Chapter 1
Soils of the Tropics

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1.1 Introduction

The Tropics of Cancer and of Capricorn, located 23½°N and S respectively, broadly define the area we recognise as the tropics and within which we find tropical environments. Whilst these limits are to a degree arbitrary, they do provide recognisable boundaries. Natural boundaries also occur in some parts of the world, for example in South Asia, where the Himalayas form a natural boundary, although this actually reaches 34°N. Within this "tropical" area, some have argued that there are no such things as tropical soils, merely soils found within this inter-tropical zone. Whilst there are soils within this zone which have strong similarities with soils found beyond these tropical limits, there are a number of soils and soil development processes which are specific to this zone. This is particularly the case within the humid and sub-humid zones of this region, where the soil environment is characterised by periods of intense weathering and leaching. In many cases there is a further distinguishing feature about these soils; their development in this region has been uninterrupted for many hundreds of thousands of years and possibly millions of years.

1.2 Factors of Soil Formation

Soils form in response to their environmental context. Historically, this relationship has often been expressed in the form of a soil-forming equation, where the nature of the soil is considered as a function of the interactions between various environmental factors. This relationship between soils and the environment was first introduced

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in the second half of the nineteenth Century by a Russian soil scientist, Dokuchaev, but it is probably most widely known by the presentation of Jenny (1941).

Jenny suggested that the nature of soils and their development was influenced by what he described as the *Factors of Soil Formation*:

1. Climate
2. Parent material
3. Relief or topography
4. Organisms (vegetation and soil fauna)
5. Time

Latterly, many have suggested that mankind should be added as a further and often very significant factor, because our impact on the soils has in many situations dramatically altered both the nature of the soils and their development, and perhaps more importantly their use.

1.2.1 Climate

By definition, in the tropics there are relatively small differences in temperature during the year. In the lowland tropics (approximately 87% of the land area of the tropical zone), mean annual temperatures are normally above 25°C. Where the mean annual soil temperatures are above 22°C and the temperature range throughout the year is greater than 6°C, the soil temperature regime is described as *hyperthermic*, and where the range in soil temperatures is less than 6°C it is described as *isohyperthermic*.

There are marked differences in terms of the rainfall distribution within this zone and consequently in the soil moisture regimes. Approximately 24% of this zone has a high annual rainfall, frequently in excess of 3,500 mm, well distributed through the year, and is often characterised, under natural conditions, by closed canopy forest. The soil moisture regime under these conditions is described as *udic*, in which the soil is not dry for as long as 90 cumulative days. This zone is often described as the *Humid Tropics,* with a natural vegetation frequently characterised by a forest cover. For much (approximately 49%) of the tropical zone, the climate is distinguished by pronounced wet and dry season(s). The soil moisture regime characteristic of this zone is *ustic*. The broad concept of this moisture regime is that the soil remains dry for part of the year (90 or more consecutive days), but when moisture is present, conditions are suitable for plant growth. This zone, often described as the *Seasonally Moist* or *Seasonally Arid Tropics*, is often characterised by a natural vegetation cover of grass and non-continuous, often low-stature tree cover. The remainder of the zone has a semi-arid or desert climate where evaporation exceeds precipitation in most months; here the soil moisture regime is described as *torric*, where soils are moist for 90 or less days per year.

Whilst the broad context of soil development is determined by the climatic conditions, local variations will occur because of the modifying influence of the other environmental factors.

1.2.2 Parent Material

Parent material is the material from which the soil is derived. Whilst in many cases the original material from which the soil has developed will be found unweathered below this soil itself, there are frequently circumstances where the soil is developed in a relatively thin layer of superficial material which has been deposited over the underlying rock by transporting processes involving water, wind or mass movement.

