Introduction to the study of soils in tropical and subtropical regions

Second edition

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Preface to the second edition

This book deals with regional soil science and covers the occurrence, properties, characteristics, genesis, classification and agricultural evaluation of soils in the tropics and subtropics. It is intended for young soil scientists who have followed courses in soil science and who want to know more about the most important soils of tropical and subtropical regions. This book may be useful too for students of agriculture, geography, biology, ecology, irrigation, land reclamation, land classification, and town and country planning. The first edition was sold out within a year. I received a number of suggestions for improvement and have revised all chapters; Chapter 2 has been completely rewritten.

The soils are described in a general way. For details, such as descriptions and analysis, I have referred to the literature. I have tried to concentrate on the main facts and on the main soils.

I wish to express my great appreciation to all the soil scientists who have sent me remarks, and who have encouraged me to work on a second edition which I hope will be of particular interest for soil scientists in tropical and subtropical countries, who are sadly lacking in textbooks. A Spanish edition of this book will be published by Editorial Blume in Barcelona. Suggestions for improvement will again always be welcome.

Wageningen, April 1970

1 General introduction

1.1 Concepts, terminology, classification

There is much confusion in soil science, in particular on tropical and subtropical soils, because quite different definitions, terms, names and systems of classification are often used; each group of soil scientists may have their own system. Various soils have not yet been adequately studied; field data and laboratory data may be incomplete or incompatible because of different methods and techniques. Some methods of analysis developed for soils of temperate regions cannot be used for tropical or subtropical soils. In many tropical countries, soils have hardly been studied. Since the end of World War II, the international exchange of knowledge has increased considerably through soil studies under the auspices of FAO, United Nations Special Fund, the International Bank of Development and Reconstruction, UNESCO, some foundations and governments. Such work has been stimulated by the International Soil Science Society, Regional Soils Science Conferences, Arid Zone Research Institutes, some other soil research institutes, and by the World Soil Map being compiled by FAO and UNESCO.

Although knowledge is continually increasing, tropical soil science is still in its infancy. Good research institutes are still too scattered in the tropics. Research work must be increased, in order to base development on scientific principles. As international co-operation has increased and soil scientists have moved more freely from country to country, it has become easier to compare soils and to transfer knowledge and experience on soils in one country to similar soils in other countries.

In this introduction we will often use general broad concepts, defined by some specific characteristics. Generally the terminology and concepts used are as explained in the Soil Survey Manual, 1951 (SSM), of the United States Department of Agriculture (USDA) and in the Comprehensive System of Soil Classification, 1960-7 (CSSC), of the USDA. French, German and sometimes Dutch names are often given too, especially when they are completely different. However it must be realized that the definitions and concepts in these languages are often not equivalent. The classification of soils often is given here for the higher categories of the former USDA system of soil classification and of the CSSC, and sometimes reference also is made to the French or some other systems of soil classification. It is outside the scope of this textbook to deal in detail with these systems; only some important characteristics are given; more accurate definitions and details should be sought in the original publications.

1.2 Environmental conditions

There is an extreme diversity of soils in tropical and subtropical regions of the world. They range from young fertile volcanic soils to very old, often infertile, red tropical soils. There are also the completely arid soils, almost without any soil profile, and the wet soils of equatorial regions, where water percolates almost continuously to deeper soil layers. If such soils are compared with the often better known soils of temperate regions in Western Europe, the Soviet Union, Australia and America, several distinct characteristics and properties can be noticed, even though they all result from the same soil-forming factors and are formed by similar processes (e.g. oxidation, reduction, soluviation, leaching, transport and accumulation). However weathering and soil formation are often quite different in the tropics, because of important differences in soil climate and in biological processes. In the humid tropics and subtropics, weathering is more severe and intense. Processes of soil formation also are more active and often continuous. The fundamental reactions act in several combinations. The relative importance of these fundamental reactions, their combinations and the more complex processes of soil formation determine the ultimate nature of the soils. Some typical characteristics of the factors of soil formation will first be briefly described. For more details, see textbooks of soil science and of ecology.

Climate

The temperature in the tropics is generally warm (25°C) and rather constant. In desert regions it may rise to more than 50°C whereas in subtropical continental deserts there may be frost during the winter. There is also a very great range in annual precipitation, usually 3000-6000 mm in the humid tropics but over 10 000 mm in some wet equatorial regions and almost zero in some extremely arid regions. Besides these variations there is also extreme diversity in precipitation between seasons (alternating dry and wet seasons) or during the day. Heavy showers of 6 mm per minute and daily totals of 600 mm do occur occasionally. Unlike rain in temperate regions, rainwater in the tropics is warm, a very important fact.

Climate (atmospheric or overhead climate) is classified by several systems such as those of Thornthwaite, Lang or Köppen. The weather is almost constant in some regions and extremely variable in others. Many soils in the tropics and subtropics are very old, even Tertiary, their formation being influenced by changes in climate in the Pleistocene Era, as Pluvials and Interpluvials. Many old soils therefore are polygenetic.

Vegetation

Natural vegetational type in any region is closely related to climatic type. For example it may be a dense tropical forest consisting of multifarious species of plant, or it may consist of a few sparse grasses in arid regions. For soil formation these differences are quite important, because the production or organic matter may vary from almost nothing in a desert to several tons per ha in a tropical forest. Organic matter governs various processes, in particular the biological activity of soil.

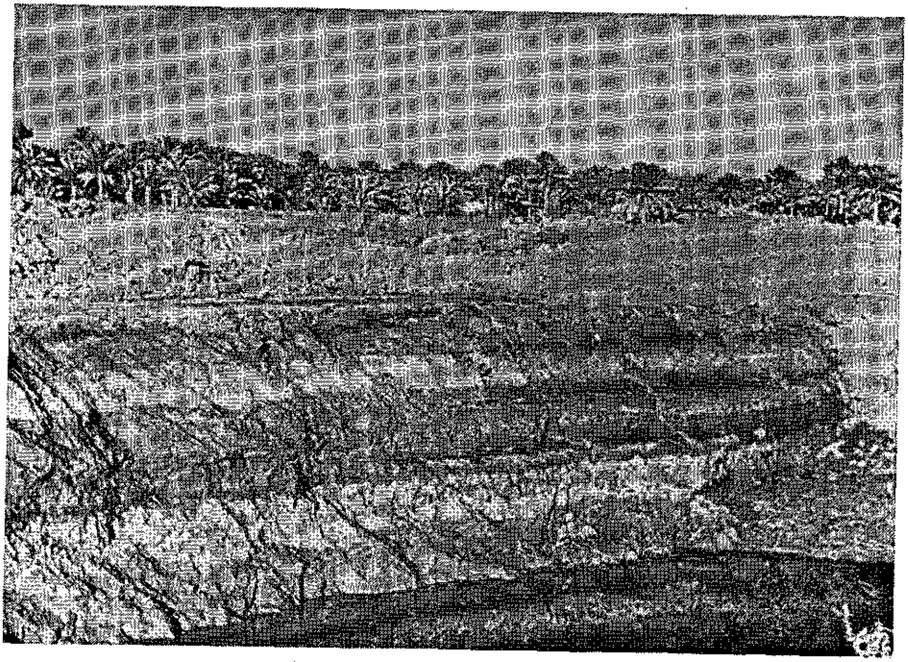
Time

Some soils in the tropics are extremely old, devoid of bases and even without weatherable minerals. Others are very young, with soil formation hardly begun. In the humid tropics, where soil formation proceeds almost continuously, soils can be altered in a short period; yet in arid regions, lack of moisture slows down many soil processes, so that changes are hardly detectable, even over several centuries.

Parent material

The soil parent material (Fr. roche mère; Ger. Muttergestein) is quite different in the various regions. Often the material, that has undergone some cycles of weathering and soil formation, is transported and deposited again, forming a new but already entirely weathered parent material (Fr. roche fille).

An extreme type of parent material is formed by fresh pyroclastic material produced by active volcanoes. Fresh volcanic ash may be transported in the wind over huge distances (thousands of kilometres), rejuvenating old soils on which they are deposited.



Stratified Alluvial soil in the Plain of Mesopotamia in Iraq.

Relief, topography

Erosion, colluviation (movement of material to the foot of slopes by gravity) and sedimentation as induced by variations in topography have affected many soils, in particular in regions with old soils. Another important effect is the relation of altitude to air temperature. In the tropics this temperature decreases about 0.6°C for every 100 metres rise in altitude. Thus high mountains in the tropics and subtropics have a kind of temperate climate.

Man

Almost everywhere in the world, the influence of man on soil formation is considerable. Clearing of forest, cutting of bushes and shrubs, and burning of savannas are normal practices of shifting cultivation. In steppe regions, overgrazing is common. Many soils are or have been cultivated; their profiles are often shallower than those of 'natural' undisturbed soils nearby. Various alluvial plains and deltas of arid and semi-arid tropical and subtropical countries are irrigated, so soil condition sometimes may change considerably; new sediments may be deposited on older land, or salinization may affect soils.

Hydrology

High watertables in arid and semi-arid tropical and subtropical regions often cause the accumulation of soluble salts in the rooting zone of soils. Floods and tides often inundate large areas in river plains, estuaries and coastal lowlands, which are rarely protected by dikes; few rivers have dams and barrages to control floods. Artificial drainage is hardly known in most tropical en subtropical countries.

These examples are only illustrations of how tropical and subtropical conditions are often different from those well known from temperate regions, as described in many textbooks.

1.3 Internal soil conditions

The differences of tropical and subtropical soils from temperate soils can almost all be ascribed to the special nature of soil-forming factors, chiefly soil climate and soil biology.

