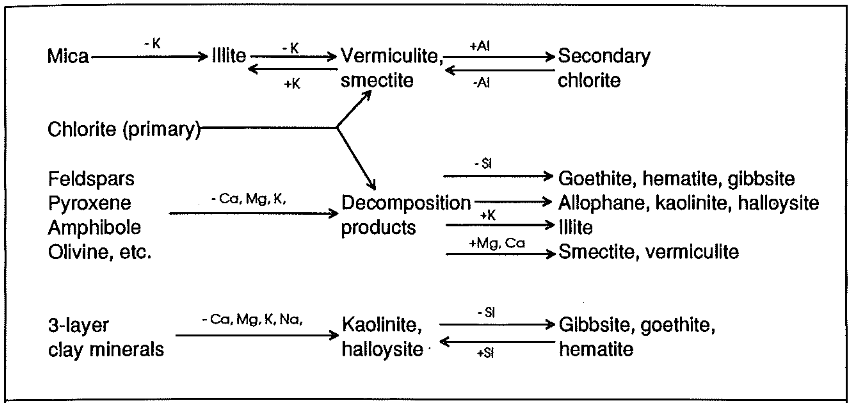
Warm, watery solutions have a higher solubility constant. This means that the warmer the soil water is, the greater its leaching and translocation effect (dissolution, transport, deposition)[17]. Not only is this significant for the leaching of nutrients and organic humic matter, but also for desilification[18], a very important process under tropical climatic conditions. Pure silicate materials (for example, poor quartz sands in West Africa) are more resistant than those containing a high proportion of elements (Mg, Mn, Fe, etc), such as olivine. In the cool dry tropics hydrolysis and the presence of secondary minerals (at pH values of 6 and higher) lead to the formation of three-layered clay minerals (illites, montmorillonites and vermiculites), when combined with concentrations of silicic acid (H_4SiO_4) and alkaline ions.

In the warm, humid tropics, on the other hand, lower pH values (less than 5.5), lower concentrations of silicic acid and the leaching out of bases generally result in the formation of two-layered clays resistant to sorption such as kaolinite and halloysite (see Figure 2.21). Gibbsite ($Al(OH)_3$) is often formed in soils derived from basic, former igneous rock or extremely poor in silicic acid. It may sometimes also form following the breakdown of kaolinite.

Humid conditions favor the formation of clay minerals such as kaolinite, gibbsite and halloysite, which have a low cation exchange capacity. These conditions accelerate the breakdown of parent material. The end result is that these soils possess only very scanty mineral reserves. Ferrallitic soils have less than 10% and often less than 5% weatherable mineral reserves.

Savanna soils are generally richer in weatherable soil mineral reserves. They have more strongly sorptive clay minerals of the three-layered type, with relatively large, negatively charged surface areas. They store more nutrients, which they can release when needed. The total base status is also more strongly characterized by the parent material. Fersiallitic soils, such as commonly occur in savannas, often still possess 20-30% weatherable material.

Figure 2.21. Weathering and reformation of primary and secondary minerals



Source: Adapted from SCHEFFER and SCHACHTSCHABEL (1982)

The total amount and type of clay mineral profoundly influence soil characteristics. They not only determine organic matter but also extensively affect the workability, structure and cation exchange capacity of a soil.

The cation exchange capacity (CEC) is a measure of the soil's ability to store and fix nutrients in a form available to plants (nutrient cations such as Ca^{++}, Mg^{++}, K^+,

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[16] The extent to which soil temperature can be influenced is discussed in Chapter 5.

[17] This does not apply to gases. Anaerobic conditions occur more readily in warm soil water.

[18] Dissolution and leaching of silicates, which are the main constituents of rock.

NH_4^+). A low cation exchange capacity (< 5-10 m.e./100 g soil) means that soils, or rather their clay minerals, have few negative surface charges for binding nutrients to them. Even when these soils receive sizeable applications of fertilizer, the benefit can quickly be lost through leaching, especially on well drained soils under heavy rainfall. Table 2.11 shows the cation exchange capacity of different ion exchangers in the soil.

Table 2.11. Cation exchange capacity of important ion exchangers in soils (m.e./100 g)

Exchanger	Cation exchange capacity (CEC)
Kaolinite	3-15
Halloysite	5-50
Illite, chlorite	10-40 (50)
Montmorillonite	80-150
Vermiculite	100-150 (200)
Organic matter	100-350
Allophane (amorphous Al-silicate)	10-50

Source: YOUNG (1976)

Fertilizers and lime applications can rapidly and significantly alter the behavior of soils with poor sorption qualities. However, it is important that large amounts of fertilizer are not applied all at once. Several smaller doses should be given, timed to coincide with the demands of crop plants. This minimizes the loss of nutrients through leaching and avoids nutrient imbalances[19].

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[19] Slow-releasing, organic forms of fertilizer are better suited to these soils (e.g. composts, manure, mulch). Organic matter (humus) markedly improves the exchange capacity of soils with clay minerals with poor sorption qualities.

Another characteristic of soils developing under warm, tropical conditions is their high content of iron and aluminum oxides. These are formed in the course of intensive weathering and leaching and can adhere to or "coat" other soil particles, consolidating them into strong aggregates. This process results in soils with a crumbly, friable structure and with predominantly good physical characteristics, despite a high clay proportion of up to 80-90%.

The iron oxides and hydroxides give the soils their color. The orange-yellow mineral lepidocrocite (FeOOH) and the brown to rust-brown goethite (*a*FeOOH) are mainly formed under constantly moist conditions. Blood-red hematite (aFe_2O_3) is formed more often under subhumid conditions.

In the regions bordering the hot and humid inner tropics, leaching and weathering intensity begin to decrease as conditions become drier. Only readily soluble salts and carbonates are completely washed out. The bases[20] are subject to an intermediate amount of leaching, while the leaching of silicates is low. Soils subject to moderate silicate weathering (fersiallitic soils) and with clay-rich horizons are more widespread here. Where they are enriched with clay, the soil structure is generally prismatic or blocklike (Alfisols, Luvisols). A higher proportion of three-layered clay minerals lends these soils more sorption capacity and greater plasticity than in the rainforest zone. The workability of these soils is optimal only under certain moisture conditions. Because of its different texture, the structure of the topsoil is not as stable. These soils are prone to waterlogging, and may be sandy (SANCHEZ 1976).

The composition of the parent material characterizes the clay mineral composition and the nutrient content of these soils. (This holds true for all climatic zones on young sediments.) Incompletely weathered soils derived from acidic rock such as granite have fewer bases and a lower pH value than those of the same age that have developed from base-rich rock. Table 2.12 provides an overview of the most important igneous rocks and their mineral composition.

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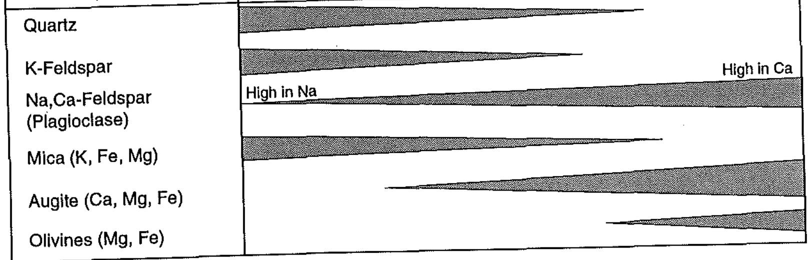
[20] The base saturation (= V) is a measure of the current nutrient status or of the leaching intensity, whereas the cation exchange capacity (CEC) indicates the potential nutrient capacity.

On poorly drained soils, thicker or thinner deposits may easily develop under anaerobic conditions. These can be either permanent or temporary. As conditions become aerobic, weathering or capillary action cause iron and aluminum oxides to form what is often called bog iron ore (limonite), and laterite layers develop which can harden permanently when exposed and dried.[21]

Table 2.12. The most important igneous rocks and the occurrence of important primary minerals

	Acidic rocks (high in Si) →			Basic rocks (high in Ca and Mg)
Plutonite (Plutonic rock)	Granite	Syenite	Diorite	Gabbro
Vulcanite (volcanic rock) (old) (young)	Quartz porphyry Rhyolite	Porphyry Trachyte	Porphyry Andisite	Melaphyre, Diabase Basalt
Metamorphic rock	Granite gneiss			Eclogite



Source: SCHEFFER and SCHACHTSCHABEL (1982)

In the humid tropics, there is a risk of laterization if the soil dries out because of land clearance or erosion of the topsoil.

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[21] Latin: "later" = brick

In the savanna zone, laterites frequently occur in hilly areas, especially where fluctuations in the water table cause periodic drying of the soil[22]. In basins in areas with clearly pronounced dry periods, water inflow rich in silicates and bases increases the presence of montmorillonitic clay minerals capable of swelling, and can lead to the formation of Vertisols (see below).

Where there is a transition from subhumid to more arid conditions, base saturation increases, as also does the exchange capacity. The aluminum saturation drops off sharply (YOUNG 1976).

Water is not always the limiting factor in plant growth. Sometimes the improved lime status of a soil can lead to an oversupply of free Ca ions, so that phosphates are fixed through apatite formation[23], and ion competition or high pH levels result in limited availability of other nutrients (Mg, K, micronutrients) (SANCHEZ 1976). In addition, N deficiency is widespread in savanna soils with a low humus content.

Often rainwater can only penetrate dry, cohesive savanna soils to a depth of 50-80 cm, so that nutrients are displaced but not leached out. On sites with relatively high groundwater levels (in valley centers and floodplains), the risk of salinization increases with increasing dryness. Salts added to the soil through fertilizer application, irrigation or through capillary rise can easily accumulate here. Irrigation should therefore be limited to sites that are well supplied with water and where salts can be washed out using a periodic surplus of surface water.

In subhumid to dry regions, the texture of the topsoil is increasingly characterized by silt and fine sand, which are especially at risk from erosion.

Figure 2.22 presents an overview of soil types and their composition (percentage of clay, silt and sand). Describing soils in this way tells us much about such important agricultural characteristics as their workability, water holding capacity, and so on. Because the characteristics of soils in the tropics are also frequently influenced by

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[22] BURINGH (1979) estimates the proportion of tropical soils at risk of laterization at about 7%. SANCHEZ et al. (1982) state that only 4% of the soils in the Amazon Basin are in danger of laterization.