The properties of the parent material which significantly affect the nature of the soil are the degree of consolidation, the grain size and the composition. Coherent and impermeable rock materials which are not fissured will offer only a limited surface area for weathering, and consequently these processes will occur only at the surface. In contrast, fissured and loosely consolidated material will expose a large surface area, and weathering will take place more extensively throughout the material. Where the soils are developed on transported, unconsolidated materials, soil development can begin immediately. Where soil development takes place on consolidated fresh rock, there must be weathering of this rock material before soil development can begin. The grain size of the parent material determines the texture (the relative proportions of sand, silt and clay) of the soil. For example, a parent material such as sandstone, with a composition including a substantial proportion of sand-sized quartz, will weather to give a sandy soil; in contrast, a fine grained material such as basalt will weather to produce a predominantly fine-textured soil. Parent material composition strongly influences the nature of tropical soils and the soil processes which operate, together with the nature of the overlying vegetation and the agricultural potential of the soil. Whilst there are detailed classifications of rock materials, a relatively straightforward approach is to use the proportion of silica present in the material as the basis for classification:

- *Felsic* parent materials have not less than 66% total silica, which includes quartz and combined silica. These soils often contain free silica as quartz and orthoclase and plagioclase feldspars, and muscovite and biotite. When freshly exposed, these materials are often pale in colour.
- The *Intermediate* group of parent materials have between 55% and 66% total silica, and contain quartz, plagioclase, less orthoclase and some ferromanganese minerals such as hornblende.
- The *Basic* (or Mafic) parent materials have less than 55% total silica, and contain ferromanganese minerals such as hornblende, olivine and augite and limited amounts of plagioclase. These materials are often dark coloured when newly exposed.

In broad terms, Basic rocks will weather more rapidly than Felsic rocks. It is important to note that soil development in the tropics has in most cases been taking place for long periods of time, and the parent materials have been subject to sustained weathering and leaching during this development.

Because of the intensity and in many cases the long duration of the weathering processes which the parent materials have been subjected to, the mantle of weathered material at the earth's surface is often of considerable thickness. This weathered mantle is generally referred to as the *Regolith* and, particularly in the tropics, what we recognise as soil development may often only be clearly evident in the upper parts of the regolith.

1.2.3 Relief or Topography

There are many strong influences on the nature of soil through relief or topography. There is the indirect influence that for every 1,000 m increase in altitude there is an adiabatic fall in temperature of 6°C. This fall in temperature will greatly affect the rate of most chemical and biological processes in the soil, and hence influence the rate of weathering and the decomposition of organic matter. The hydrological variations within a landscape will also influence the nature and pattern of the soils, with the soils in the upper part of the slope/topographic system generally being freely drained and soils in the lower parts often receiving solutes and particulate materials from upslope, and often being characterised by poorer drainage conditions.

1.2.4 Organisms

Organisms as a soil-forming factor include both vegetation and soil fauna. Of the soil organisms, termites, earthworms, bacteria and fungi are particularly important in the key task of the incorporation of organic residues from the surface of the soil and dead root material from within the soil, breaking these materials down physically and chemically to release plant nutrients, and to produce relatively stable organic by-products which may have key roles in affecting other soil properties such as aggregate stability.

There is a strong two-way relationship between soil and vegetation in both natural and cultivated environments. Soils exert an influence on the type of vegetation present, and the vegetation will influence the soils and soil processes through the addition of organic residues to the surface, which play a key role in nutrient cycling. Vegetation also induces changes in soil moisture because of its demands arising from plant respiration, its action as a "protective" cover at the surface and, where the plants are leguminous and able to establish nitrogen-fixing rhizobial symbioses, its input of nitrogen-rich residues to the soil. Most important amongst these effects is the input of organic residues to the soil surface.

1.2.5 Time

Time is very different from the other soil-forming factors, because its influence is in determining the duration of the interactions between the soil and the other environmental factors. Through time, the nature of these relationships will change. In much of the tropics, there is strong evidence to suggest that many soils have been developing at a site for many hundreds of thousands of years and possibly millions of years, although not necessarily under the same combinations of environmental factors. Time is a factor which distinguishes tropical soils and soil development in the tropics from the cool temperate climates where during the Pleistocene the landscape was glaciated or subject to periglacial conditions and the soil cover removed or disrupted, with the consequence that soil development in these areas has often occurred over much shorter periods of time, possibly as little as a few tens of thousands of years.