The soil climate or pedoclimate in the humid and wet tropics encourages rapid soil formation. The water that penetrates and percolates soils is always warm (24°-25°C), on average over 15°C warmer than in Central or Northern Europe. The soil is much warmer too. Results are:

a. Ionization of water is four times as high as at 10°C
b. Silica is eight times as soluble
c. Solution proceeds much quicker
d. Less CO_2 penetrates the soil
e. The hydrolytic power of the solution is much higher
f. Soil water is less viscous
g. More water penetrates deeper in the soil.

These effects are important, because they indicate soil-forming processes and differences in soil characteristics and properties from those in temperate regions. This is the most important reason why a special branch of soil science has developed for the study of tropical soils: tropical soil science (Fr. sols tropicaux, science des sols tropicaux; Ger. tropische Böden, tropische Bodenkunde; Du. tropische gronden, tropische bodemkunde).

Another important fact about climate is that the total amount of water that penetrates soil is less than total precipitation, because of surface run-off and considerable evaporation from the leaves of plants and from soil. Even in flat regions of the tropics effective rainfall is often less than three-quarters of the precipitation.

In arid regions total precipitation is very limited and falls in a few months. Many soils have a thin surface crust or surface seal, and almost no vegetation. There too, effective rainfall is much less than total precipitation. Much of the water that penetrates at all into the upper layer evaporates rapidly; the subsoil, being continuously dry, is called the 'dead horizon' (Fr. horizon mort de sécheresse). In semi-arid regions there is a similar effect but less pronounced.

In the subhumid regions wet and dry seasons alternate. The total monthly precipitation in 'dry' months in such areas is less than 60 mm. The length of the dry season in the tropics is important. Soil formation takes place only during seasons when the soil is moist, so that pedogenetic processes are normally discontinuous.

Biological processes in the soil depend mainly on the contents of organic matter and moisture, and on soil temperature. The most intense biological activity is in warm and moist soils of the humid tropics. The vegetation produces much organic matter but is rapidly decomposed. Mineralization of organic matter is most important. Under natural tropical forest, percentage organic matter is almost constant in the soil. In wet equatorial regions, where organic production is often maximum, mineralization is also important. But temporary wet conditions slightly delay decomposition of organic matter; there is some humification too and some humic acids may percolate quickly through the soil, causing some podzolization.

In bush savanna, biological activity is rather intense during the moist season; at least when it is hot. Rapid mineralization for a short period keeps the content of organic matter almost constant. In semi-arid regions with sparse grass, production of organic matter is slow and decomposition is rapid.

The favourable warm moist aerated conditions and open structure of soils and the high production of organic matter induce high biological activity in most tropical regions. Plants root deep; there is often a thorough biological homogenization of the upper soil layer for a metre or more. Such soils are porous, with an irregular pore system and high permeability.

Classification of soil climate is more important than of atmospheric climate for soil science. Soil temperature, moisture content in relation to the permeability, structure and water-storage capacity are factors that may vary considerably during the year.

In true tropical soils the difference between the average summer and winter soil temperature (at 50 cm depth) is less than 5°C. In the subtropics this difference is more than 5°C, often even 10° or 15°C. Soils with a dead horizon must be distinguished from those that are always moist. The dead horizon may be present continuously at shallow or medium depth, or may be seasonal. Soils that are always moist may be grouped into those through which large, moderate or small amounts of water percolate to the deeper layers. The biological activity of the soils is closely related to these pedoclimatic classes.

1.4 Important groups of soils

In this book the soils of tropical and subtropical regions will be arranged in some broad groups, each characterized by a specific soil climate and inherent soil-forming processes. Other characteristics often show wide variation, and there are many soils, called intergrades, with intermediate characteristics.

Arid and semi-arid soils have a permanent or seasonal dead horizon because of scarse precipitation. They occur in some tropical but more particularly in subtropical regions.

The main processes are calcification and gypsification (accumulation of lime or gypsum at some depth below the surface). Characteristic soils are: Desert soils, Sieroziems, Reddish-Brown and Brown Subtropical soils. They are classified mainly as Aridisols (CSSC) and occur in desert, semidesert and dry steppe regions; they cover about 30 % of the earth surface.

Halomorphic soils often occur in similar dry regions (arid and semi-arid soils) and in low coastal regions. These soils are saline, saline-alkali or alkali (sodic) soils. Saline soils are characterized by the accumulation of harmful soluble salts in the soil; alkali soils have a high proportion of sodium ions in the base-exchange complex, which gives the soil rather poor physical properties; solods are strongly degraded soils. The respective processes are called salinization, alkalization and solodization. According to morphometric soil characteristics Solonchaks, Solonetses, Solodized-Solonetses and infrequently Solods occur. These soils are intrazonal soils. Many saline soils result from poor practices of irrigation.

Ferrallitic soils are old tropical soils, occurring in the humid and wet tropics. Excess rainwater percolates through the soil, leaching bases and silica, and increasing the proportion of sesquioxides in the alluvial horizon. The soils are very deep, very permeable, and are often uniformly red. The main process in soil formation is ferrallization, and in some soils influenced by groundwater also plinthization.

Characteristic are the Lateritic soils, in some countries also called Latosols, Kaolisols or Ferralsols. Most of the Ferrallitic soils belong to the orders Oxisols and Ultisols (CSSC).

Ferruginous soils are old soils too. They also are often red but are normal in depth. Their soil climate is alternately dry and moist. The dry season is also the warm season.

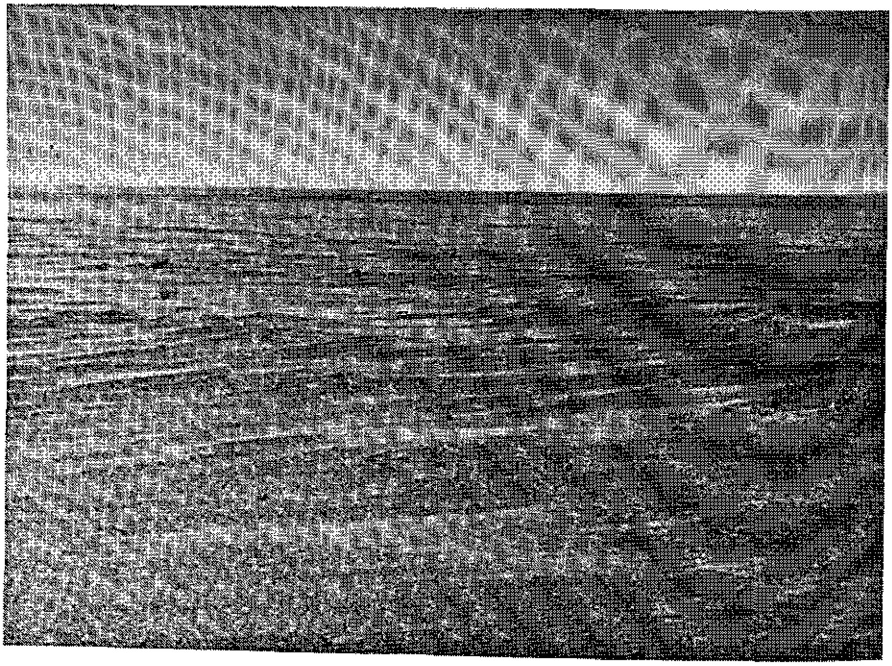
The main soil-forming processes are argillation (Fr. lessivage d'argile; Ger. Tondurchschlämmung) by which a textural B horizon with an accumulation of fine clay (argillic horizon) is formed, rubefaction (formation of red iron compounds) and to a lesser extent ferrallization.

In subtropical regions with a warm dry summer and a cool wet winter, Red and Brown Mediterranean soils, including the Terra Rossa, are the most important representatives of Subtropical Ferruginous soils. There rubefaction is the main pedogenetic process.

Alluvial soils occur in floodplains, estuaries, on seashores, in former lakes and old irrigated regions. They are azonal soils. The parent material has been deposited recently and is often highly stratified.

The initial processes are geological, in particular sedimentation, forming characteristic patterns in alluvial areas common to the whole world. The pedological process is soil-ripening, comprising initial soil formation from mud, gleying, and the formation of acid sulphate soils.

Alluvial soils occur in all countries and are often called floodplain soils, estuary soils, marsh soils, lacustrine soils and irrigational soils. Specific soils are Sawah soils and the very acid Cat-Clay soils. Many soils in this group have been called Hydromorphic soils. Some Alluvial soils of tropical and subtropical regions have characteristics entirely different from those of temperate regions, because the parent material (Fr. roche fille) has been intensely altered by several cycles of weathering and soil formation before it was transported and redeposited. Most Alluvial soils now are classified as Fluvents in the order of Entisols and as Aquepts in the order of Inceptisols, if they also have the typical characteristic of wetness, due to a high watertable (CSSC).



Duststorm on an alluvial plain in the Sudan on the Red Sea coast. In many areas of the world soil material is transported and redeposited either by wind or by water.

Vertisols are very heavy dark montmorillonitic clay soils, that shrink during drought and swell when wet. Characteristic morphological phenomena are gilgai microrelief and slickensides in the subsoil.

Besides cracking and swelling, self-mulching and churning are typical soil-forming processes. These soils are known as Black Tropical soils, Regur soils, Black Cotton soils, Tirs, Dark soils of tropical and subtropical regions, Margallitic soils and since 1951 as Grumusols. In CSSC they belong to the order Vertisols, which occur in many countries, in particular India, the Sudan and Australia.