[23] $Ca_5X(PO_4)_3$; X = F, Cl or OH

iron and aluminum oxides, which may lead to irreversible hardening on exposure, or by clay minerals with varying tendencies towards swelling, it is always advisable to consider these factors as well.

Clay is defined as soil particles with a diameter of < 2μm or < 0.002 mm; silt is 2-63 μm or 0.002-0.063 mm; and sand is 63-200 μm or 0.063-2.0 mm.[24]

The processes summarized above in a zonal context can also occur irrespective of zone, owing to local factors such as parent material, topography, rainshadow, and so on. Moreover, it should be borne in mind that soils exist which, regardless of present-day climatic conditions, were first exposed during an earlier geological era and are now atypical for current climatic conditions.

At higher altitudes, the cooler temperatures and greater precipitation have widely varying effects on the soil. Moreover, soil formation is strongly influenced by relief which can cause conditions to vary abruptly (from the windward to the leeward side of a mountain, for example).

On sloping ground, especially on upper slopes, the soils are often less deeply weathered because the topsoil is constantly carried away. As altitudes increase, temperatures fall, mineralization of organic matter declines and humus accumulates (often between 5 and 20%) (YOUNG 1976; BURINGH 1979). JAGNOW (1967) measured an exponential increase in humus with decreasing temperature and increasing rainfall (see also Section 2.3.4).

Weathering of minerals is less rapid. On volcanic parent material, allophanes are formed. These amorphous aluminum-containing silicates form relatively stable complexes with organic matter which, at moderate temperatures, counteract the breakdown of humus as well as weathering (SANCHEZ 1976).

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[24] In the anglophone system the borderline between silt and sand is 50 μm. The International Soil Science Association suggests the following breakdown: clay < 2μm, silt 2-20 μm, fine sand 20-200μm and coarse sand 200-2000μn.

P and K deficiencies are common in mountain soils. Shallow A and C soils (Lithosols, Regosols, Entisols) are often found at elevations of about 3000 m. On level sites such as the *Punas* in South America where there is good drainage, soils with B horizons are also found (Inceptisols or Cambisols; see Section 2.3.5).

Soils with a heavy layer of humus are often formed where there is poor drainage (SANCHEZ 1976). Where the water supply is moderate to scanty, three-layered clays that are capable of swelling may be formed under some circumstances.

At intermediate elevations of about 2000 m, soils are often found that are similar to those of temperate climates.

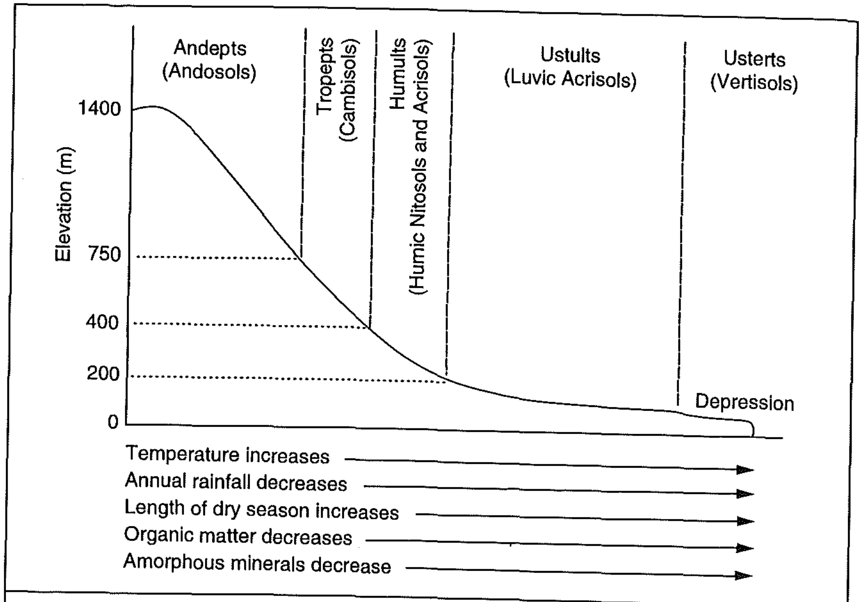
As a result of heavy leaching, these usually well drained soils are poor in bases and, with pH values of 4 to 6, possess low to moderate fertility.

Depending on the weatherability of the parent material, very fertile soils can also be found in highland areas. Often these have developed from volcanic ash (Andosols, see Section 2.3.4). Such soils cover large areas of the tropics (Hawaii, Java, Central and East Africa, Andes). They have a high nutrient content and good water holding capacity. At lower elevations, however, they tend to become increasingly scoured and poor in nutrients (Figure 2.22).

When using highland soils for agricultural purposes, the frequent local variations in soil conditions (due to topography, soil removal and deposits, different parent materials, etc) must be given as much consideration as the abrupt changes from shallow to deep soils.

Anti-erosion measures are especially important on sloping terrain given the often intensive rainfall of the tropics. This is relevant not only to cropland but also to grassland, where overgrazing and excessive trampling on just a few pathways can trigger the rapid spread of erosion (see also GIL 1979).

Figure 2.22. Soil associations* on the slope and at the base of a volcano in Indonesia



* Soil terminology using the FAO nomenclature given in parentheses (see Chapter 2.3.6)

Source: Adapted from DUDAL and SOEPRAPTOHARDJO (1960), in SANCHEZ (1976).

2.3.2 Some special factors determining fertility in tropical soils

The low CEC and shortage of weatherable minerals on the old, kaolin- and oxide-rich soils of the hot and humid tropics present considerable problems for land use. On Oxisols and Ultisols, CEC usually lies under 10 m.e./100 g soil (sometimes even under 5 m.e./100g), which means that the capacity of the soils to fix and store nutrients is very poor. This is especially so when land is cleared and cultivated for a few years with an annual crop, for then the organic matter, which is especially important for CEC on weathered tropical soils, is depleted (see Table 2.19).

An important feature of ferrallitic soils rich in kaolin, humus or allophane (Andosols) is the fact that their sorption capacity is strongly dependent on pH, i.e. they possess a high proportion of variable charges.

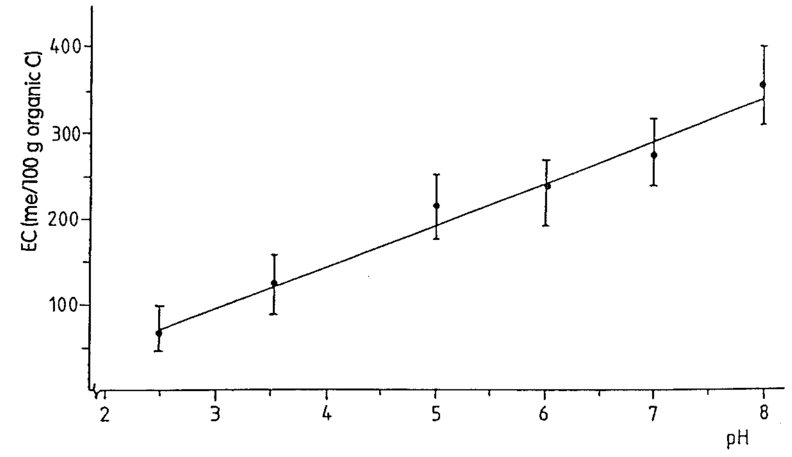
CEC is therefore not the only point to be considered in evaluating tropical soils. A distinction should also be made between the potential exchange capacity (EC_{pot}) and the effective exchange capacity (EC_{eff}). The former depends mainly on the type and composition of the clay minerals and the organic matter (Table 2.13). The less sorptive the clay (three-layer minerals with large, negatively charged surfaces) and the less humus a soil has, the lower is its potential exchange capacity.

In principle, this is also true for the effective exchange capacity (EC_{eff}), since this can never be higher than the potential capacity. The effective capacity is largely influenced by the pH value of the soil. The lower the pH and the higher the proportion of variable charges, the further the effective exchange capacity falls below the potential (SCHEFFER and SCHACHTSCHABEL 1982). A wide gap between potential and effective exchange capacity is characteristic of the Andosols, Ultisols and Oxisols, which are already acidic under natural conditions (see Table 2.13). In the surface soil the difference is largely due to the organic matter, which gains appreciably in sorption power with increasing pH (see Figure 2.23). For example, the exchange capacity of soils in Wisconsin was found to increase by almost 300 m.e./100 g between pH 2.5 and 8, i.e. about 50 mval per unit pH (HELLIG et al. 1964; cited in SCHEFFER and SCHACHTSCHABEL 1982).

In Andosols, the difference between EC_{pot} and EC_{eff} is chiefly due to the allophane. In Oxisols and Ultisols, which also have higher exchange capacities at higher pH values, this gap is due more to the kaolin-oxide clay mineral status.

On soils with pH values under 5, the exchange particles elements are coated with hydrogen and nutrient cations (Mg, K, Ca) and often also with aluminum (Al) ions, which may lead to aluminum toxicity and phosphate fixation through the formation of Al-phosphates.

Figure 2.23. Exchange capacity (EC) of the organic matter in 60 soils in Wisconsin, as influenced by pH buffered percolation solution with Ba-content*



* Vertical lines = standard deviation.

Source: HELLING et al. (1964), cited in SCHEFFER and SCHACHTSCHABEL (1982)

According to SANCHEZ (1976), acidity is a major problem in many tropical soils. This is especially true of the soils in South America and, to a lesser extent in Africa (ROOSE 1981). Only at pH values exceeding 5 does aluminum become hydroxide, so that toxicity is no longer a problem. (The signs of aluminum toxicity are reduced, stunted growth and disrupted Ca and P metabolism).

Mineral fertilizers that have a physiologically acidic effect (such as NH_4SO_4) promote Al toxicity because they release Al ions into the soil solution (BACHE and HEATHCOTE 1969; KREBS 1975; SCHEFFER and SCHACHTSCHABEL 1982).