1.2.6 Man

Increasingly, man is recognised as a major influence on many ecosystems. Crutzen (2002) suggested that the influence of man has been so great that we should distinguish the period of this influence as a separate geological epoch, the Anthropocene. If we consider soils in general, it is evident that man has had a major influence on the nature of many soils through soil management practices, and in broader context through environmental changes. This is certainly true in the tropics, although the period of major human intervention in many parts of the tropics is much shorter than in other parts of the globe. There have been major soil changes and extensive degradation of soil as a result of inappropriate management, and many tropical soils have been degraded as a result of broader environmental changes. Often because of the inherent properties of the soils in this region and the nature of the tropical environment, tropical soils have less resilience to these changes and are often more rapidly degraded.

1.3 Soil-Forming Processes

Soil-forming processes are often associated with the type of soil that results when the process is operating, for example a Podzol is the product of the Podzolisation soil-forming process. These processes which may be described as *Composite Processes* represent different combinations of a range of basic or *Specific Processes*. The composite processes will have some of the specific processes in common, but the key differences are in their relative magnitudes and duration.

The specific processes include a range of processes which might be considered as transformation processes in which minerals (weathering) and organic materials (decomposition) are altered. In transfer processes, materials are moved within the soil (the transfer may in some cases follow from the transformation of materials). In removal processes, materials are lost from the soil system completely. While the specific processes will occur in all regions of the globe, under tropical conditions their absolute and relative intensities may be greater because of the higher temperatures and duration of soil wetness.

Water plays a key role in many of these processes. Within the soil, water occurs as the soil solution, and the volume of water present in the soil at a particular time will depend on the climatic regime of the soil and its capacity for retaining water and allowing water to flow through the soil, either vertically or laterally. In an udic moisture regime the soil will be moist for much of the time, and differences in the nature and intensity of specific processes will depend upon the water retention characteristics and the flow of water through the soil. In contrast, under a torric moisture regime the soil will be moist only infrequently. Soils with an ustic moisture regime will have periods when the soil is moist and periods when the soil is relatively dry. Of importance are not only the presence of water, but also its nature, principally its temperature, pH and solute content.

Chemical transformation of minerals (weathering) includes the breakdown of primary minerals and the synthesis of secondary minerals (important amongst these are the clay minerals such as smectite, illite and kaolinite). In cases where these processes have occurred at high rate and intensities or for long periods of time, the secondary minerals will also be subject to strong weathering, with transformation of smectite clays to kaolinite, illite to kaolinite and kaolinite to gibbsite. Minerals vary markedly in their susceptibility to this chemical transformation. In broad terms, quartz and muscovite are the most resistant to chemical weathering; feldspars and biotite form part of an intermediate group and orthoclase is the least resistant. This sequence of weathering susceptibility does not differ significantly between tropical and other climatic zones, but the rates of weathering tend to be higher and the duration of the weathering longer in the tropical zones because of the higher temperatures of the water and possibly because the soil solutions are often more acidic.

Transfer of materials within the soil will be as solutes in the water moving through the soil. The soluble products of the weathering processes are removed from the soil through the process of leaching. The effectiveness of the leaching depends on the volume of water passing through the soil, the temperature and pH of the water, and its rate of flow through the soil. The materials released during the weathering process also vary in the ease with which they can be leached. The following considers broad groups of materials in terms of the relative ease with which they can be leached under normal conditions in the soil.

- *Soluble salts* (e.g. chloride and sulphates) are readily removed when leaching occurs.
- *Exchangeable cations* (e.g. Ca^{++}, Mg^{++}, K^{+} and Na^{+}) are very soluble and readily lost under moderate leaching. Silica has a low solubility in the pH range 3.5–8.0, and quartz has a very low solubility.