Andosols are soils formed in ashy volcanic parent material, that are dark, almost black. They have a high moisture capacity and are fertile. There is an initial process of soil formation, that accompanies the rapid weathering of the fresh volcanic sediments. This results in the formation of allophane, an amorphic hydrated aluminium silicate of varying composition. Sometimes, especially in the coarser andesitic parent material, a duripan is formed. These soils have distinctive characteristics and occur wherever volcanoes are still active (e.g. Indonesia, Hawaii). They always differ from surrounding non-volcanic soils and have completely different agricultural potentialities.

Tropical Podzols are developed in very poor quartz sands in some tropical lowlands. In mountainous regions various podzolic and forest soils occur, similar to those of temperate regions.

All these soils will be examined in later chapters. The most important processes, soil characteristics and properties will be mentioned. Soils described here are typical representatives. In the field the situation is often complicated by intergrades covering larger areas than the typical soils.

1.5 Agricultural evaluation

The capacities of tropical soils are often expressed as natural fertility, based mainly on the presence of minerals which can weather and release plant nutrients. In dense tropical forest the soil is often expected to be fertile but after reclamation fertility declines sharply and crops yield poorly. Arid and semi-arid irrigated soils are considered fertile because of their high productivity relative to unirrigated dry soils of the desert nearby. Natural fertility is high only in recent Volcanic soils and in some Alluvial soils. In modern agriculture low natural fertility is no longer a problem, because all necessary plant nutrients can be added as fertilizers, although for some tropical soils there are practical difficulties over how to apply them. The problem for modern agriculture is the physical condition of soils, rather than natural fertility.

There are various limiting factors, that prevent high crop yields: e.g. soil salinity and alkalinity; shortness of the growing season due to climate or floods; restricted drainage; occurrence of hard pans; water deficit. The problem of low yields and the often primitive or traditional agriculture in various tropical and subtropical regions is not primarily a soils problem; it is mainly a problem of poor social and economic conditions. Soils need not be evaluated for subsistance farming; much more important is evaluation of soils for agricultural potentialities.

Agriculture may be improved by:

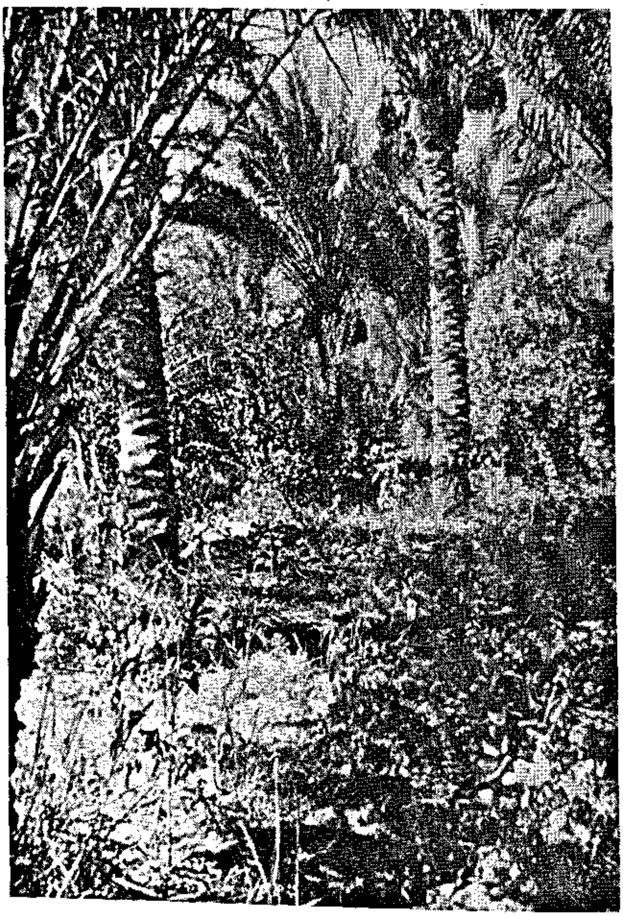
a. Better farm management, including weeding, growing better crop varieties and control of diseases and pests

b. Better soil management, including land-levelling, drainage and desalination, application of fertilizers, manure and green manure and supplementary irrigation

c. Growing various new crops more intensively, including double or triple cropping

d. Use of improved implements and modern machinery.

A real problem in the near future will be lack of fresh water for irrigation or supplementary irrigation. Within some decades there will be too little water for human needs almost everywhere. The high production obtained on some modern farms and plantations shows that much more can be produced on most tropical and subtropical soils, although some are so poor that it is still impractical to try to increase production.



Irrigated fruit garden on the river levee of the Tigris near Baghdad, Iraq, on one of the best agricultural soils in the world. There are citrus trees under date palms and in addition three crops of vegetables are grown annually.

In some restricted regions two, three, four and even five crops are grown in the same field each year. For example in Iraq on non-saline levee soils of the River Tigris near Baghdad, there are date groves underplanted with citrus trees, and three vegetable crops are grown under the citrus.

In Taiwan and elsewhere, two or three rice crops can be grown on good irrigated fields. For a few soils, that cover quite large areas in the tropics and subtropics, production could be increased two, five and sometimes even ten times, if modern methods and techniques were applied. In recent years results have been encouraging with new varieties of rice, wheat and maize.

There is also much land that can be reclaimed or improved but this is not possible on all soils and under all conditions. An important task of soil science is to select the potentially good soils, to indicate how to improve them and to predict agricultural potential. Soil scientists must acquire more knowledge and experience of tropical and subtropical soils, because many of them are not yet well known. There is a real need for much more research in all tropical and subtropical countries.

But the main factor in agricultural production is the farmer. Generally soil productivity depends largely on the abilities and socio-economic status of the farmer. No real progress will be made until his lot is improved and it pays him to work better, harder or longer.

Farmers in tropical countries seem always to have chosen a farming system adapted to their living conditions. Tropical farming is often rather primitive or traditional. Technically much improvement is possible and crop production could easily be increased, if capital were invested. However land and labour are readily available, and capital is scarce. Even if capital is invested, output does not always increase, so that there is little incentive to improve agriculture in many parts of the tropics.

Within the scope of this book, agricultural evaluation of the soils can only be superficial, ignoring such economic and social difficulties.

1.6 Tropical soil science

Before World War II most work on tropical soils was in Indonesia (Mohr), Trinidad (Hardy) and the Congo (Bayens); other important studies were in Cuba (Bennett & Allison, 1928), Puerto Rico (Roberts, 1942) and in Hawaii (Cline, 1955).

Information on Indonesian soils was first collected by Mohr and later by Mohr & van Baren (1954).

After World War II the First Commonwealth Conference on Tropical and Subtropical Soils was held in England in 1948 (Proceedings published in

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2 Arid and semi-arid soils

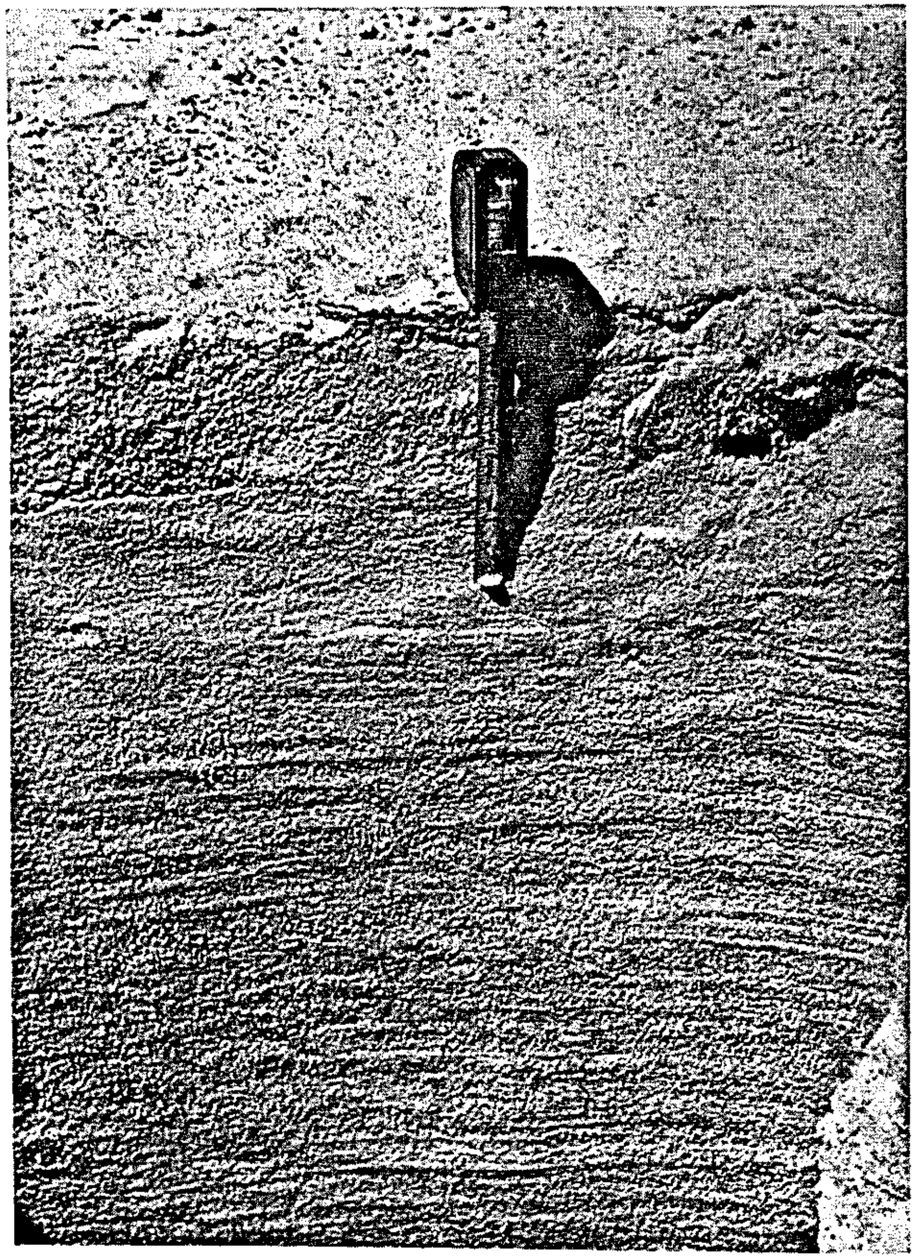
2.1 Introduction

Arid and semi-arid soils are typical of regions with a low to an extremely low rainfall. They therefore can be found in desert and dry steppe regions, that occur mainly in the subtropics, although there are also dry regions in the tropics. More than 30 % of the land surface of the earth consists of these soils, which are generally too dry for cropping. Some regions can be used for extensive grazing. If enough fresh water is available and soil conditions are suitable, land can be irrigated. Such land is simple to reclaim, because there is only a scanty grass vegetation, sometimes with small bushes. According to some specialists some 80 million ha of such land can be cropped in the future. Hence these soils are of real agricultural interest. However a disadvantage of irrigating arid and semi-arid soils is that they may become so halomorphic that the land is damaged and becomes unproductive. There are also natural halomorphic soils, in particular in depressions, that collect run-off from surrounding land or that have a shallow watertable. Halomorphic soils will be discussed in Chapter 3.