Table 2.13. Sorption relations in the A horizon of selected soils in tropical and subtropical climates

	pH	C	EC_{pot}	EC_{eff}	Saturation (%)				
		(%)	(mval/100g)		Al	Ca	Mg	K	Na
Vertisol (Sudan)	6.8	0.9	47.0	45.2	0	71	25	0.4	3.8
Andosol (Hawaii)	4.5	11.7	53.1	13.3	3.7	71	20	3.8	2.2
Oxisol (Puerto Rico)	3.5	2.8	13.0	2.6	89	2.7	3.5	3.1	1.2
Ultisol (Puerto Rico)	3.5	3.3	25.6	7.2	72	15	8.3	2.8	1.4
Aridosol (Arizona, USA)	9.9	0.4	36.4	36.4	0	45	5.5	2.5	47

Source: SCHEFFER and SCHACHTSCHABEL (1982)

Liming can alleviate or eliminate Al toxicity. A definite improvement in soil fertility, however, can only be achieved if the subsoil is affected. If this does not occur, the penetration of roots through the soil will often be confined to the upper soil strata, limiting the volume of soil available to the plants. Soils with a low penetrable volume are usually regarded as infertile (ROOSE 1981). Thus, for example, the incidence of water stress in crop plants is exacerbated by shallow root penetration in Al-saturated subsoils.

Special methods for adding lime to the subsoil must therefore be used in many cases. Only on very porous soils (e.g. Oxisols or Ferralsols) will the lime work down to the lower soil layers by itself within a relatively short time. Farmers must beware of applying lime excessively, as this can easily result in undesirable side-effects such as reduced availability of slow-release fertilizers (e.g. rock phosphate), micronutrient deficiencies (e.g. zinc, manganese) and heavy weed infestations (SANCHEZ and SALINAS 1981; KANG and OKIGBO 1981). Overdoses of lime also accelerate the decomposition of organic matter. They promote nitrification, rendering nitrogen subject to increased leaching. This is in contrast to ammonium, which can be fixed by organic matter and clay minerals (MENGEL 1968).

SANCHEZ and SALINAS (1981) discuss in detail the problem of soil acidity on Oxisols and Ultisols. They recommend a "low-input" strategy, the aim of which is not to precipitate the exchangeable aluminum completely (pH 5.5), but rather to avoid undesirable side-effects by choosing aluminum-tolerant crops and varieties where necessary, securing their nutrient requirements, and preventing toxicity. They recommend the following formula for calculating the required dose of lime per hectare:

Lime required in t $CaCO_3$ equiv./ha = 1.8 Al - RAS (Al + Ca + Mg) /100[25]

While the critical Al saturation level is partly influenced by the soil, it depends mainly on the Al tolerance of the crop or variety. Thus, for example, Al saturation values of 22 to 60% were found in ten different wheat varieties. Brazilian varieties bred on Al-rich soils exhibited a higher tolerance than Mexican varieties. The critical Al saturation for upland rice varieties ranged from 22-70%. The corresponding lime requirement was 0.2 - 1.4 t $CaCO_3$ per ha.

Some tropical grasses, such as *Brachiaria humidicola*, *Andropogon gayanus* and *Melinis minutiflora*, tolerate Al saturation levels of 70-90%, while others (*Panicum maximum, Pennisetum purpureum*) withstand only 20-25%. Tropical legumes are generally more tolerant than grasses. The critical Al saturation for *Stylosanthes* spp., for example, is 70-90%. Here too, there are wide differences between species. For example, *Leucaena leucocephala* can tolerate only about 30% Al saturation. Some crops generally known for withstanding Al toxicity include cassava, cowpea, banana, and rice. Phaseolus beans, maize, soybean and sweet potato fall into the sensitive category, though some individual varieties are known for their higher tolerance. Relatively Al-tolerant fruits include the passion fruit, pineapple, guava and mango, while some trees that tolerate Al are hevea, coffee, the peach palms, oil palms and *Gmelina*, etc (for further details see SANCHEZ and SALINAS 1981).

Manganese toxicity can appear in compacted or waterlogged acidic soils with a pH of less than 5.5. It is often associated with Al toxicity. Higher contents of iron oxides produce a good water movement and usually good soil structure. At times, however, this can lead to iron toxicity, especially under waterlogged conditions. The toxicity is brought about by reduced iron (Fe^{2+}), which is dissolved from the oxide at lower pH values and lower redox potential. As is apparent from the following equation, the formation of Fe^{2+} is possible under relatively neutral pH conditions:

$$Fe(OH)_3 + 3\,H^+ + e^- = Fe^{2+} + 3\,H_2O$$

This means that, as the acidity and lack of air in a soil increase, so does the likelihood of iron toxicity (for example, after the incorporation of non-decomposed organic matter into waterlogged soil). Here too, already humified organic matter (e.g. compost) helps counteract iron toxicity through the formation of larger complexes.

As a rule, however, it is not the toxicity of iron that limits plant growth, but rather the tendency of iron oxides to fix phosphate. Phosphate deficiency (or phosphate

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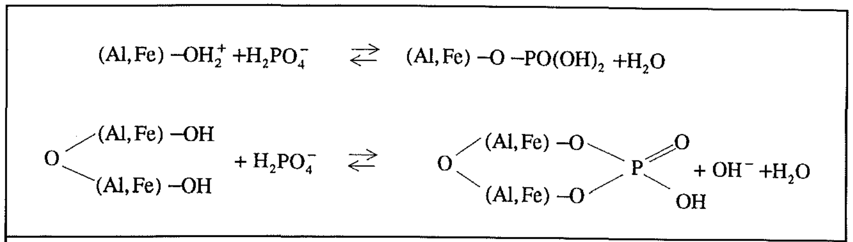
[25] RAS is the critical "relative Al saturation level" for a particular crop plant in %. This is the Al saturation that is tolerated by a plant without its showing symptoms of Al toxicity (on which there is unfortunately little or no data available). As part of a "low external-input" strategy, this can be defined as the threshold at which the crop plant still produces 80% of its yield (given complete Al neutralization and optimal supply of P)(SANCHEZ & SALINAS 1981).
Al, Ca, Mg: exchangeable cations in meq./100 g soil (1 N KCl extraction).

adsorption) is especially pronounced in weathered tropical soils with a high content of iron oxides. The specific sorption of P in soils containing iron and aluminum oxides (see Figure 2.24) is relatively stable, so that this phosphate is rendered unavailable to plants. Fertilizing with easily soluble phosphates (superphosphates) at normal dosages therefore often produces only negligible and short-term results, as most of the phosphate becomes fixed. The amount of phosphate fixed in this way can be considerable. For example, on iron oxide-rich kaolin soils MOLL (1980) reported P fixation rates of 300 - 800 kg/ha in the upper 10 cm of soil alone.

Figure 2.24. Specific adsorption of phosphate in iron or aluminum oxides



Source: SCHEFFER and SCHACHTSCHABEL (1982)

Phosphate adsorption falls as the pH value increases because hydroxide ions compete with phosphate for the sorption places. But the availability of phosphate in tropical soils does not depend only on the content of iron-aluminum oxides. It is also strongly influenced by the amount of organic matter in the soil and, in the case of Andosols, by the allophane content.

Allophane can bind considerable quatities of anions under acid conditions. However, organic matter only adsorbs phosphorus specifically (fixation) if it contains complexly bound Fe^{3+} or Al^{3+} (which is not uncommon in the tropics).

Clay and humus adsorb phosphorus quite weakly. The humus is a very important storer of P, as 30-60% of the entire P supply of a soil is stored in organic form (IPINMIDUN 1972, SCHEFFER and SCHACHTSCHABEL 1982). Phosphates fixed by micro-organisms and stored in organic compounds (e.g. inosite hexaphosphoric acids) are a slow-release source of phosphorus and the main form of organic phosphorus after the phosphorus loosely bound to humic and fulvic acids.

High biological activity contributes in numerous ways to the mobilization of phosphorus. Mycorrhizal fungi, for example, are able deliver phosphorus from plant litter or from the vicinity of slow-release phosphorus sources directly to the plants (see also Section 8.2). The enzyme activity of decomposing micro-organisms also contributes to the breakdown of P. Also largely dependent on biological activity is the very slow dissolution process of relatively stable, adsorbed phosphorus, derived primarily from the exchange of OH^-, HCO_3^- and organic anions formed through microbial activity and root exudates (SCHEFFER and SCHACHTSCHABEL 1982). This was confirmed in recent studies at the Centro Internacional de Agricultura Tropical (CIAT) in Colombia, in which it was found that phosphorus hitherto considered unavailable to plants is in fact released from Fe-Al compounds through these biological activities (SANCHEZ and SALINAS 1981).

Molybdate, and sometimes sulfate and borate, can also be fixed in a similar way to phosphorus, i.e. they can be adsorbed specifically.

The non-specific adsorption of anions is pH-dependent. It starts to occur in the moderately acidic pH range of Fe-Al oxide-rich kaolin soils (at pH 6). The oxide-rich soils then function almost like anion exchangers and adsorb at pH values less than the zero point of charge. When much organic matter is present (zero point of charge in the strongly acidic range) and when the pH value is increasing, the anion adsorption falls off and cation sorption improves markedly.

Zinc deficiency is often found in calcimorphic soils, but also in acidic Oxisols, as in the *cerrados* of Brazil. This is not just poor availability; an absolute lack of zinc is often found.

2.3.3 The role of organic matter (humus) in tropical soils

Most well known soil scientists agree that organic matter plays a key role in tropical soils. This is even true of production systems using high external inputs. YOUNG (1976) states that the significance of organic mass in tropical soils is greater than any other soil characteristic, apart from moisture. SANCHEZ (1976) also emphasizes that the maintenance of organic matter is of "fundamental importance to the productivity of tropical soils". JAGNOW (1967) concluded: "If soil fertility in the tropics is to be maintained, fertilization must first and foremost be organic". What this means in practical terms is summarized by IGNATIEFF and EMOS (1963), who write, "A proper management of tropical soils which have only recently come under cultivation must aim to maintain both the structure as well as the content of organic matter; in soils that have been farmed for a long time, the aim should be to increase the organic mass and to improve structure". There is no end to the list of these and similar statements on the importance of organic matter on typical, weathered tropical soils (JONES 1971; AGBOOLA and COREY 1973; ROOSE 1981, to name but a few).

As mentioned in the previous chapter, "the tropics" is a comprehensive term covering a highly heterogeneous range of conditions. Even the primary functions of organic matter can be quite different on different tropical sites (see below), though they are always very important. The following is a summary of some of the most essential functions of organic matter:

- Organic matter functions as an **exchanger or sorption agent.** Especially in kaolinic soils with naturally very low cation exchange capacity (see Table 2.11), organic matter contributes considerably to the storage and release of nutrient ions. On acidic, weathered soils, organic matter is responsible for almost the entire cation exchange capacity (YOUNG 1976). AGBOOLA (1975), working in western Nigeria, found a highly significant and very close correlation between the content of organic matter in the soil and the exchange capacity ($r = 0.988$).