- The solubility of *iron* is dependent on its speciation; in broad terms, ferrous iron (FeO) is relatively soluble, but ferric iron (Fe_2O_3 or FeOOH) is relatively insoluble. Under free drainage, iron is predominantly found in the ferric forms, so is considered to be only of very limited solubility. Where there is high groundwater, the iron may be reduced to the ferrous form, and hence its solubility (and mobility) increases.
- *Aluminium* occurring in the form Al_2O_3 is soluble only at very low pH values, and in most soils is considered immobile.

The silica:sesquioxide ratio has been used as an indicator of the degree of weathering and leaching. In many soils, particularly those in temperate regions, this ratio is well above 2.0, but in the tropics, as the weathering releases silica and this is removed, there is a relative accumulation of sesquioxides (iron and aluminium oxides). In many tropical soils this ratio is below 2.0. When weathering is intense and iron is removed, the silica:alumina ratio is used. This will fall below 2.0 only where weathering and leaching are intense.

Under freely draining conditions where the dominant processes are strong weathering and leaching, and where these processes have been operating uninterrupted for long periods of time, the soil that develops will be deeply weathered, with diffuse boundaries between the horizons. The subsurface horizon under these conditions is often known as an oxic (Soil Taxonomy — see Sect. 1.4) or ferralic (WRB — see Sect. 1.4) horizon. These horizons are often relatively thick (greater than 30 cm), have a low percentage of weatherable minerals, a low ability to retain and exchange cations (cation exchange capacity), and a very small proportion of the fine earth of the soil in the silt fraction, and are often clay-textured. These horizons are often characterised by a fine, sand-sized stable aggregation of the clay, sometimes referred to as pseudosands. Because of this fine stable structure, the horizons often have a high hydraulic conductivity. Water flow through these soil horizons is often described as biphasic, with an initial rapid percolation through the macropores and a second flow, much slower in the microporosity. Nortcliff and Thornes (1989) suggested that this may explain why the chemical composition of the groundwater under these horizons does not reflect the composition of the water in the micropores. A distinctive feature of these horizons is that, particularly when the iron content is high, phosphate and other anions may be strongly adsorbed.

In addition to the transfers and removals in solution, there may also be transfers as suspensions. A key process involving suspension is the vertical translocation of clays. The clays are removed from upper layers as a result of physical or chemical dispersion (eluviation), transported in colloidal suspension in the water flowing vertically through the soil pores and fissures, and deposited on the surfaces of the pores and fissures at depth within the soil (illuviation). This processes is particularly marked where the clays are smectitic or illitic, and less prominent where the clays are predominantly kaolinitic. This process of clay translocation is favoured by processes which facilitate the dispersion of the clays: these may be physical, such as the rapid wetting of soil material at the end of a pronounced dry period, or chemical, where the soil solution contains mineral and organic material which facilitates dispersion. Where these processes are actively operating, there may be a marked vertical contrast in the distribution of clay, with distinctive decreases in the upper part of the soil from the zone from which the clay is being eluviated, and an increase in clay (sometimes referred to as a *clay bulge*) in the lower part of the soil. Where deposition has occurred it is possible, using soil thin sections and microscopic analysis, to identify clay skins (also referred to as argillans or clay cutans) which have distinct characteristics, such as a narrow range of particle size compared to the bulk of the soil, and orientation in the clays which provides evidence of a transporting process acting on materials in suspension. Where the deposition is clearly evidenced, the horizon is often described as an argillic (Soil Taxonomy) or argic (WRB) horizon.

Lateral translocations include both movements in solution through soils at different positions in the landscape and movements in solution and suspension over the surface. These processes will strongly influence the nature and patterns of soil found at different positions in the landscape.