2.2 Soil-forming factors

Most important is climate. Only the upper part of the soil becomes moist during a relative short period. The lower part of the soil is continuously dry, and is often called a 'dead horizon' (Section 1.3). In true desert, natural vegetation is absent, except perhaps for some algae and fungi. Towards dry steppe, annual grasses, some bulbous plants and small scrubs come to the fore. As precipitation increases, short perennial grasses and shrubs take over.

The growing season is very short. The soil is exposed to strong solar radiation. Strong winds frequently cause sand and dust storms. The soil surface is often blown away (truncated soils) or aeolian (wind-blown) material from elsewhere has accumulated on top of former soils. Deserts are often defined as regions with less than 100 mm average annual precipitation and



Profile of a real desert soil in Egypt. There is almost no soil profile developed because of continuous aridity. Average annual rainfall is less than 50 mm.

semideserts as regions with less than 300 of 400 mm. However typically the total precipitation is very irregular from year to year, between seasons of the year and from place to place. If the average annual precipitation is 150 mm, there may be years with 75 and years with 350 mm rainfall. In some regions rain falls only in winter (Middle East), elsewhere only in summer (Sudan) or fairly regularly throughout the year (S.W. Australia). Some regions may have an almost uniform high tropical temperature throughout the year (Sudan, northern Venezuela); others may have a subtropical or even a continental climate (Kazakhstan) with hot dry summers and cool or cold winters, even with some frost and snow. In all regions the air is extremely dry. Effective rainfall is much less than total rainfall. Often most is lost as run-off because of a surface seal, a thin (1 or 2 mm) hardly permeable brittle crust; much rainwater only penetrates the surface and soon evaporates. Rain often falls in short heavy local showers. For soil formation and agriculture the amount of rainwater retained deeper in the soil after it is percolated through the upper part of the soil is most important.

Natural vegetation is only a minor factor in soil formation since vegetation is very scarse. Arid soils contain hardly any organic matter (0.2 to 0.5 %) and semi-arid soils somewhat more (1 to 2 %), especially in transitional regions with a moister climate. Plants in semi-arid regions may have an extremely large and deep rooting volume. The amount of organic matter of a plant underground may be ten times as much as above ground. The little organic matter is well spread throughout the soil and decreases slowly with depth. In moister parts of semi-arid regions, soils may have a small quantity of organic matter, decreasing with depth. Such soils are often called isohumic soils.

In many regions soil parent material is rich in lime and gypsum. All types of parent material, even volcanic, may occur. Since rainfall is low, chemical weathering is slow and mineral reserves are often high. Physical weathering is particularly intense in deserts, where diurnal temperature range is greatest. Very stony and rocky deserts and semideserts may have some more soil development because the rainwater falling on boulders and rock outcrops is added to the soil between them. In some regions extensive clay plains occur. These plains may be of fluviatile or lacustrine origin. Some of these plains have very heavy expanding clay soils that belong to the order Vertisols (Chapter 7).

Only a few deserts contain sands and sand dunes; even if they occur, they are usually restricted in area. Silt and clay dunes, which sometimes occur, consist of composite silt or clay particles of sand-grain size, cemented by lime, gypsum or sometimes salts.

Some soils are extremely gypsiferous because of primary weathering of gypsum rock material or of regular accumulation of gypsum dust. Some lacustrine soils are extremely calcareous.

The topography, in particular the mesorelief, is an important factor if there is run-off. Even minor differences in elevation are important if surface run-off results in sheet and even gully erosion. The run-off finally enters deep wadis, through which an enormous amount of water flows immediately after a heavy shower.

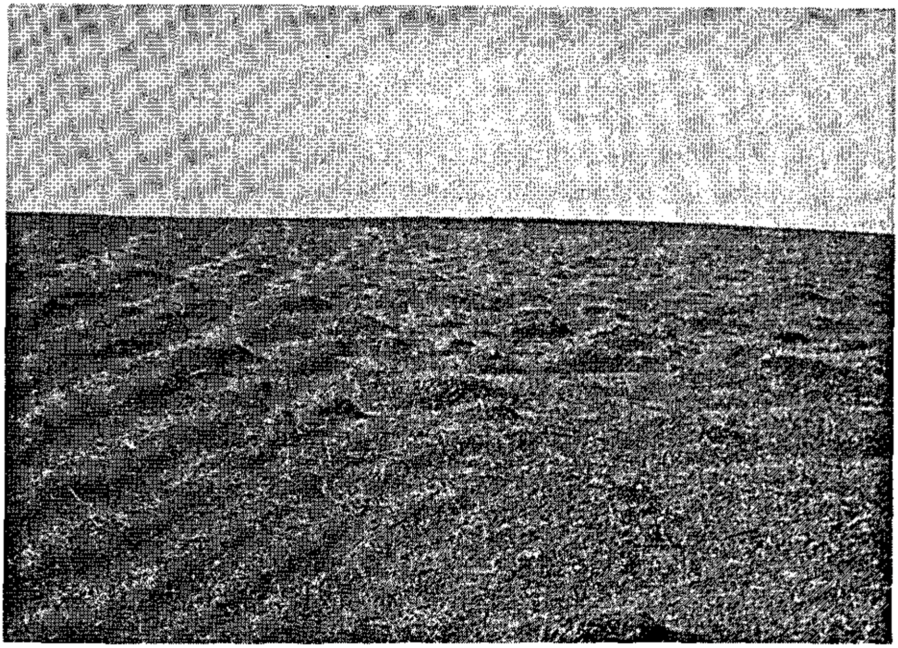
The time factor is only important in older soils. Soil formation is slow, because it is active only for the short period each year when the soil is moist. Much time passes before specific processes show their effects. Some old soils, formed in the Pleistocene Epoch, have characteristics that developed in a pluvial period.

Man has been a factor in irrigated regions, where a moist to wet soil climate is introduced in arid or semi-arid soils. This has often lead to salinization and alkalization. Moreover irrigation sediments that have accumulated over the centuries may have changed soils drastically. Many semi-arid regions have been transformed into deserts by overgrazing. This has induced soil erosion.

2.3 Soil-forming processes

All processes of soil formation are active only for the short period when soils are moist. All arid and semi-arid soils are usually dry, i.e. they are dry for at least half of the year in the layer from 18 to 50 cm below the surface. Moist soils are completely dry to a much greater depth and for a much longer time. If there is no influence of groundwater the lower part of the soil is always dry. Since only the upper part of the soil is briefly moistened and since vegetation is sparse and consequently low in organic matter, soils have an ochric epipedon.

Redistribution of carbonates and gypsum is the main process in most soils. When the soil becomes moist, some carbonates and gypsum are leached to a somewhat deeper part of the soil, where percolation stops. In the subsequent dry period, soil moisture evaporates, and carbonates and gypsum remain in the formerly moist lower part. Finally the surface soil remains calcareous or gypsiferous, and carbonates and gypsum accumulate lower in the soil. This shows as a horizon with whitish lime spots, often as lime powder or small concretions and, somewhat lower in the soil, a horizon with grayish gypsum crystals. These horizons may ultimately become real calcic and gypsic horizons. The horizon with accumulation of gypsum is below the horizon in which lime is accumulated, because gypsum is more soluble in



Gypsiferous land in the dry steppe of north-western Iraq. The sandy textured gypsum soil has a hummocky relief because of wind erosion.

water than calcium carbonate. Very often there is also a horizon with accumulation of some easily soluble salts below the horizon with gypsum accumulation. The depth at which these accumulations occur depends on the quantity of water that percolates through the soil, the water retention capacity and the permeability of he soil. In regions wih a higher effective rainfall (e.g. 300 mm) lime, gypsum and salt may accumulate at depths of 50, 90 and 130 cm. If the lime horizon is deeper than 100 cm, the soil is not considered an Aridisol.

In very dry desert regions the soil moisture reaches only one or a few decimetres down. As it evaporates and moves upward in the surface layer, lime or gypsum or both accumulate in the upper few centimetres of the soil.

In some soils the calcic horizon is indurated into a continuous petrocalcic horizon, by alternate moistening and drying, often also by cementing with silica. If more than 50 % of the hardened horizon is silica this is called a duripan. Such pans only occur in older soils. Petrocalcic horizons have often formed at the foot of slopes by lateral movement of highly calcareous groundwater.

In gravelly soils lime or gypsum forms pendants below pebbles and stones.