- Especially on soils with low mineral exchange capacity, organic matter functions as a **buffer system** for the pH-value and ion concentration. It regulates the balance of nutrients in the soil solution.

- Organic matter is the product of a "bio-accumulation" of nutrients in the topsoil. It is therefore a **nutrient carrier** (vehicle) because the small amounts of calcium and magnesium and the available phosphorus in the Oxisols and Ultisols of the humid tropics and moist savannas are concentrated in the humic topsoil. Thus for example, IPINMIDUN (1972) found that in the savanna soils of Nigeria, 20-60% of the phosphorus was accumulated in the organic matter. In de-limed surface soils, up to 90% of the total sulfur may be fixed in the organic matter (SCHNITZER and KHAN 1978). With the loss of the organic matter or of the topsoil, these nutrients are usually lost to the system. The nutrient concentration in the weathered subsoil is generally far lower (SCHEFFER and SCHACHTSCHABEL 1982).

- Organic matter also works as a slow-release source of nutrients, thereby reducing the risk of leaching. This function is especially important in the evergreen and semi-evergreen rainforest regions and also seasonally in subhumid regions, as well as on all permeable soils (sand, Oxisols).

- In iron oxide-rich soils, the turnover of organic matter contributes to the **mobilization of phosphorus**. This can also be the case on calcimorphic soils, when the organic matter gives off H^+ ions and adds Ca^{2+} ions, thus increasing the solubility of calcium phosphates. This effect occurs when rock phosphate is applied as fertilizer (SCHEFFER and SCHACHTSCHABEL 1982).

- On sites that have a tendency to iron or aluminum toxicity, humifying organic matter works to combat **toxic metal concentrations** by forming stable complexes with a high molecular weight (ALLISON 1973; SANCHEZ 1976).

* Organic mass **improves the water-holding capacity of soils**, in that it can hold up to three to five times its own weight in water. YOUNG (1976) cites findings from Ghana, where a reduction in organic matter from 5% to 3% caused the water-holding capacity to drop from 57% to 37%.

* In almost all soils, **organic matter improves structure**. Humus contributes to the formation of aggregates. The clay-humus complexes are a good protection against wind and water erosion and help promote permeability while simultaneously improving water storage (YOUNG 1976; SANCHEZ 1976; LAL and GREENLAND 1979).

* Organic matter is essential as a **habitat and source of nutrients for micro-organisms** (fungi, bacteria) and for soil fauna such as earthworms and termites. As such it enables the continuous biotic engineering of soil particles (through microbial excreta, earthworm casts, etc) which is very important for the maintenance or improvement of soil structure and for protection against erosion (GLIEMEROTH 1958; KULLMANN 1966; GRAFF and MAKESCHIN 1979). This function is especially vital in soils which, because of their medium-fine texture, tend to become puddled or eroded at the beginning of rainfall.

* A soil rich in humus and fauna possesses considerable protection against possible crop diseases. The vast variety of antagonists, competitors, hyperparasites and antibiotic excreta from predator nematodes, fungi, bacteria and other organisms which inhabit a teeming soil prevent the rampant spread of pathogens and soil-borne pests (HUBER and WATSON 1970). There are also indications that large applications of humus improve the resistance of plants to pest infestation (SCHAERFFENBERG 1955) and that the substance humin can have a growth hormone effect (FLAIG 1975).

Table 2.14 shows the relationships between various soil properties on sites in Nigeria.

Table 2.14. Correlation coefficients for relationships between some soil variables on several sites in western Nigeria

	Correlation coefficient					
Variable	P	K	Mg	Ca	Org. mass	CEC
K	0.362	-				
Mg	0.943**	0.524	-			
Ca	0.977**	0.562	0.965**	-		
Org. mass	0.982**$^{1)}$	0.824*	0.981**	0.987**	-	
CEC	0.642	0.642	0.976**	0.982**	0.988**	-
% Clay	0.504	0.600	0.622	0.632	0.922**	0.574

$^{1)}$ Significant for 2% organic mass upwards
* Significant; ** Highly significant

Source: AGBOOLA (1975)

2.3.4 Some observations on humus dynamics

Proper care of organic matter requires not only some system of management (see Sections 3 to 8), but also some basic knowledge of the dynamics of organic matter in the tropics.

Attention was drawn in Section 2.1 to the close relationship between humus content, rainfall (soil moisture) and temperature. According to JENNY and RAYCHAUDHURI (cited in YOUNG 1976), the relationship with temperature is especially close. Where annual **rainfall** is 750-1000 mm, carbon content increases by 0.5% with an increase in annual rainfall of 100 mm.

At a mean **annual temperature** of 14°C the oxidation of organic matter is reduced, so that the amount of rainfall is of far less consequence. The higher humus content in warm mountain regions (around 20°C) as opposed to the constantly hot lowland tropics can be explained at least partly by the fact that most plants grow best at 20 to 25°C, whereas bacterial decomposition only reaches its maximum at 30 to 35°C (MOHR et al. 1972).

A third important factor is the **clay content of the soil**, which is usually closely related to humus content. For example, on soils in West Africa JONES (1973) found a close correlation between clay and humus content, as also did AGBOOLA (1975). See Table 2.14 as well as BIRCH and FRIEND (1956) and YOUNG and STEPHEN (1965, cited in YOUNG 1976). According to FLAIG (1975), only three-layer clay minerals have a protective effect on humus; kaolinite and quartz show no effect.

The dynamics of humus formation are more intensive in the tropics than in temperate climates. In warm humid periods, decomposition generally takes place very rapidly (depending on the state of the soil and on air and pH conditions). In dry seasons, decomposition essentially comes to a standstill because of the reduction in biological activity. Table 2.15 lists the most important processes and factors influencing the C content of the soil.

Only some of these processes will be dealt with here, as most are discussed in other chapters. The following information is derived primarily from NYE and GREENLAND (1960) and YOUNG (1976).

Some 10 to 20% of organic biomass goes into the formation of humus, whereas 80 to 90% is lost as CO_2 through oxidation. Oxidation is less in plant parts below ground, so that here about 20 to 50% is left to become humus. Mineralization and oxidation - that is, the liberation of anorganic ions and the production of CO_2 - are the decisive processes in the breakdown of humus.

Table 2.15. The most important processes influencing the humus content of soils

- **Processes that influence the vegetation (proportion of biomass):**

Photosynthesis Respiration Uptake of nutrients Transport of materials	Plant growth
Accumulation of litter Accumulation of wood Root exudates Burning	Dying of plants

- **Processes involved in litter decomposition:**
  Breakdown (decomposition)
  Humification
  Oxidation
  Erosion
  Burning

- **Processes involved in dead root decomposition:**
  Humification
  Oxidation

- **Processes influencing soil humus:**
  Mineralization
  Oxidation
  Erosion
  Leaching

- **Processes that are caused or accelerated by people:**
  Burning
  Clearance of vegetation
  Agricultural activities
  - Losses:
    - Harvesting of plants
    - Grazing
    - Encouraging oxidation (e.g. frequent plowing, aeration)
    - Total suppression of weeds
  - Gains:
    - Natural or intensive fallows
    - Harvest residues
    - Incorporating or leaving mulch on fields
    - Application of stable manure
    - Application of compost
    - Green manuring
    - Field-grass-crop rotation

Source: Adapted from YOUNG (1976)

C-heterotrophic micro-organisms consume and transform organic matter. By incorporating anorganic ions, they work to some extent to combat mineralization. For broad C/N ratios (exceeding 20:0), and also for broad C/P ratios (exceeding 200:1), this can lead to the temporary fixation (immobilization) of these nutrients in the soil.[26] SANCHEZ (1976) hypothesizes that the lack of nutrients available to plants, including the lack of P in Andosols (see below) and of P and Ca in Ultisols, may promote the accumulation of humus by inhibiting micro-organisms. He cites studies from America in which the application of P and Ca fertilizer resulted in higher C breakdown rates. AGBOOLA (1981) also observed increased C breakdown on an Alfisol following the application of mineral fertilizer.

Making predictions regarding humus dynamics is difficult. The figures given in Table 2.16 are average values collected over many years. Because they include the period when the land was first brought into cultivation, they probably do not represent current breakdown rates, which are almost always significantly higher. YOUNG (1976) quotes numerous studies in which the decomposition rate of soil humus lay at around 10-20% during the first 2-3 years of cultivation. On Ultisols in the Amazon Basin, humus decomposition in the first year of cultivation was 25% (SANCHEZ et al. 1982). In the savanna too, the values for the early cultivation period are often over 10%.

The intensity of turnover falls off after a certain number of years of cultivation; that is, something like negative feedback takes place. On a red Oxisol in Senegal, for example, the decomposition rate was 2.9% between the third and the fifteenth year, and 0.4% from the sixteenth to the fiftieth year (SIBAND 1972). In other words, the further the humus content falls away from its optimal "equilibrium content", the less rapidly it decomposes (Figure 2.25).

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[26] A blockage of N or P is especially unwelcome during the main growth phase of crops; micro-organisms, on the other hand, take up N and P from the soil solution in order, for example, to decompose straw (HOWARD 1943).