1.4 Soil Classification

Soil classification is to many soil scientists the starting point for a disagreement! In the past, the classifications were often based on soils within national boundaries and divisions were made to accommodate the soils that were found nationally and the relative balance between different soil types. Within the tropics, particularly the African tropics, the soil classification in use in a particular country often reflected that of the Colonial “ruler”, hence there were systems that had broad principles derived from British, French and Belgian soil scientists. The countries of former French Africa used in the past a broadly common system; there was a markedly different system within what was the Belgian Congo; within the former British Africa there were often locally relevant classifications. Initially, there were few attempts to relate national classifications to any form of international standard, or to see any form of cross-referencing to aid interpretation across national boundaries.

In 1960, the USDA introduced a system of classification which sought to classify all soils of the world (Soil Survey Staff 1960). Initially called “Soil Classification: A Comprehensive System, 7th Approximation”, this system revolutionised soil classification in that it sought to introduce a whole new set of terminology and established limits for class units within the classification. This has been widely used and much revised, and has changed its name to Soil Taxonomy, the most recent version of which was published in 1999 (Soil Survey Staff 1999). Within Africa and as a result of the collaboration of Belgian and French soil scientists, D’Hoore (1964) produced a monograph which described the soils included in the 1: 5,000,000 Soil Map of Africa, and was a product of the Commission for Technical Co-operation in Africa (CCTA). In 1974, FAO produced the legend to the Soil Map of the World (FAO-UNESCO 1974), which whilst not a true soil classification provided broad indications of classes and soil types.

Today there are two widely used international soil classifications; the above mentioned Soil Taxonomy and the World Reference Base for Soils (WRB), which has its roots in the Soil Map of the World produced by FAO-UNESCO. Both classification systems use the identification of horizons which are diagnostic of the operation of particular soil-forming processes or combinations of processes influenced by the nature of the soil-forming factors. They recognise the importance of soil climates in determining the nature of the soils, and seek to set limits for the membership classes. Both are the subject of ongoing appraisal and revision, and the most recent version of WRB was published in 2007 (IUSS Working Group WRB 2007). Whilst there are some similarities between these two widely used soil classification systems, and there have been attempts in recent years to seek to reduce the differences in the diagnostic characteristics chosen and the limits set for membership, there is still no universal agreement on which should be used. Because of this, I have chosen to approach the description of the soils using the broad climatic zones present in the lowland tropical regions, and seek to refer to similar soils classified within these two schemes.

1.5 The Soils

Within the tropics there are probably occurrences of soils also found in extra-tropical regions, but there are a limited number of soils which are predominantly found in the tropical zone and are to a degree characteristic of this zone.

1.5.1 Soils of the Humid Tropics

The zonal soils of the humid tropics, often associated with a natural vegetation of rainforest, are characterised as deeply weathered, with low inherent fertility and strong acidity. The soils have an udic moisture regime, and as a consequence are moist throughout most of the year; they are characterised by intense weathering and rapid leaching. The soils are very varied in terms of colour, but red, dark red, reddish yellow and yellow colours predominate. Within the CCTA Soil Map of Africa (D'Hoore 1964) these soils were described as *ferrallitic soils*, and have broad equivalents in *Oxisols* (Soil Survey Staff 1999) and *Ferralsols* (IUSS Working Group WRB 2007).

These soils exhibit weathering to depths of 10 m or more, particularly where development is on crystalline rocks. The soil profiles are deep, but often lack clearly recognisable horizons. There are differences with depth within these soils, but the differences are transitional rather than abrupt. The soils are often described as structureless with textures often described as clayey, but where the clays are finely aggregated into pseudosands they may feel loamy-textured. Hydrologically, the soils often behave as loamy-textured soils with high hydraulic conductivities, but may also show the biphasic nature of water flow referred to above (see Sect. 1.3).