Sometimes an indurated gypsic horizon or a petrocalcic horizon may be at or near the surface, because of soil truncation. Such horizons, when at the surface or at a shallow depth, limit the agricultural potential of the soils. In some regions, where lime or gypsum is regular added to the soil by fresh layers of aeolian dust, calcic of gypsic horizons may be very pronounced.

Redistribution of lime or gypsum results in the formation of a cambic horizon. In non-carbonatic or non-gypsiferous soils the cambic horizon is characterized by structural elements or peds, and often also by a colour change, to reddish or reddish-brown if there is some organic matter. This process of reddening is a weak type of rubefaction of ferrugination (Chap. 5). Some iron is mobilized, transformed and irreversible dehydrated mainly to haematite, that forms a film on the surface of other soil particles. The cambic horizon can also be yellowish or light grayish if much of the parent material is carbonate or gypsum or when little iron-containing mineral is present.

Another important process, in particular in old soils, is the formation of an argillic or natric horizon, a process called argillation. It comprises mobilization, transportation and accumulation of fine clay (smaller than 0.2 μm) particles. Argillation of fine clay, which occurs even in calcareous soils, is the result of sudden wetting of a dry soil, causing an appreciable rise in pH and a temporary mobilization of clay, probably for a few hours only. The mobilized clay is transported over a short distance by percolating water and it accumulates on ped surfaces of a slightly deeper horizon, that finally becomes an argillic horizon or if sodium ions are present in excess, a natric horizon. In many soils the argillic horizon is incomplete, and there is only a more compact and somewhat harder horizon 5 or 10 cm below the surface. Sometimes some horizons in the subsoil are somewhat more clayey than the upper and lower horizons due to formation of new clay in that horizon, which is moist longer than the rapidly drying surface and than the rarely wetted dead horizon deeper in the soil.

Especially in real desert soils, a surface seal (Section 2.2) has formed by wetting with rain, action of raindrops and rapid drying of the surface, in which soil particles often are cemented by lime. Such a surface seal restricts infiltration of rainwater, which is therefore lost as run-off, causing sheet and even gully erosion.

2.4 Soil characteristics

Ochric epipedon is characteristic for almost all soils. Some may intergrade to mollic if they occur in an area with an almost semi-humid climate.

Accumulated lime occurs in calcareous parent material in desert regions in the surface layer and in regions with more precipitation at some depth. The depth of the lime depends on infiltration, permeability, water retention and the quantity of water percolating through the more superficial layers. The carbonate is mainly present as powdery pockets, sometimes with a hard nucleus that may become a small lime concretion. It forms a *calcic horizon* when it is more than 15 cm thick, has more than 15 % carbonates and at least 5 % more carbonates than the C horizon. It is called a *petrocalcic* horizon when it is indurated and massive with a laminar surface and when it forms a continuous layer. If more than 50 % of the hardpan consists of silica (opal) it is called a *duripan.*

Accumulated gypsum may occur at the surface in desert areas. Mostly it is some decimetres below the carbonate. It is only present when the parent material contains gypsum or if aeolian gypsum has accumulated on the surface. A *gypsic horizon* is more than 15 cm thick and has at least 5 % more gypsum than the C horizon.

Limy crust (Fr. croûte calcaire; Eng. calcareous hardpan or caliche) is a petrocalcic horizon often occurring at or near the surface.

Gypsum crust (Fr. croûte gypseuse; Eng. gypsum hardpan) is an indurated layer of gypsum, sometimes called a petrogypsic horizon.

Pendants of carbonate or of gypsum may occur in gravelly layers under pebbles or stones, in particular when the soil is regularly enriched by limy or gypsic dust.

Argillic or *natric horizon* (Chap. 3 and 5) occurs in old soils. The upper boundary is near the surface (5 or 10 cm).

Cambic horizon occurs in soils that are not highly calcareous or gypsiferous. It is mostly characterized by redistribution within it of lime or gypsum, or by soil structure, or by a rather compact and more clayey layer that is not an argillic horizon, or by weak rubefaction.

Aeolian material is often present on the surface. Sometimes it is a uniform sheet of fine loess-like or fine sandy material a few centimetres to a few decimetres thick. Sometimes there are microdunes, mesodunes or even high dunes (Ergs).

Truncated soils are quite common and are caused by wind erosion. If the original soil was gravelly a layer of gravel and pebbles is left behind on the surface, forming a *desert pavement* that protects the soil from further erosion. Such soils are often called Regs. In stony soils a stone layer is formed at the surface. In volcanic regions a layer of gravelly pumice or of disintegrated basalt from a lava flow may cover older soils to form Hammada soils.

Fluvio-arid deposits are sediments deposited in depressions or at the foot of slopes consisting of material that is eroded by sheet and rill erosion.

Stratification is often observed, even near the surface, because biological activity is so low and because many soils have been redeposited. Below the surface crust in regions with cold winters, there is often a *laminated horizon* formed by soil moisture moving upward towards the colder soil surface and freezing.

Surface seals, thin, dense and brittle crusts, are most common in real deserts.

Hard, polygonal cracking surface layers occur in arid clay soils of flat plains (Russ. takyr). There is a dense honeycomb pattern of small cracks 5 or 10 cm deep.

2.5 Soil classification

Typical soils of arid and semi-arid regions are classified in the order *Aridisols* characterized by soils that are dry for more than half the year ('usually dry'), have an ochric epipedon, and a cambic, argillic or natric horizon, and often a calcic, petrocalcic or gypsic horizon or a duripan whose upper boundary is within a metre of the surface.

There are two suborders: the *Argids* (with an argillic or natric horizon); and the *Orthids* (without these horizons).

The suborder Argids is subdivided into five great groups:

Haplargids with a normal argillic horizon

Paleargids with a pronounced argillic horizon or a petrocalcic horizon

Natrargids with a columnar natric horizon (Chap. 3)

Durargids with a duripan

Nadurargids with a natric horizon and a duripan (Chap. 3).

The suborder Orthids is also subdivided into five great groups:

Camborthids with a cambic horizon, often with redistribution of lime or gypsum but insufficient to form a calcic or gypsic horizon

Calciorthids with a calcic or gypsic horizon or both

Paleorthids with a petrocalcic horizon

Salorthids with a salic horizon within the top 75 cm (Chap. 3)

Durorthids with a duripan.

All great groups have various subgroups. Important are:

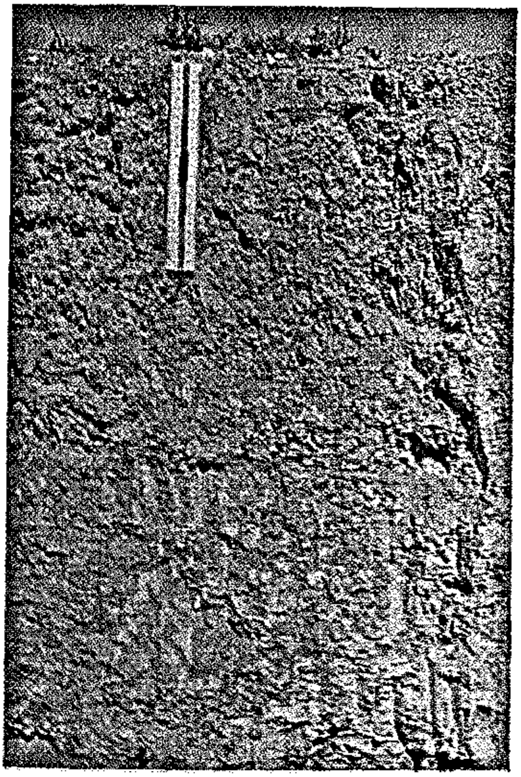
Lithic — soils less than 50 cm deep on hard rock

Stratic — soils with stratified layers

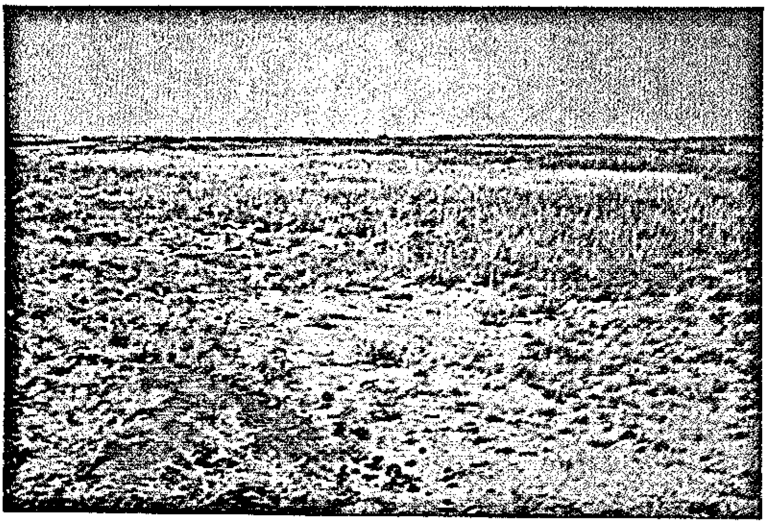
Arenic —soils with textures of loamy-fine-sand of coarser in the top 50 cm.

Important differences come at the level of families because of variations in soil parent material and soil temperature.