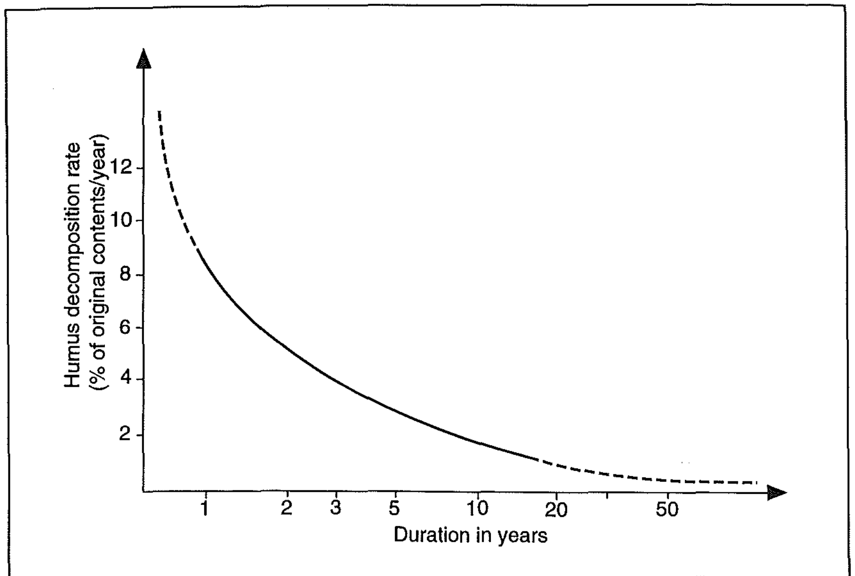
Table 2.16. Estimated decomposition rates of organic matter in soils lying fallow and under cultivation

	Zone I (Rainforest)	Zone II (Moist savanna)	Zone III (Dry savanna)
Decomposition rate under fallow (%/year)	3.0 (2-5)	0.9 (1.2)	0.8 (1.2)
Decomposition rate under cultivation (%/year)	3.3	4.5	4.5

Sources: Average values according to NYE and GREENLAND (1960); values in parentheses from SANCHEZ (1976)

The extent of humus decomposition in the tropics is greater than in temperate climates and only arrives at a "relative" standstill at levels of about 30-40% of the original content (Table 2.17). These are values which, according to YOUNG (1976), lie far below the desirable level. At least in tropical lowlands, desirable C contents can be achieved only through planned humus management, as demonstrated in the work of RANGANATHAN et al. (1980) and AGBOOLA and COREY (1973), among others. Bush fallow was, and sometimes still is, a means of restoring the humus status of the soil. These and other measures prove increasingly effective the further the soil is from its optimal C content.

Figure 2.25. Schematic representation of the dynamics of humus decomposition after a soil with natural vegetation is brought into cultivation



Source: Adapted from SIBAND (1972), YOUNG (1976), SANCHEZ et al. (1982)

Based on the model by NYE and GREENLAND, YOUNG (1976) offers the following simplified formulae to express this relationship:

$$I = A - pA = A\ (1 - p),$$

in which I = the increase in humus content, A = the addition of humus to the soil, and p = the approximate humus content under natural conditions. This means that if p = 1, no real growth is to be expected as the soil will soon have converted the added humus. However, if p = 0.5, then the soil has only half its optimal humus content; therefore A (1 - 0.5) = 0.5 A. That is, half the humus added is taken up to restore the humus level of the soil. These formulae are too simple and are only applicable within certain limits (see YOUNG 1976 and RANGANATHAN et al. 1980). Yet assuming that they provide even an approximate description of reality, it becomes obvious how greatly the humus effect of applying fertilizer is influenced by the existing humus level of the soil. Figure 2.26 clearly illustrates this connection (In reality a linear relationship is hardly likely.)

Table 2.17. Humus content of topsoils in the tropics according to zone

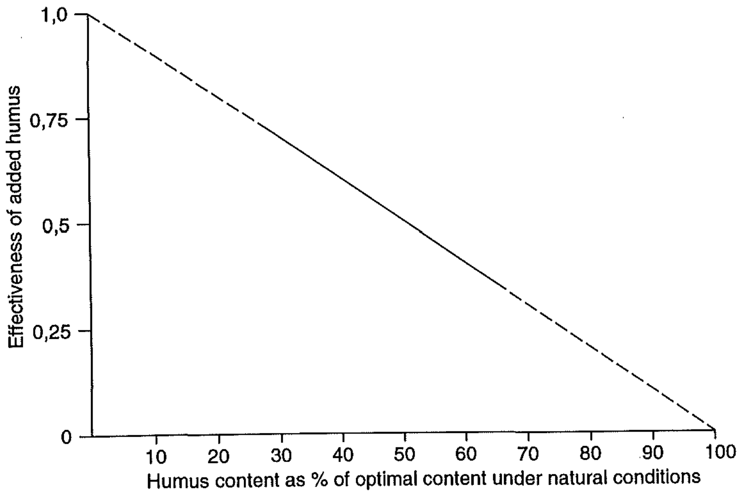
	Zone I (Rainforest)	Zone II (Moist savanna)	Zone III (Dry savanna)
Humus under natural vegetation (%)	3-5	2-3	1-2
Humus under annual cropping with no special measures (%)	1-1.6	0.6-1	0.3-0.6
Desirable C content (%)	2.5-3.5	1.2-2	0.6-1.2

Source: Adapted from YOUNG (1976)

Raising the humus content to over 75% of its level under natural vegetation is physically difficult and not economically viable owing to high labor costs (YOUNG 1976).

In the following section, using the NYE-GREENLAND model, we will seek to show how crops and fallows influence humus dynamics in various zones of the tropics, when the aim of the system is to maintain a humus content of 75% of the original level. The annual gain from fallow is estimated from data by NYE and GREENLAND (1960).

Figure 2.26. Relationship between the relative humus content of soils and the effectiveness of measures to supplement humus



Losses according to the following loss formula: Loss in x cropping years = K_K x p x C_G x E_k, where K_K: Humus decomposition constant (e.g. 0.03 = 3%), p: Approximation factor for natural balance (see above), C_G: Humus content of natural balance (kg/ha), E_k: Years of cultivation.

Although the calculations for different zones presented in Tables 2.17 and 2.18 can only very roughly approximate reality, the results agree in essence with empirical data on shifting cultivation. It is clear that natural fallow is considerably more effective in the permanently humid tropics than in subhumid regions.

In conclusion, Table 2.19 shows measured values for humus dynamics on cultivated soil in southern Senegal. The data were collected by SIBAND (cited in CHARREAU 1975), for different years after a forest soil had first been brought under cultivation. Here the relative decomposition rate of humus was 5.4% in fields that had been cultivated for 3 years, falling to 1.7% for those cultivated from 3 to 12 years, 1.2% from 12 to 46 years, and 1.1% thereafter.

Expressed as a percentage of the original content, the loss of humus in the last 44 years was only 0.4% (see Figure 2.25). Table 2.19 is a further illustration of how the negative effects of diminishing humus content alter important characteristics that determine soil fertility. For example, the cation exchange capacity (CEC) fell by 68% when organic matter declined by 70%.

Table 2.18. Restoration of organic matter content under natural fallow

	Zone I Rainforest	Zone II Moist savanna	Zone III Dry savanna
Loss of humus in cropland in 3 years of cultivation (kg/ha)	4000	4500	1350
(%)	6.5	9.0	9.0
Average annual fallow gain* (kg/ha)	250-600	70-160	20-50
Period needed to compensate for losses* (years)	7-16	28-64	27-67

* First figure assumes a humus consumption of 10% of organic dry matter, second figure assumes a humus consumption of 25% of organic dry matter.

Source: Adapted from YOUNG (1976)

A commonly held view is that humus in the tropics is different in character and behavior from that in temperate climates. SCHNITZER (1977) compared humic matter from different climates and could discover no fundamental differences.

Table 2.19. Development of some important soil characteristics in forest soils brought under cultivation during 0-90 years of cropping in southern Senegal

No. of years after first cultivation	C-content (%)	C/N-ratio	Clay (%)	Available water (%)	CEC (m.e./100g soil)	pH
0	1.65	18.3	11.1	4.1	7.8	6.3
3	1.38	17.5	10.2	4.7	5.2	6.0
12	1.16	17.0	10.5	3.7	3.2	5.9
46	0.68	15.8	9.0	2.8	2.0	6.0
90	0.35	14.3	7.4	3.3	1.6	5.9

Source: SIBAND (1972), cited in CHARREAU (1975).

At this point a few basic statistics on organic matter in soils should be noted: At a soil density of 1, 1 cm of soil weighs 100 t/ha; if the humus content is 1%, 100 t of soil would contain 1000 kg humus or about 500 kg of organic C[27]. At a C/N ratio of 10:1, about 50 kg N/ha would be present. These relationships can easily be used to calculate different values. For example, 30 cm of topsoil weighs 3000 t/ha at a density of 1 or 4500 t/ha at a density of 1.5, and 2% humus in the upper 30 cm of soil is the equivalent of 90 000 kg of humus/ha[28].

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[27] Conversion factors: from humus to organic C = 0.58, from organic C to humus = 1.72.

[28] At a C/N ratio of 10:1, this equals 4500 kg N/ha, or at 15:1, 3000 kg N/ha.

Depending on its composition and pH value, humus has a cation exchange capacity (CEC) of about 150-350 m.e./100 g. It can be assumed that the CEC of humus per pH unit between pH 4 and pH 8 rises on average by 50 m.e./100g, in which case the following applies:

Humus at pH 4: 100 m.e. CEC/100 g
Humus at pH 5: 150 m.e. CEC/100 g
Humus at pH 8: 300 m.e. CEC/100 g

For example, if a soil has 1% humus at pH 5, then the humus contributes 150 m.e./100 g soil to the CEC. At 2% it contributes 300 m.e./100 g, etc.

2.3.5 Important tropical soils and their classification

Advances in knowledge and classification of tropical soils make it difficult for the lay person to find his or her way through the constantly changing terminology. In addition, there are many different classification systems, making international comparisons difficult.

A very common soil description, but one that often means different things to different people, is "Latosol". According to KELLOGG (1949), this term applies to almost all typical zonal soils of the humid tropics. Heavy leaching and intensive weathering produce the characteristic features of a Latosol, namely its red color and strong degree of weathering. KELLOGG's definition covers not only the typical soils of the tropical forest but also savanna soils. In these very old soils, salts and calcium have been completely leached out, while the washing out of alkali metals, alkaline-earth metals and silicic acid is well advanced. Such soils contain heavy accumulations of Fe-oxides, Al-oxides, gibbsite and kaolinite.

The pH values of these soils are less than 5.5. The topsoils have a stable, earthy structure, good hydraulic conductivity, good root permeability and good aerobic conditions. Nutrient deficiencies (CEC < 15 m.e./100 g), low utilizable water holding capacity, phosphate fixation, and aluminum and/or iron toxicity are factors that may severely inhibit plant growth.

In extreme cases, laterites may form irreversibly in the subsoil, or also on the surface of eroded soils. According to MARTIN and DOYNE (1927), this occurs when the ratio of SiO_2 to Al_2O_2 is less than 2. Laterite formations, also known as "hardpans", often develop along the upper edge of rising groundwater in dry soil. Sesquioxides (Fe-, Al-oxides) in runoff water accumulate on the surface and harden. BURINGH (1979) and SANCHEZ (1976) state that only 7% of tropical soils (more in Africa) are genuine laterites.