The intense weathering and rapid leaching results in the rapid breakdown of most minerals and a residual concentration of resistant primary minerals, iron and aluminium oxides and hydrous oxides and quartz. Quartz will often remain as the sand fraction, but most other minerals will be weathered to clay-size materials, with very little silt-size material remaining. These minerals have low cation exchange capacities, which is a characteristic feature of these soils. The soils have organically enriched layers at the surface. Because of the high productivity of natural vegetation systems developed in these soils, there is a large input of organic debris at the surface. Nonetheless, as a consequence of the environmental conditions which are conducive to rapid degradation of these materials, the organically enriched surface layers are not deep. Because of the importance of the nutrients cycled through the vegetation, dense networks of fine roots are often found in the upper layers of these highly weathered soils and within the organic litter at the surface; these roots may access the nutrients released during organic matter decomposition. Stark (1971) and Jordan (1985) have suggested this as evidence for an almost closed nutrient cycle in natural tropical forested environments, where the bulk of the nutrient pool is held in the biomass rather than in the mineral soil.

In summary, these soils, particularly in their subsurface horizons, often have the following broad characteristics:

- Acidic to strongly acidic pH values: pH below 5.5 and often below 5.0
- Low cation exchange capacity: less than 20 $cmol_c$/kg, but often much lower
- Low to very low base saturation: usually below 20%
- Silt: Clay ratio of less than 0.15 and often lower
- Low content of weatherable minerals in the silt and fine sand fraction
- Silica:sesquioxide ratio below 2.0
- Silica:alumina ratio may be below 2.0
- Kaolinite (1:1 type) is the dominant clay mineral with rare 2:1 minerals
- Gibbsite [$Al(OH)_3$] is present
- High exchangeable Al may occur in some soils

Soil Taxonomy identifies the *Oxic* horizon and the WRB the *Ferralic* horizon, with some or all of the above characteristics, as diagnostic of these soil-forming environments.

These soils generally have good physical properties; they are deep, with rapid permeability and strong microstructure. Because of the good structure and rapid permeability, these soils are not normally susceptible to erosion unless poorly managed. Because of the high hydraulic conductivity characteristic of these soils, plants may suffer moisture stress during dry periods. This may be particularly marked if, because of aluminium toxicity in some soil layers, the plant roots are not able to fully exploit the moisture held in the full depth of the soil.

As mentioned above, most nutrients are held in the biomass; for this reason the nutrient pool is rapidly depleted, and the soils will sustain only low levels of renewed plant growth if the process of nutrient cycling is interrupted by removal of the vegetation. On clearance of the natural vegetation, it is therefore essential that strategies are introduced to maintain soil organic matter levels and to recycle nutrients through the biomass. These may involve mulching, manuring, agroforestry or periods of fallow.

In addition to the low levels of plant nutrients provision from the mineral fraction, these soils have a high potential to fix phosphorus. In addition, given the low pH conditions found in these soils, aluminium toxicity may be a constraint on plant growth (see Chap. 10). The conditions of low nutrient status are further exacerbated by the rapid leaching common in these soils. If nutrients are released through normal weathering or added as organic or inorganic fertilisers, they will be rapidly leached from the system.

1.5.2 Soils of the Seasonally Moist Tropics

The zonal soils of the seasonally moist tropics are often associated with vegetation comprising grassland and low-stature, often sparse trees. Such vegetation is known locally as Savanna (Africa) and Cerrado (Brazil). The corresponding soils are characterised by moderate to intense weathering and leaching, with a well-developed clay-enriched B horizon (known as an argillic horizon in Soil Taxonomy and an argic horizon in WRB, which also identifies a *nitic* horizon as a clay-enriched subsurface horizon where the enrichment may be due to illuviation and in situ weathering). There is more input of moisture from precipitation than loss through transpiration and evaporation in some seasons, and during this time water and materials in solution are leached from the soil. Within the CCTA Soil Map of Africa (D'Hoore 1964) these soils were described as *ferruginous soils*, and have broad equivalents in *Ultisols* where the soils have a relatively low base status, and *Alfisols* where the soils have higher base status (Soil Survey Staff 1999), and in *Alisols*, *Nitisols* and some *Lixisols* (IUSS Working Group WRB 2007). The soils exhibit a wide range of colours, but are commonly red, reddish brown or yellowish red. These reddish colours are caused by the separation and dehydration of iron compounds in the sharply contrasting wet and dry seasons.