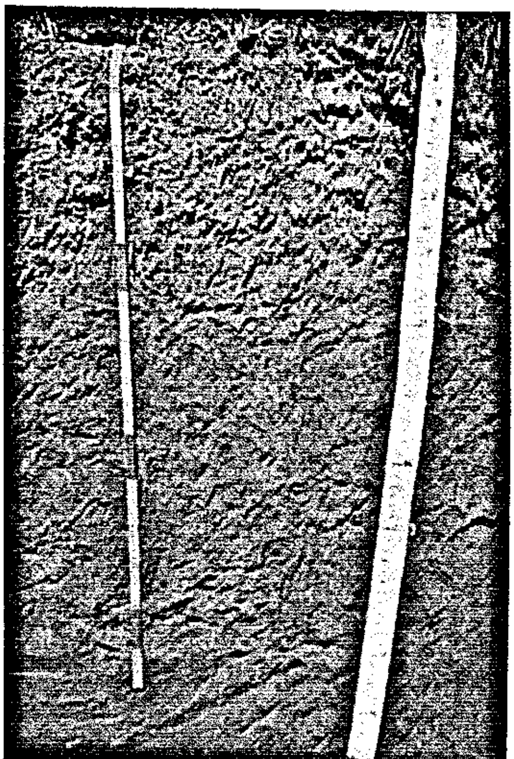
The *Gypsic* family contains more than 40 % carbonate and gypsum and



Profile of a Brown soil, Calciorthid, Central Anatolia. In the subsoil are white patches of lime accumulation (calcic horizon).



Saline land in Central Iraq with two types of soils salinity. The white land represents a severely saline soil with sodium chloride crust (External Solonchak). The brown land is characterized by the presence of calcium and magnesium chloride (Sabakh).



Profile of a Red Latosol in West Africa. The soil is very uniform to a great depth. There is almost no horizon differentiation (By courtesy of Ir F. W. van Es).

more than 35 % of the sum of carbonate and gypsum is gypsum.
The *Carbonatic* family contains more than 40 % carbonate and gypsum and more than 65 % of the sum of carbonate and gypsum is carbonate.
The *Cindery* family contains more than 60 % volcanic ash, cinders or pumice predominantly larger than 2 mm.

The differences caused by climate (e.g. tropical, subtropical, continental) are extremely important, in particular for agriculture. There are 8 classes for soil temperature at a depth of 50 cm. Four temperature classes refer to soils in which the differences between T_s (mean summer soil temperature measured in the Northern Hemisphere in June, July and August) and $T_{\bar{w}}$ (mean winter soil temperature measured in December, January and February) are more than 5°C. Four other classes refer to soils in which T_s - $T_{\bar{w}}$ is less than 5°C. According to the $T_{\bar{a}}$ (mean annual soil temperature) these groups are as follows:

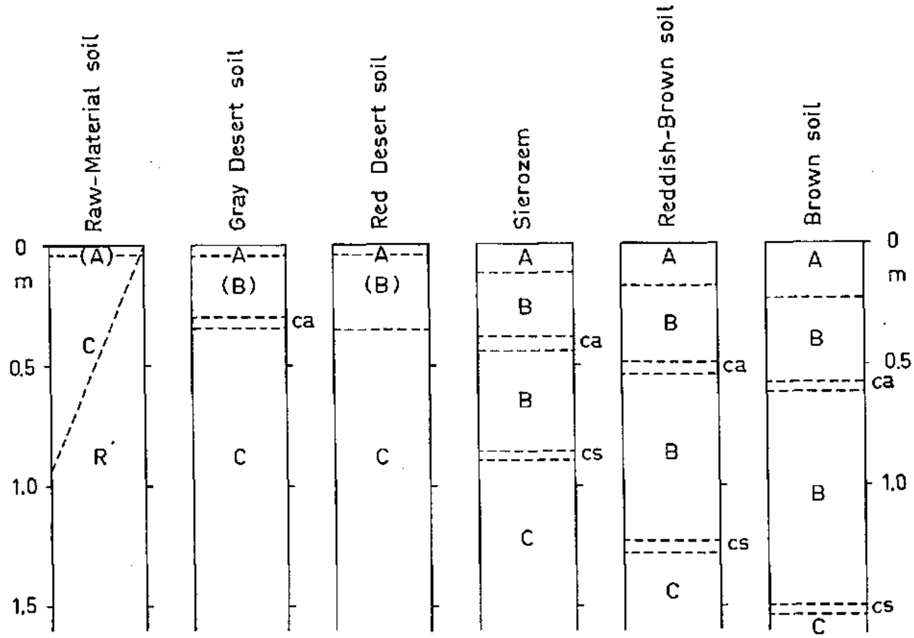
$T_s - T_{\bar{w}} > 5°C$	$T_{\bar{a}}$	$T_{\bar{a}} - T_{\bar{w}} < 5°C$
Frigid	< 8°C	Isofrigid
Mesic	8° - 15°C	Isomesic
Thermic	15° - 22°C	Isothermic
Hyperthermic	> 22°C	Isohyperthermic

Aridisols in the tropics belong mainly to the Isohyperthermic family, those of the subtropics mainly to the Hyperthermic and Thermic families and those at high altitudes to the Mesic family.

Besides the Aridisols there are also some soils belonging to the orders Entisols and Vertisols, which occur in arid and semi-arid regions all over the world.
Torrerts are Vertisols (Chap. 7) that are usually dry; they are the heavy cracking clay soils of desert regions.

In the order Entisols there are three great groups:
Torripsamments with the texture of loamy-fine-sand or coarser, that are usually dry, e.g. sandy desert soils
Torrifluvents with young alluvial soils and almost without pedogenesis in arid and semi-arid regions
Torriorthents with young soils without a cambic horizon, usually dry.

In the former USDA system, soils of arid regions were Zonal soils of the suborder Light Coloured soils of Arid Regions, with the following great soil groups:



Schematic profiles of some arid and semi-arid soils.

Desert soils, similar to Torripsamments, Torrifluvents, Torriorthents, and Torrerts
Sierozems (USA) or Gray Desert soils, similar to Calciorthids
Red Desert soils, similar to Haplargids and Paleargids
Reddish-Brown soils, similar to Calciorthids or Camborthids
Brown soils, similar to Calciorthids, Haplargids or Calciustolls.

Some other soils which often are mentioned are:
Sierozems (USSR), a group of semidesert soils (P_a = 500 to 600 mm) in the dry farming zone
Gray-Brown Desert soils (USSR), a group of typical desert soils, with a desert crust and lime accumulation at the surface
Takyrs (USSR), a group of shallow cracking clay soils in flat plains of desert regions.

On the new soil map of the world (FAO, UNESCO), the soils of arid and semi-arid regions will be shown in the groups *Yermosols*, the real desert soils, almost without an A horizon or with a very weak one, and *Xerosols*, the semidesert soils, with a more prominent A horizon, and more soil development than the Yermosols.

2.6 Some intergrades and related soils

Most important are intergrades to the Halomorphic soils (Chap. 3). In transitional zones to subhumid regions soils may be 'usually moist' in the 18 to 50 cm layer (i.e. this layer is moist for more than half the year). Such soils are not Aridisols. The Argids change mainly into Ustalfs and Xeralfs, the Orthids into Ustochrepts and Xerochrepts.

2.7 Agricultural evaluation

Soils of arid and semi-arid regions have little values unless they can be used for dry or irrigational farming.

In semi-arid regions, the natural grass vegetation may be sufficient for sheep ranging, particularly if rain falls fairly regularly throughout the year (Australia); otherwise herds have to be moved to other grass-steppe regions or to fallow land and irrigated areas where crops have been harvested.

Dry farming is generally risky in areas with $P_{\bar{a}}$ less than 300 mm, particularly if precipitation is irregular in the growing season. Some rain at the end of the growing season considerably increases yields. In most semi-arid regions, a fallow system of agriculture is practised in order to conserve some water in the subsoil for the next growing season.

Overgrazing and cultivation of soils that are too dry have caused severe wind erosion in many regions. Many farmers, particularly in overpopulated regions, take too much risk. Farm mechanization also may lead to cultivation of land that is too dry for agriculture. Fertilizers mostly have little effect, because the limiting factor is rainfall. In some regions of Australia trace element fertilizers (e.g. Mo) have tremendously increased grass production.

If fresh water is available (rivers, storage reservoirs, wells), more continuous irrigational agriculture, sometimes with two or three crops in one year, according to the climate, is possible on good soils. Potentially good soils in arid and semi-arid regions should have a reasonable water-storage capacity, a medium to high permeability, a deep watertable, highly penetrable to roots and an almost flat topography. Irrigational agriculture is most successful if attention is also paid to good soil and farm management, including better crop varieties, fertilization, weeding and pest control. Good soil drainage is essential to avoid salinization.

2.8 Regional distribution

Reference is made to various small-scale soil maps of the world, to the new world soil map of FAO and UNESCO to be published in the present decade and to geographical maps in atlases showing the position of desert and semidesert regions.

Arid and semi-arid soils are described and shown on maps of the following continents, countries and regions:

Africa	d'Hoore (1964)
America	reports in the series 'Soil Survey Reports', Washington
Asia	Rosanov (1951)
Australia	Stace *et al.* (1968)
Iran	Dewan & Famouri (1964)
Iraq	Buringh (1960)
Turkey	Oakes (1957), Driessen & de Meester (1969), de Meester (Ed.) (1970)
Soviet Union	Lobova (1960)
Coastal deserts	Meigs (1966)
Syria	Mulders (1969)
World	McGinnies (1968)

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3 Halomorphic soils

3.1 General introduction

Halomorphic soils are saline and alkali soils (Du. zout- en alkaligronden; Fr. sols salins et sols à alcali; Ger. Salzböden und Alkaliböden) occurring intrazonally in many parts of the world, especially in arid and semi-arid regions, and in regions with a pronounced dry season.

Saline soils contain enough soluble salts to harm plant growth. The concentration of salts in the soil solution is too high.

Alkali soils may or may not be rich in soluble salts but have enough exchangeable sodium ions on the adsorbing complex to interfere with plants growth. Clay and humus are dispersed, worsening the soil's physical properties.