According to the FAO nomenclature, such a laterite must exhibit an iron-rich, clay-rich and red-flecked B horizon at a depth of 0-125 cm which can harden irreversibly on drying (following clearance or draining, for example). This is referred to as a "plinthic horizon".

If the B horizon is enriched by round Fe concretions (iron bodies), it is described as "ferric". If the concretions are larger, the term "plinthic" is used. In the U.S. Soil Taxonomy (SOIL SURVEY STAFF 1975) such soils bear the prefix "Plinth".

Latosols occur in what the FAO calls Ferralsols, Acrisols, Luvisols and Gleysols (for definitions, see below). In the U.S. system, they occur primarily in Oxisols, Ultisols and Alfisols in the tropics.

The term Latosol, however, is not always used in the above sense. Often it refers generally to tropical soils that have been heavily weathered, and are leached and poor in nutrients. Used in this sense, the term refers to 51% of tropical soils and is very vague (SANCHEZ 1976). To avoid confusion and misunderstanding, its use should be avoided altogether.

2.3.6 The FAO System

From an international standpoint, the classification of soils is a controversial topic. Similar or identical terms are often defined differently; different terms are used for the same thing; and different languages add to the confusion when making comparisons (see also FAO 1960). The Soil Map of the World published by FAO/UNESCO (1974) is the world's first soil map with a uniform classification throughout.

This map is still relatively imprecise (1.4 cm^2 represents 6250 ha), and larger-scale maps exist for only a few regions. It can be assumed that it will gradually be adopted worldwide, at least for the purposes of simple, international map-making and broad comparisons. The World Soil Map is not based on any one system, but is rather a collation of national soil maps influenced by the U.S. system. The soils that occur in a particular region and exhibit a certain relationship to one another are grouped together in associations or "major soil units".

In the following sections some of these units, with their most important characteristics, will be described. In addition, some important terms needed for characterization are defined (based on BURINGH 1979 and others). Some of the terms used to identify soil units are defined in Table 2.20.

The legend of the FAO world soil map (FAO/UNESCO 1974) includes tables correlating the FAO system with various national systems (see also DUDAL, 1968, pp 11-18).

Histosols (0)

Histosols are organic or peat soils with an organic surface layer of $\geq$ 40 cm. They contain at least 20-30% organic matter, depending on clay content. About 1% of tropical soils are Histosols. These soils are problematic for agriculture because they are usually wet. Their use is possible after draining, but is associated with rapid humus depletion. Histosols occurring over small areas are often used for vegetable growing, or else for reed production (*Cyperus, Phragmites*).

Table 2.20. Some terms used in the FAO nomenclature to identify major soil units

Acric	extremely poor in nutrients
Argillic	horizons with clay accumulation
Chromic	soil with deep brown or red-brown B horizon
Dystric	base saturation < 50% (relatively poor in nutrients)
Eutic	base saturation > 50% (relatively rich in nutrients)
Ferralic	soil with Ferralsol properties, low CEC, high in Fe-, Al-oxides
Ferric	soil with iron concretions (ca. 2 cm ϕ)
Gleyic	soil with hydromorphic properties at 0-50 cm depth
Haplic	soil with less strongly developed typical characteristics
Humic	soil with "umbric" horizon, i.e. relatively humous
Mollic	dark A horizon with high base saturation
Ochric	relatively weakly defined A horizon without "mollic" and "umbric" characteristics
Orthic	normal soil formation; no special features
Oxic	oxidic, complete mineral weathering; porous, permeable (referring to B horizon)
Plinthic	with plinthite from 0 to 125 cm (laterite develops from plinthite)
Rhodic	bright red
Vertic	Vertisol characteristics (swelling, shrinking)
Xanthic	bright yellow

Lithosols (I)

Lithosols are very shallow soils (<10 cm deep) on bedrock. They possess little available soil volume for root extension and offer crop plants scant growth potential (water, nutrients). They dry out quickly. Where rainfall is abundant, the thin surface layer must be guarded from erosion. Trees and shrubs with their more extensive roots, are more able to penetrate to deeper strata than are annual crops and are often the best form of utilization.

Vertisols (V)

Vertisols are very heavy clay soils (≥ 30% clay) which develop wide, deep cracks in the dry season. Their topsoil has a characteristic microrelief (Gilgai). In the subsoil smooth slikensides form through the swelling and shrinking of the abundant three-layered clay minerals.

Vertisols occur predominantly in basins with sluggish drainage or on broad plains with variably moist climates. They are characterized by high base saturation and high CEC (up to 60 m.e./100 g soil). Their real and potential nutrient capacity is normally high. Despite their dark color Vertisols contain only 1-3% organic matter. Their pH value is ≥ 6. The availability of P and K is fairly limited.

Vertisols have poor physical properties. Their tendency to swell makes them prone to waterlogging, and working them while moist is almost impossible. They are equally difficult to work when dry, since they become exceedingly hard. These soils can be improved by proper drainage, notably through broadbed-and-furrow cultivation.

Applying organic fertilizer is essential for maintaining and improving fertility, since it improves the structure of these densely layered soils (YOUNG 1976). Because of the difficulty of working Vertisols, they are traditionally used as grazing land or, when more intensively managed, as a hay meadow or for growing fodder crops.

Alternatively, farmers may use them to plant water-tolerant annual grain crops during the main season, or to raise a late-planted crop on residual soil moisture after the rains have ended.

On a limited scale, nutrients that accumulate in valleys can be brought back up to the leached out slopes via livestock manure (see LUDWIG 1967 and MILNE 1947).

Fluvisols (J)

Fluvisols are young alluvial deposits in river valleys, estuaries and coastal regions. They do not form any distinct horizons other than ochric, histic and sulfic horizons (see below).

The natural yield capacity of Fluvisols greatly depends on the parent material from which the sediments are derived (young material rich in bases, or weathered, base-poor material). Generally, Fluvisols are found in some of the highest-yielding areas of the tropics, such as the Indus and Ganges Deltas. Rice, jute, sugarcane, fruit and vegetables, and also grain and other fiber plants, are often grown on Fluvisols.

The profile often changes within short distances. Clay films, lime horizons, salinization (especially associated with irrigation) and lack of water volume or a high groundwater level, can limit root extension and yield capacity. Periodic waterlogging can be expected in most Fluvisols. Intensive use often leads to nutrient impoverishment, humus depletion, and a deterioration in structure. Care must therefore be taken to maintain nutrient levels and organic matter to ensure that the biological potential of these soils can be exploited on a long-term basis (see FAO 1981).

Solonchaks (Z)

Solonchaks are structureless saline soils with free salts (often with accumulations of salt on the surface). They occur in arid regions and generally have a high groundwater level with a high salt content (chlorides, sulfates).

Solonetz soil (S)

This is a highly alkaline soil ($pH \geq 8.5$) with more than 15% sodium saturation. It exhibits a typical columnar structure in the B horizon.

Gleysols (G)

Gleysols are hydromorphic soils. In other words, their characteristics are developed in the presence of water. They are waterlogged almost throughout the year. Under a sometimes thick organic layer, they exhibit a friable, light-colored layer of clay that graduates into a water-impermeable stratum where typical manganese concretions are found. The CEC is moderate and P and C contents are usually above average.

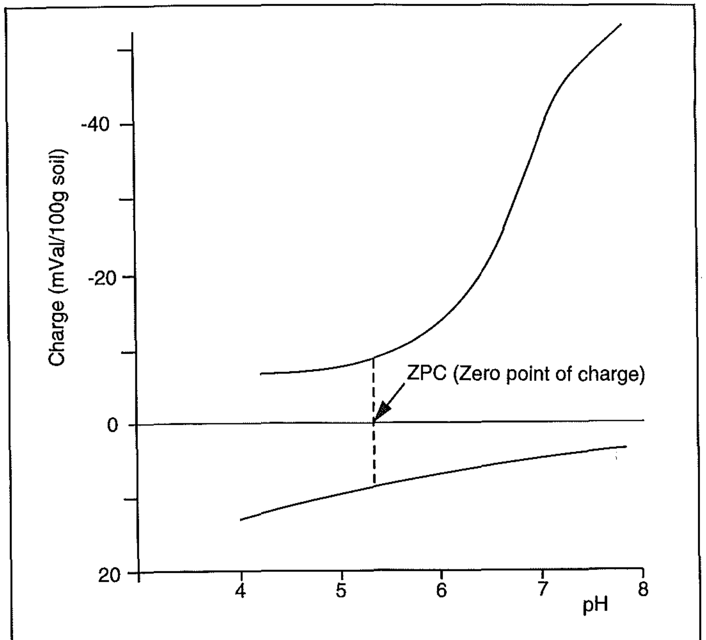
These soils occur in depressions and plains of the humid and subhumid tropics and vary widely in character (mollic, plinthic, etc). Impermeable layers, anaerobic conditions and poor workability make it difficult to use Gleysols for agricultural purposes. Only shallow-rooting plants that tolerate waterlogging are suitable (oil palms, napier grass, sao palms and others). Traditionally, Gleysols were used as good grazing land. MILNE (1947) recommends intensive fodder cropping (see Vertisols).

Andosols (T)

Andosols are soils developed from volcanic ash. They frequently form a heavy topsoil with dark humus (up to 30% organic matter). The specific density (around 0.85 g/cm^3) is very low compared with other soils (1.4 to 1.6 g/cm^3). Most Andosols are well supplied with water and have a high water-holding capacity. Constant weathering causes a continuous release of nutrients, permitting permanent agricultural use. Acidic reaction and Phosphorus deficiency (partial sorption of phosphorus on allophane and clay-humus complexes) often limit productivity (see Section 2.3.2). Acidic Andosols, which possess a high variable charge because of the allophane and humus, can be improved by liming, which raises the pH level and improves the sorption characteristics (see Figure 2.27).

Andosols occur mostly in mountainous regions of the humid tropics (Indonesia, South America, East Africa). Erosion control is absolutely essential to safeguard valuable soil on cultivated slopes.

Figure 2.27. Charge relations of an Andosol (subsoil) derived from rhyolite, New Zealand*



*Clay fraction: approximately 100% allophane

Source: SCHEFFER and SCHACHTSCHABEL (1982)

Arenosols (Q)

Arenosols are sandy soils with various B horizons which, in diagnostic terms, fall below the threshold of the definition "moderately pronounced". The Arenosols include soils of several groups. Lower clay content and a higher proportion of sand (more than 50%) lend them special characteristics.