In contrast to the Ferrallitic soils of the humid tropics, these soils are relatively shallow, with depth to weathered rock not normally exceeding 2.5 m. The less intense weathering and leaching will normally result in higher contents of weatherable minerals. The distinctive feature of these soils is the development of the textural B horizon. In addition to showing the clear "clay bulge" referred to above, this horizon will normally have clear evidence of translocated clays in the form of clay cutans or argillans.

Many of the soils of this climatic zone have higher base status than the zonal soils of the humid tropics, but the range of base saturation is large, from below 30% to as high as 90%. Because the soil is moist for only part of the year, weathering is moderately intense. The contrast between wet and dry parts of the year results in the release of iron oxide during the wetter parts of the year and its dehydration during drier parts. This process, known as rubefication, gives the often characteristic red colours commonly found in these soils. During the wet season(s) the soil will be close to field capacity. During and immediately after rain, excess water will drain rapidly, leaching soluble constituents. In the dry part of the year, the upper horizons dry out and leaching ceases.

Whilst the soils of this climatic zone are diverse, there are some broad characteristics which summarise many of these soils:

- The soils are weakly to moderately acid, with a pH generally above 5.5.
- The silt:clay ratio is low but often above 0.15.
- Clay minerals are predominantly kaolinite and the oxides and hydrous oxides of iron, but some 2:1 minerals are present.
- The cation exchange capacity is normally above 15 $cmol_c$/kg.
- Silica:sesquioxide ratio is normally below 2.0.
- Silica:alumina ratio is above 2.0.
- Gibbsite is very uncommon.

The range of soils developed in this zone will vary in response both to the number and duration of the periods of soil moisture and to the nature of the parent material from which the soils have developed. Soils with lower base saturation, developed on low base status parent materials or where leaching has been more intense, include the *Ultisols* of Soil Taxonomy with a base saturation in the B horizon less than 35%, and the *Alisols* in WRB. Both these soils may also exhibit low pH surface layers, and Al toxicity may occur at relatively shallow depth, inhibiting the growth of some plants. Aluminium toxicity is often more common in the low base status soils in the seasonally moist tropics than under humid tropical conditions. *Alfisols* (Soil Taxonomy) are characteristic of soils developed on higher base status parent materials and where weathering may be less intense. Whilst the WRB allows no direct comparison, the WRB *Lixisols* and *Nitisols* tend to be of higher base status, and correspond to some of the *Alfisols* found in tropical regions.

The soils found in this region vary considerably in their agronomic potential, but most have a higher fertility than soils of the humid tropics. Where the soils are developed on base-rich parent materials, the soils may be considered locally very fertile. The supply of water is markedly seasonal, and plants must be capable of surviving periods of drought or be able to grow during the periods when the soil is moist. Soil organic matter levels are lower in these soils than under rainforest, and a key task when these soils are managed is to maintain soil organic matter levels through additions of manures and plant residues. Because of the relatively high levels of free iron, phosphorus may be fixed and as such be a limiting nutrient for plant growth unless carefully managed. During the dry season, the surface layers from which clay has been lost may harden and, although this is temporary and generally disappears once the rain starts, the initiation of normal land preparation may be delayed as a consequence. If the loss of clay from surface layers is combined with marked declines in soil organic matter, the surface soil may become unstable and the soil may become vulnerable to erosion, particularly at the onset of the rains following the dry season, when the soil is afforded limited protection by plant cover. Particularly vulnerable are poorly managed soils on sloping lands. Management must ensure that the erodibility of the surface soil material is reduced and that infiltration capacity is maintained or improved both to prevent the loss of soil and to ensure that rain infiltrates into the soil.