Saline-alkali soils contain excess soluble salts and have a high percentage of sodium ions on the adsorbing complex.

Salts in soils originate from:

a. Sedimentary rocks laid down in marine lagoons, which are now at the surface, often forming hills and mountains
b. Irrigation water, which always contains some salt, so that evapotranspiration causes gradual accumulation of salt in the soil and finally severe salinization
c. Brackish and saline groundwater, which rises into the root zone
d. Seawater in coastal regions, where soils are inundated
e. Air as cyclic salts or salty aeolian dust.

Excess of soluble salts in the soils are harmful to plants, because:

a. They increase the osmotic pressure of the soil moisture, affecting the plant's ability to take up water from the soil (physiological drought)
b. They disturb the ion balance in the soil solution
c. Some ions poison the plant (e.g. boron)
d. They upset and decrease the biological activity of the soil.

Crops develop poorly and irregularly. The yield and quality of the crop is low and most crops are more susceptible to diseases. Much research work on saline and alkali soils has been done, but still more has to be done.

Soil profile in an alluvial clay soil with a horizon of salt accumulation (salic horizon).

In recent years many soil scientists have specialized in saline and alkali soils in semi-arid and subhumid tropical and subtropical regions, where agricultural development projects are being planned and implemented. Unfortunately in the past and even now many projects fail, because after some years salinity and alkalinity increase. Very often this results from failure to leach and drain the soils. Is is debatable whether permanent agriculture can be established in areas which are saline or alkali, or which are potentially saline or alkali. Although many projects fail, permanent agriculture will often be possible, as long as soil and farm management are correct.

3.2 Soil-forming factors

Long periods of dry and warm or hot weather are important for the formation of saline and alkali soils. Another important factor is hydrology: high watertable, intensive irrigation, inundation by the sea or by brackish water. In many irrigated areas, man's misuse of the land has often caused salinization and alkalization. Relief is often important, because salinization is most severe in depressions or at the edge of depressions. The factor time has to be taken into account for alkalization. Salinization is often a rapid process.

3.3 Soil-forming processes

Salts occurring in soils

The salts occur as crystals in soil, as a solution in soil water or groundwater. The concentration of salts continually changes. It increases with evapotranspiration. It decreases when fresh water is added to the soil, e.g. as rain or as irrigation water. Adding more fresh water to the soil and carrying off the water in which salts have gone into solution (leaching and drainage) may decrease the salt content to such an extent that soils gradually become non-saline. Often the watertable must also be lowered to prevent capillary water from reaching the root zone of crops.

When the concentration of Na^+ in the soil solution becomes high, Ca^{2+} on the adsorbing complex is replaced by Na^+ and a soil gradually turns alkali. By adding gypsum ($CaSO_4.2H_2O$) to the soil, the Na^+ of the complex is replaced by Ca^{2+} and the soil turns non-alkali.

Salts like gypsum ($CaSO_4.2H_2O$), chalk ($CaCO_3$) and magnesite ($MgCO_3$) are not very soluble. They do not harm crops and can be further discounted.

Really harmful soluble salts are:
Chlorides ($NaCl$, $CaCl_2$, $MgCl_2$)
Sulphates (Na_2SO_4, $MgSO_4$)
Nitrates ($NaNO_3$, KNO_3)
Carbonates and bicarbonates (Na_2CO_3, $NaHCO_3$) and borates.

The types, the mixtures and the properties of these salts vary, and resistance to them differs between crops or plants. There is even sometimes a difference between varieties of one crop. At different growth stages, plants often react differently to the same concentration of salts.

The best parameter of salts in the soil solution is osmotic pressure (OP). The quantity and types of salts occurring in a soil can also be measured chemically. Methods are time-consuming and concentration of salts in the soil solution changes rapidly with evapotranspiration, irrigation or changing temperature. Hence for uniformity soil scientists have agreed to measure salt in an extract of a water-saturated soil sample at 25°C on a Wheatstone or salt bridge which measures resistance (in ohms) for two electrodes, a square centimetre in area and a centimetre apart, whose reciprocal is called electrical conductivity (in mhos). Electrical conductivity is in soil science indicated by EC, in the saturated extract by EC_e, and in the soil paste as EC_s. Mostly EC_e is given in millimhos (mmho), sometimes in micromhos (μmho). Instead of a water-saturated soil, EC is sometimes measured in a one to one or one to five mixture of soil and water, indicated as EC_1 and EC_5. The advantage of measuring the electrical conductivity of a soil sample is speed; the disadvantage is that it is not related to osmotic pressure.

Sometimes salt content of a soil is expressed as total soluble salt (TSS) as a percentage (%), in parts per million (ppm), in milligrammes per litre (mg/l) or in milliequivalents per litre (meq/l). The type of salts occurring in soil can only be found by chemical analysis. In seawater almost all the salt is $NaCl$, but in soils of semi-arid regions $NaCl$ is often less than half the total, which also includes $CaCl_2$, $MgCl_2$ and Na_2SO_4.

In alkali soils the Na^+ adsorbed on the soil complex is expressed as a percentage of the total cation-exchange capacity (CEC), sometimes referred to as T value. The percentage Na^+ is expressed as ESP (the exchangeable-sodium percentage). This is not entirely adequate, because under special conditions a high percentage Mg^{2+} on the complex may cause similar deterioration of soil as does Na^+. Therefore, a soil in which $Na^+ + Mg^{2+} > Ca^{2+} + H^+$ is also called an alkali soil. If Na_2CO_3 or $NaHCO_3$ is also present in the soil solution, the pH of the soil will be higher than 8.5.

The following table gives classifications for $EC_e.10^3$ and ESP values.

Class	Name	$EC_e.10^3$	TSS %
0	salt-free	0- 4	0.00-0.15
1	slightly saline	4- 8	0.15-0.35
2	moderately saline	8-15	0.35-0.65
3	strongly saline	>15	>0.65

Name	ESP
non-solonized	0- 5
weakly solonized	5-10
moderately solonized	10-15
heavily solonized	15-20
solonetz	>20

The salinity classification is from the United States Department of Agriculture (Richards, 1960) and the alkalinity classification from the Soviet Union.

In the United States an ESP of 15 and an $EC_e.10^3$ of 4 are considered critical for crops. If ESP is more than 25 or 30 %, most plants die.

With these classifications we now can write down the critical values of $EC_e.10^3$ and ESP for saline and alkali soils, as defined in Section 3.1.
In a saline soil $EC_e.10_3 > 4$ and $ESP < 15$.
In an alkali soil $EC_e.10^3 < 4$ and $ESP > 15$.
In a saline-alkali soil $EC_e.10^3 > 4$ and $ESP > 15$.

These values are rough but they apply to many soils. Another indication is the pH that is often below 8.5 in saline soils and above 8.5 in alkali soils (because of the presence of Na_2CO_3 or $NaHCO_3$). In saline-alkali soils, pH is usually below 8.5.

Sodium adsorption ratio (SAR) of the soil extract is also used to indicate soil alkalinity. It is derived from the formula

$$SAR = Na^+ / [0.5 (Ca^{2+} + Mg^{2+})]^{0.5}$$

where the cations refer to concentrations in meq/1. An SAR value of 12 is often about equivalent to an ESP value of 15.

The equivalence of the various parameters can be obtained from the following equations.

$$TSS = 0.064 \times EC_e.10^3$$

where TSS is measured as a percentage.

$$OP = 0.36 \times EC_e.10^3$$

where OP is measured in atmospheres.

$$TCC = 10 \times EC_e.10^3$$

where TCC is the total concentration of cations in meq/1.

The numbers in these equations vary with type of salinity or alkalinity and with the proportions of different types of salt in the soil.

In the Netherlands soils inundated by seawater are characterized by C value which is measured in early spring when soils are at field capacity. The C value (measured in the 5-20 cm layer for arable land) indicates whether crops can be grown. The C value is calculated from the values A and B in the formula $C = B \times A^{-1} \times 1000$ in which A is moisture and B is NaCl, both in g per 100 g dry soil. A rough interpretation of the C value for clayey polder soils under the specific average climatic conditions of the Netherlands is:
C less than 10, spring barley can be sown;
C less than 7, sugar-beet can be sown;
C less than 4, spring wheat can be sown;
C less than 3, potatoes can be planted.
If C is less than 5, there is an increase in sodium on the adsorbing complex and alkalinity will cause soil structure to deteriorate.

Sometimes the halophytic natural vegetation is used as an indicator to recognize saline soils and even to recognize salinity classes, based on presence or absence of indicator plants. They are sometimes even used to map soil salinity. Such maps, however, are often unreliable, because most plants can tolerate a range of salinity. Often specific plants have disappeared through grazing, burning or cutting.

Some difficulties still remain. Several types of salt may be present in one soil and they vary in amount between soils; plants vary in reaction to different amounts and proportions. The concentration of salts in the soil solution is influenced by the composition of these mixtures, by time and by soil temperature. In a soil profile, total salt content and composition of salts is different in the different layers. Even within one soil horizon, there are differences. Hence soil samples for salinity have to be taken at regular intervals throughout a profile.

Quality of irrigation water, salt content, and depth and composition of groundwater are very important factors in saline and alkali soils. They should always be studied in association with salinization and solonization. Very often published studies have ignored these characteristics.

There are also some simple tests. One can taste soils; if a soil tastes salty it is in salinity class 3. A slightly bitter taste indicates Na_2SO_4. If a small moist soil sample does not taste saline and is dried in the sun, salt crystals on the surface indicate salinity class 2.

Soil alkalinity and groundwater alkalinity can be tested by adding some drops of phenol pH indicator; if the soil turns purple or the groundwater turns red, it is alkaline.