The sands and loamy sands are relatively structureless and easy to work, and usually have a low C content. They possess good root permeability and water volume, but also dry out very quickly. Under conditions of less than about 1000 mm annual rainfall, they have a base saturation of more than 40%, with a slightly weak acidic to neutral reaction. At over 1000 m annual rainfall, Arenosols are mostly acidic with a base saturation of less than 40% (YOUNG 1976).

When cultivating these soils, care must be taken to maintain the organic matter (depletion should not be intensified through frequent tillage). They can be improved with applications of stable manure. Deep-rooting plants are more suitable than those with shallow roots.

Podsols (W)

Podsols are pale, sandy soils in the topsoil under raw humus. They have a bleached, white-gray E horizon, and humus colloids and sesquioxides accumulate and harden in the B horizon. Podsols develop in the tropics only on poor quartz sands, and sometimes in mountainous regions on argillite (schist). These soils are strongly acidic and poor in nutrients, and are virtually useless for agriculture. They are often occupied by azidophilic vegetation (e.g. rhododendrons). If necessary they can be lightly used as forest and grazing land.

Ferralsols (F)

Ferralsols are deeply weathered, uniformly red, yellow-red or yellow soils, composed mainly of kaolinite clay (cemented through iron oxides), sesquioxides and gibbsite. Ferralsols are typical soils of the constantly humid tropics. The absence of weatherable minerals resulting from heavy leaching and weathering (down to 2 m deep and more) in the past means that these soils are poor in nutrients. The cation exchange capacity is less than 20 m.e. per 100 g clay, the CEC of the soil as a whole is usually less than 10 m.e. per 100 g, and the pH values are mostly under 5. The profiles are very deep, uniformly weathered and leached (down to 50 m and deeper).

According to the FAO classification system, the soils have a B horizon in which iron oxides have accumulated. The profiles do not exhibit any clear differentiation in structure and coloring. A friable structure is typical. Blocky structures disintegrate very readily to a floury consistency. Shiny clay films are completely absent (compare Nitosols). Ferralsols normally have a high hydraulic conductivity and favorable aerobic conditions, and are easily penetrable by roots.

These favorable characteristics contrast with their sometimes low water-holding capacity and poor nutrient status (N, P and sometimes also S). In addition, iron and aluminum toxicity occur. Annual crops can be grown only at great risk, as they lead to the rapid loss of organic matter (2 to 5%), to erosion, and to a drop in soil fertility after only 2 to 3 years. The only forms of use possible in the long term are field-fallow systems with long fallow periods or forest-like forms which keep the nutrient cycle closed and the ground constantly covered. The export of nutrients must be kept to a minimum.

Where fertilizers are applied (e.g. on oil palm plantations), they are better utilized on humus-rich Ferralsols than on soils with a low humus content (BURINGH 1979).

Nitosols (N)

Nitosols are rich red to red-brown in color, lessivated[29], clay-rich soils of the humid tropics. They have a horizon with clay concentration and no abrupt borders, which gradually becomes poorer in clay with increasing depth. Nitosols do not have hydromorphic, lateritic or Vertisol-like horizons, but instead exhibit a deep, uniform profile that permits good root extension and has a high usable water-holding capacity. They are derived from base-rich rock (e.g. basalt, mica, schist) and still have remnants of weatherable minerals from which a limited amount of nutrients can be supplied. Kaolinite is dominant. The cation exchange capacity (CEC) is about ≥ 20 m.e. per 100 g of clay.

The name comes from the Latin word "nitidus" (shiny) and refers to the characteristic shiny clay films of the polyhedral aggregate surfaces. This typical feature distinguishes Nitosols from Ferralsols or Luvisols. The soil structure of Nitosols is loose to friable. The Nitosols are among the relatively productive soils of the tropics. In Africa, where they represent 1 to 2% of tropical soils according to YOUNG (1976), they support cocoa, banana and coffee. These soils are moderately at risk from erosion, but with care and management of the organic matter and preferably constant ground cover, they can support permanent cropping.

Because of their good physical properties, these soils can support high yields, provided fertilizer applications are regular and well balanced.

Acrisols (A)

Acrisols are old, acidic clay soils with low base saturation (less than 50%) and a pronounced clay-enriched horizon (Bt) derived from lessivation (clay deposits) and clay accumulation. The name derives from the Latin *acris* (sour). Developed from base-poor, quartz-rich parent rock (granite, sandstone), they are typical of the subhumid tropics. Acrisols are chemically impoverished, particularly in the subsoil,

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[29] Lessivated soils are soils with accumulations of clay in the subsoil (B horizon).

where aluminum, iron and manganese toxicity can occur. They are often deficient in nitrogen and trace elements.

The physical characteristics of Acrisols are mediocre to poor. The dense B horizon often limits root penetration and water volume. Hydromorphic and lateritic characteristics frequently develop.

Permanent cropping on these soils demands considerable skill. It is especially important to maintain or increase the organic matter, owing to the high risk of erosion. Characteristically, these soils experience an imbalanced water regime and, with the depletion of humus, tend to puddling and compaction (ROOSE 1981). The method of tillage must take these problems into account. Where cropping is carried out without appropriate measures to prevent erosion and protect humus, Acrisols are often eroded down to the Bt or lateritic horizon (YOUNG 1976).

Acrisols are commonly used for crops, but yields tend to be low. According to SANCHEZ (1976) and BURINGH (1979), grazing and forestry are the best uses (in a natural state: andropogon grasses, shrub savannas). Cautious liming can improve fertility to some degree, but often does not penetrate as far as the subsoil. Additional measures may be necessary because of micronutrient deficiencies.

Luvisol (L)

Like Acrisols, Luvisols have a typical clay-enriched horizon, but also higher base saturation (over 50%). They are therefore better suited for crop growing than Acrisols[30].

Vertisol-like characteristics or "ferric" properties with iron oxide concretions are widespread in Luvisols. Red and deep brown ("chromic") B horizons occur, as well as lateritic, hydromorphic and in semi-arid regions lime-enriched ("calcic") horizons.

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[30] In the US Soil Taxonomy, the dividing line between an Ultisol (corresponds to Acrisol) and an Alfisol (Luvisol) is set at 35% base saturation, the aim being to distinguish soils of extremely low base status from otherwise similar soils.

These soils are suitable for crop growing, but the risks are similar to those for Acrisols (See also ROOSE 1981; LAL and GREENLAND 1979).

Cambisols (B)

Cambisols are brown soils. They undergo little or no ferrallitization, lessivation or podzolization. Weathering is only slight; that is, there is almost no accumulation of the products of weathering.

Cambisols are soils with borderline characteristics similar to brown forest earth. The somewhat weathered B horizon may be richer in clay and reddish in color (The original carbon content has usually been extensively leached out.). However, these features are not pronounced enough to be able to speak, for example, of iron-enriched ("oxic") horizons, etc.

Cambisols are often found at tropical mountain sites. The proportion of weatherable minerals is greater than 3%, and the CEC is over 16 m.e./100 g clay. These soils usually possess good cropping characteristics, with good root permeability and little tendency to compaction. The water capacity and nutrient properties strongly depend on texture and parent material.

2.3.7 Classification according to the U.S. Soil Taxonomy

The U.S. Soil Taxonomy (SOIL SURVEY STAFF 1975) is the most comprehensive and logical system presently existing for the worldwide classification of soils. Important horizon characteristics and the nomenclature within each order are quantitatively defined, using primarily chemical and morphological criteria. BURINGH (1979) therefore speaks of a "morphological" system. The names of soils consist almost entirely of Latin and Greek syllables.

The great disadvantage of this system is that many soils can be classified only through precise laboratory tests, which are often not possible to arrange. In the field, therefore, soils can often be categorized only very roughly.[31]

Different definition criteria and thresholds also mean that a comparison (for example, with the FAO nomenclature) is often possible only in one direction. Thus a Gleysol in the FAO Legend is not always an Aquept, because there are many suborders with the syllable "Aqu-" to which the FAO term "Gleysol" could refer.

"Soil Order" is the first level of the U.S. Soil Taxonomy. It contains ten names ending with "sol" (summarized from BURINGH 1979; SCHEFFER and SCHACHT-SCHABEL 1982).

In this first level, the soil names correspond closely with FAO nomenclature (see Table 2.21), so that the names can therefore be compared from left to right and from right to left. This is not possible further down the classification system.

Some soils in the FAO Legend appear only in the second category of the U.S. taxonomy. In the table, the underlined letters are used to form the names of suborders, with the letter group of the suborder placed in front. For example: 1st Order Ultisol, Suborder Aquic; the soil receives the name Aquult. The most important suborders are shown in Table 2.22.

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[31] If, for instance, a lessivated savanna soil has more than 35% base saturation, it is an Alfisol; if less, an Ultisol.

Table 2.21. "Soil Order" of the U.S. Soil Taxonomy, compared with FAO classification

1. Ent - isol	Underdeveloped recent soils with few or faint horizons (FAO: Regosols, Arenosols, Fluvisols)
2. Vert - isol	(Lat. vertere = to turn); Dense, dark soils high in swelling clay (FAO: Vertisols)
3. Inc-ept-isol	(Lat. inceptum = beginning); Weakly developed soils with a B horizon (cambic horizon) but no other diagnostic horizons (FAO: Cambisols, Fluvisols)
4. Ar-id-isol	(Lat. aridus = dry); Soils with characteristics of dry climates. Arid moisture regimes, poor in humus (FAO: Yermosols, Xerosols)
5. M-oll-isol	(Lat. mollis = soft); Soils with a deep, dark and humus-rich (mull) A horizon (FAO: Chernozems, Kastanozems)
6. Sp-od-osol	(Gr. spodos = wood ash); Soils with a podzolized (pale, leached) B horizon (FAO: Podsols)
7. Alf - isol	(from pedalfer = old name for soils completely leached of carbon); Soil horizons with clay accumulation, but still moderate base saturation (V > 35%) (FAO: Luvisols, Nitosols, Acrisols with V > 35%)
8. Ult - isol	(Lat. ultimus = last); Tropical soils with horizons of clay accumulation, highly weathered silicates and low base saturation (V < 35%) (FAO: Acrisols, and partially Nitosols and Luvisols)
9. Ox - isol	(from oxide); High in sesquioxides, highly weathered, leached soils (inner tropics(FAO: Ferralsols)
10. H-ist-osol	(Gr. histos = web, fiber); Peat and other organic soils with a deep layer of humus (FAO: Histosols)