1.5.3 Other Soils

The two broad groups of soils described above are those which are found predominantly in the tropics and subtropics. Where the climate is *torric*, the soil is moist for less than 90 days. Under these conditions, weathering is severely restricted, and leaching is often a very rare event. Materials which are brought into solution during periods when the soil is moist may be transferred within the soil profile rather than leached out at the base. With this limited leaching, salts may accumulate in the soil profile, giving rise to halomorphic soils; where carbonates accumulate, calcimorphic soils develop.

A widely occurring but not extensive soil in the tropics is the *Vertisol*. The Vertisols are dark, churning, heavy clay soils which develop on relatively flat environments on base-rich parent materials. They are subject to limited leaching losses because of arid conditions and impeded drainage. The soils have a high proportion of clays which swell on wetting and shrink on drying, forming wide cracks from the surface as they dry out. When dry, they are extremely hard and massive, and may break into large prismatic structures. When wet, the soils are sticky and plastic and have a very low permeability. These soils occur within the Tropics under *udic, ustic* and *torric* moisture regimes, with consequent very marked differences in the periods when the soils are wet. Their base status will be strongly influenced by the nature of their parent materials.

Laterite, frequently referred to in the context of the soils of the tropics, is a material for which there are many local vernacular terms. Unfortunately, the materials covered by these terms are exceptionally varied. The first documented description of laterite is by Buchanan (1807). Buchanan was working in India, and described a material that when found in situ could be cut easily, but once left exposed to the atmosphere hardened irreversibly. In its hardened form it was being used locally as bricks, hence the name, which was coined from the Latin for brick, *later*. This contrast between the soft nature of the material when freshly exposed and the hardened nature after exposure has resulted in the material being widely discussed, although it may not be particularly extensive in some parts of the tropics. Since the initial description by Buchanan, the term laterite has been used for a very wide range of both soft and hardened materials.

More recently, the term has been replaced in Soil Taxonomy by the term *plinthite* and in WRB by the *plinthic horizon*. Whilst there are differences in details between the two definitions, they do have broadly similar meanings. They derive not from the Latin for brick but from the Greek! Plinthite is described as an iron-rich, humus-poor mixture of clay with quartz and other minerals. It changes irreversibly to an ironstone hardpan or to irregular aggregates on exposure to repeated wetting and drying, especially if exposed to the heat of the sun.

Plinthite forms by the segregation of iron. The iron may be derived in situ or may have been transferred vertically from other horizons or laterally from other soils. Plinthite normally forms in a horizon that is saturated with water for part of the year. Under these conditions, iron is segregated in the form of soft, more or less clayey, red or dark red redox concretions, formed as a result of iron migration under anaerobic conditions and subsequent deposition in localised concentrations when aerobic conditions prevail; these concretions will irreversibly harden on exposure to repeated wetting and drying. Plinthite is firm when the soil is moist and hard when the soil is dry. Plinthite includes much of what has previously been described as laterite.

1.6 Conclusions

Whilst the tropics cover a diverse range of environments and environmental conditions, in terms of soils and soil development the key characteristics are the relatively high temperatures of the lowland tropics and the rainfall patterns and distributions. Many soil processes operate only when the soil is moist: consequently, the characteristics of the rain regime, with some regions experiencing year-round rainfall and other regions marked wet and dry seasons, will strongly influence the nature of soil development. The relatively high temperatures experienced in the lowland tropics will also markedly affect the rate of the processes which operate.

Many of the temperate landscapes of the globe were markedly affected by Ice Ages during the Pleistocene period, when soil development was severely curtailed. In many cases, soils were stripped from the surface of the land, and soil development had to commence on freshly deposited materials after the ice had retreated. By contrast, the tropics have probably had uninterrupted soil developments in some parts of the region for many hundreds of thousands of years. It is unlikely that all of the conditions of soil formation which prevail today have persisted throughout this period, but nevertheless soils have been subject to suites of development processes over very long time periods, and the nature of the soils is likely to reflect this. As a consequence, many of the soils of the lowland tropics exhibit features which are not seen in soils in other regions.

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