Source: SOIL SURVEY STAFF (1975), FAO/UNESCO (1974)

Table 2.22. The most important categories used to formulate tropical suborders

Alb-	(Lat. albus = white); Having a pale ("albic") alluvial horizon
And-	(Jap. ando = dark soil); Volcanic ash soil, corresponds to Andosols (FAO)
Arg-	(Lat. argilla = clay); Having a horizon with clay accumulation (argillic horizon)
Ferr-	(Lat. ferrum = iron); High in iron
Fluv-	(Lat. fluvius = river); Alluvial soil, corresponds to Fluvisols (FAO)
Hum-	Rich in humus
Ochr-	(Gr. ochros = pale); Having a light A horizon
Orth-	(Gr. orthos = genuine); Normal formation
Psamm-	(Gr. psammos = sand); High sand content, sandy texture corresponds to Arenosols and some Regosols (FAO)
Trop-	(Eng. tropical); Constantly warm, humid

Source: Compiled from SOIL SURVEY STAFF (1975)

Table 2.23. Terms describing the moisture regime of soils

Aqu-	(Lat. aqua = water); Aquic, i.e. soils with hydromorphic features in these soils the subsoil is almost always moist or saturated; corresponds to Gleysols and Gleyic Soils (FAO)
Ud-	(Lat. udus = humid); Udic means that the soils are usually moist (dry for less than 90 days, i.e. pF < 4.2 equals 15 bar)
Ust-	(Lat. ustus = burned); Ustic means that the soils are moist for more than half the year and up to 90 days in a row or dry for a total of 180 days
Xer-	(Gr. xeros = dry); Xeric, i.e. semi-arid climate
Torr-	(Gr. torridus = dry); Torric, essentially dry, desert climate

Source: Compiled from SOIL SURVEY STAFF (1975)

The suborders are further divided into "Great Soil Groups", which roughly correspond with German soil types (SCHEFFER and SCHACHTSCHABEL 1982). The names for these are formed by adding further syllables (more than 50) in front of the assembled names of the suborders. Here are a few examples: "Acr-" stands for soils that are extremely weathered. An "Acr-orth-ox" is an extremely weathered, acidic, true Oxisol (corresponds to an Acric Ferralsol in the FAO nomenclature). "Palae-" is used for soils with advanced development. A "Palae-ust-ult" is a highly developed Ultisol with a dry summer moisture regime.

The next categories (subgroups and families) are formed by adding adjectives. For example: "Rhodic Palaeustult" - as above, but with an unusually deep red color. Also important are the terms describing the moisture regimes of soils. These are shown in Table 2.23.

2.3.8 The French Classification System

The French classification system or Système ORSTOM (Office de la Recherche Scientifique et Technique d'Outre-mer) as described in AUBERT (1964) and YOUNG (1976), is used in all former French African countries. It is a natural classification system, based on climate and soil genetics (degree of development), and groups soils primarily according to morphological, physical and chemical properties. The soils are divided into a hierarchy of ten classes, subclasses, groups and subgroups. The classes are listed in Table 2.24.

Most of the typical tropical and Mediterranean soils fall under Class VIII, which embraces the sesquioxide-rich soils with mull-like, mineralizing organic matter. This Class is divided into three subclasses:

1. **Sols rouges et bruns Méditerranéens ou subtropicaux** (Red and brown Mediterranean and subtropical soils). These are characterized by their relatively high iron oxide content and silicate-rich compounds, and are further divided into groups and subgroups according to color, clay accumulation, degree of crusting, etc.

Table 2.24. Classes of the French system

I	Sols minéraux bruts (raw soils)
II	Sols peux evolués (weakly developed soils)
III	Sols calcomagnésimorphes (calcimorphic soils)
IV	Vertisols et Paravertisols (Vertisols and Vertisol-like soils)
V	Sols isohumiques
VI	Sols à mull (mull humus soils)
VII	Podzols et sols podzoliques (podzolized soils)
VIII	Sols à sesquioxydes et à matière organique rapidement minéralisée (Mediterranean and tropical weathered soils)
IX	Sols halomorphes (saline soils)
X	Sols hydromorphes (hydromorphic soils)

Source: ORSTOM, cited in AUBERT (1964) and YOUNG (1976)

2. **Sols ferrugineux tropicaux ou fersiallitiques** (soils with iron oxides or fersiallitic soils). These are soils with a high content of free iron, but not of free aluminum. The base saturation of the B horizon is higher than 40%. They are divided into two groups according to the accumulation of clay particles:

- **Sols ferrugineux non lessivés** (without clay accumulation)
- **Sols ferrugineux lessivés** (lessivated with clay accumulation)

The *sols ferrugineux non lessivés* are again divided into two subgroups according to whether or not the upper horizon is poor in iron sesquioxides as compared with the lower horizon.

The *sols ferrugineux lessivés* are divided into four subgroups: those with concretions, those without concretions, soils with hardening, and soils with pseudo-gleying (prone to occasional waterlogging).

3. **Sols ferrallitiques** (ferrallitic soils) are soils with free iron and aluminum, sesquioxides of iron and, to a greater or lesser extent, aluminum. This subclass is divided into four groups:

* **Sols faiblement ferrallitiques** (moderately ferrallitic soils): The decomposition and weathering of the minerals in these soils is not very advanced; the ratio of SiO_2/Al_2O_3 in the colloid particles is still ≥ 2 and the content of weatherable material may still be quite substantial. These can be strongly desaturated (*désaturé*) or sometimes still possess a considerable proportion of unweatherable poor clay (*ferrisolique*). Subgroups further distinguish *sols faiblement ferrallitiques* with hydromorphic characteristics or hardening.

* **Sols ferralitiques typiques ou fortement ferrallitiques** (typical ferrallitic soils): these display the typical characteristics of the subclasses. They are almost completely weathered, leached, poor in nutrients, high in free iron and aluminum and have a Si_2/Al_2O_3 ratio of less than 2. They are grouped according to the color of their A and B horizons: red, yellow, beige, and those with yellow over red horizons. A further subgroup with hardening and crusting is also distinguished.

* **Sols ferrallitiques lessivés** (lessivated, ferrallitic soils): in these soils, one of three situations may obtain: (a) only the bases in the upper half of the profile may be strongly leached out, while the other colloidal particles appear relatively evenly through the whole profile; (b) the profile may possess accumulations of sesquioxides, clay and bases; or (c) the profile may be hardened and have heavy accumulations in the subsoil (laterite). These soils are divided into three subgroups, depending on which of these situations obtains.

* **Sols ferrallitiques humifères** (humus-rich, ferrallitic soils): this group contains the ferrallitic soils with at least 6% organic matter in the upper 20 cm of soil. These soils are divided into black, brown, and red-brown subgroups. In addition a distinction is made between the very acidic raw humus soils and the humous ferrallite of mountain sites.

2.3.9 Comparison of some important soil types according to the various systems

Table 2.25 compares the soils of the tropics according to the FAO, U.S. Soil Taxonomy and French classification systems.

Table 2.25. Approximate correspondence of some important soils of the tropics

FAO	U.S. Soil Taxonomy	French Classification
FLUVISOLS	Fluvents	Sols minéraux bruts et sols peu évolués d'apport alluvial et colluvial
REGOSOLS	Psamments Orthents	Sols minéraux bruts et sols peu évolués d'apport éolien
ARENOSOLS		
Ferralic A.	Oxic Quartzipsamments	Sols ferralitiques moyennement ou fortement désaturés (à texture sableuse)
GLEYSOLS		
Eutric G.	Tropaquepts	Sols hydromorphes peu humifères à gley
Dystric G.		
Humic G.	Humaquepts	Sols humiques à gley
Plinthic G.	Plinthaquepts	Sols hydromorphes à accumulation de fer en carapace ou cuirasse
ANDOSOLS	Andepts	Andosols
PLANOSOLS		
Eutric P.	Paleudalfs	Sols ferrugineux tropicaux lessivés
Dystric P.	Paleustalfs	
CAMBISOLS		
Dystric C.	Dystropepts	Sols ferrallitiques fortement et moyennement désaturés, rajeunis
Eutric C.	Eutropepts	Sols ferrugineux tropicaux (non lessivés); Sols ferrallitiques faiblement désaturés, rajeunis
Humic C.	Humitropepts	Sols ferallitiques fortement et moyennement désaturés, humifères, rajeunis
LUVISOLS	Tropudalfs Paleudalfs Paleustalfs	Sols ferrugineux tropicaux lessivés
ACRISOLS		Sols ferallitiques fortement désaturés
Rhodic A.	Rhodudults	Sols ferralitiques désaturés lessivés
	Rhodustults	Sols ferrallitiquement désaturés lessivés
FERRASOLS	Oxisols	Sols ferrallitiques
LITHOSOLS	Lithic subgroups	Lithosols et Sols lithiques

Source: Adapted from the FAO World Soil Resources Report No. 33 (1968), Revision Sept. 1970 (from AUBERT and TAVERNIER 1972)

Table 2.26 presents some soil descriptions in English as they used to appear in the literature and are still sometimes used today. On the left of the table are the old names and on the right the corresponding names in the FAO system, which does not describe the same soil in every case, but does generally agree in most points.

Table 2.26. Some commonly used older soil descriptions and their corresponding names in the FAO system

Alkali soils	-	Solonetz and soils containing Na
Alluvial soils	-	Fluvisols
Black cotton soils	-	Vertisols
Dark Red Latosols	-	Orthic and Acric Ferralsols
Desert soils	-	Yermosols and Xerosols
Ferrallitic soils	-	Ferrasols and/or Ferric Acrisols
Ferruginous soils	-	Ferric Luvisols and/or Ferralic Cambisols
Fersiallitic soils	-	Acrisols
Grumusols	-	Vertisols
Hydromorphic soils	-	Gleysols and Gleyic soils
Immature soils	-	Regosols
Kaolisols	-	Ferralsols
Meadow soils	-	Gleysols
Muck soils	-	Histosols
Organic soils	-	Histosols
Terra rossa	-	Chromic Luvisols
Terra Roxa Estruturada	-	Eutric Nitosols and Luvisols
Terra Roxa Ligitima	-	Rhodic Ferrasols
Tropical Podzols	-	Humic Podzols
Volcanic soils	-	Andosols

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