Of course these field methods are rough. For many purposes a rough indication of salinity or alkalinity is enough. Measurement of $EC_e.10^3$ and ESP are often sufficient, particularly if they exceed the critical values, or if they are almost zero. But for slightly or moderately saline, or weakly or moderately solonized soils, the results of such measurements and analysis should be interpreted carefully in the light of other soil characteristics.

Processes involved

Salinization is the accumulation of soluble salts in the soil. The rate and depth of accumulation of salts in the soil varies. Salinization is common in arid and semi-arid regions, where precipitation is too low to maintain a regular percolation of rainwater through the soil. As a consequence soluble salts crystallize and accumulate in the root zone of the soil. In many areas salts accumulate in the soil by capillary rise of brackish or saline groundwater. In marine soils along coasts and estuaries and in polders where soils

Photograph of the side of a new drainage canal in Iraq. This photograph demonstrates the vertical distribution of various types of salts. The surface soil mainly contains sodium sulphate, the brown subsoil calcium and magnesium chlorides and the white lower part sodium chloride.

are inundated with seawater, salinization is a normal process. Accumulation can also be caused by irrigation, salt dust or seepage from watercourses. Different types of salts and mixtures of salts can accumulate at different depth. A rising and falling watertable and in particular irrigation practice can alter the salinity of the soil.

As the textural, structural and porous composition of most soils varies horizontally and vertically, the salt content of soils often also varies widely. If there is a severe salinization, a salic subsurface horizon may form. A salic horizon must contain at least 2 % salt and must be 15 cm or more thick, and the thickness (in cm) × the percentage must be 60 or more. Such a salic horizon is diagnostic in soil classification (CSSC). If salt reaches the surface, a salt crust may form.

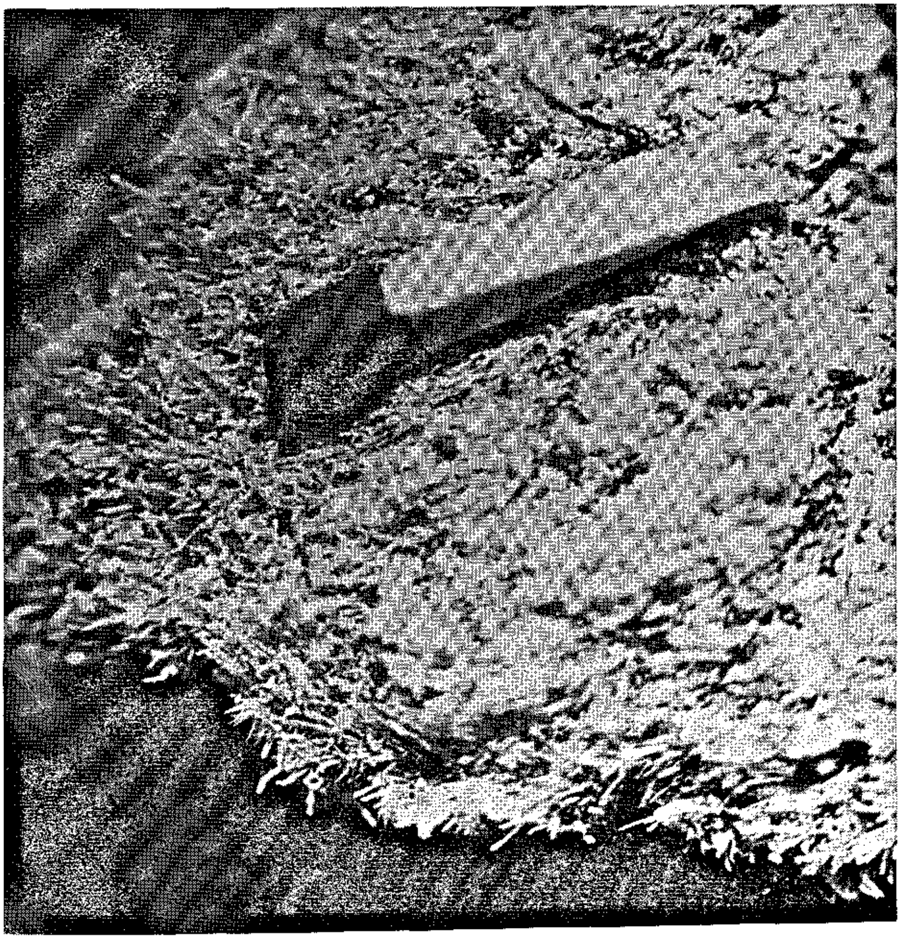
Saline soils, as has been mentioned, are characterized chemically of by electrical conductivity. However they often have some typical characteristics. Besides salt crystals, salt crusts and salic horizons, these soils mostly have a loose quite porous granular structure. If there is much Na_2SO_4, they may be fluffy or puffy; if hygroscopic salts such as $CaCl_2$, $MgCl_2$ or nitrates are present they give the soil a moist appearance even during dry periods. Such saline soils with clear morphometric characteristics are often called Solonchaks.

Alkalization is the formation of soils with a highish percentage of exchangeable sodium; often sodium carbonate and sodium bicarbonate are present too, increasing the pH beyond 8.5, often to 9 or 10.

Clay particles and the humus are easily eluviated from the A to the B horizon and accumulate as a natric subsurface horizon. This natric horizon is characterized by a prismatic structure with clay and humus coatings on the ped surfaces. If enough humus is present, these coatings may darken the layer.

The textural B horizon with cutans resembles an argillic horizon, has all its characteristics, and is diagnosed as natric by exchangeable sodium being more than 15 % (CSSC). Soils with these characteristics formerly were called Solonetz (sometimes Sodic soils; in Hungary: Szik soils).

Solodization is an intensive leaching and degradation, which can follow alkalization in older soils. The soil, at least the upper part, turns acid. The exchangeable sodium is replaced by H^+ ions, and there is very strong argillation. (This is the process of leaching of mobilized clay particles from the A to the B horizon, which becomes a textural B horizon.) Consequently there is finally a very pronounced natric horizon with a columnar structure.



Detailed photograph of sodium sulphate efflorescense in a soil. The salt crystals are needle-shaped.

In the A horizon a leached and bleached A_2 or albic horizon is formed.

As the columns of the B horizon have rounded upper surfaces, the lower boundary of the albic horizon tongues into the B horizon. Solodization is a slow process. Soils with the morphometric characteristics indicated here were formerly called Solod, Soloth, or Solodi. They are quite rare, occurring on some older plains and terraces, often in small patches. There are more soils with similar but less pronounced characteristics, and less acid, that are called Solodized Solonetz, intergrades between the Solod and the Solonetz, also often occurring in small patches and called slick spots or scabby spots.

Nitrification is the oxidation of ammonia into nitrate by the action of soil micro-organisms. This nitrate may accumulate.

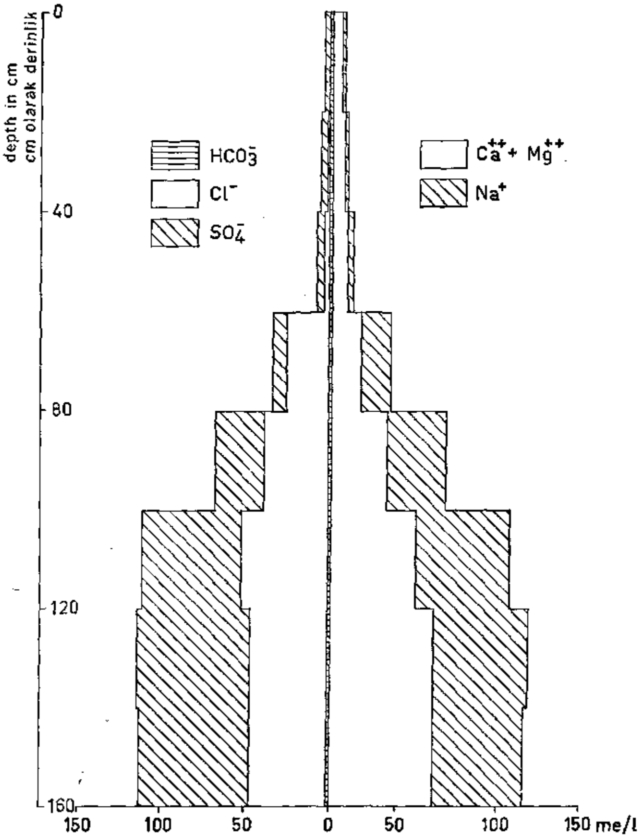
Nitrate salinization is, however, rare but may occur in arid regions. Rainfall has to be low and vegetation is spare. The nitrates are hygroscopic and attract moisture from the air, making the soil look moist.

Desalinization is the leaching of salt from the soil. This can be done by applying excess irrigation water if there is no rainy season. As fresh water penetrates the soil, is dissolves the salts. The salt content of this water gradually rises as it percolates and this water is carried off as saline or brackish drainage water. Desalinization depends on the quality and quantity of the percolating water, the drainage system, soil morphology and the salts occurring in the soil.

Salinization and alkalization by seawater is a different process. Seawater contains 35 g salt/litre, most of it as NaCl (about 27 g/litre), therefore the most important ions are Na^+ and Cl^-.

The salt content of soil after inundation with seawater is very variable. It depends on the duration of inundation, the moisture content of the soil before flooding and the season of the year. Salt contents of 20 to 25 g/litre are often measured in the soil solution. In the Netherlands, precipitation in winter and early spring exceeds evapotranspiration. In winter there is desalinization. In spring and summer the salt content in the soil solution of land that has been inundated by seawater gradually increases. The surface soil is desalinized first. The high ESP in the surface soil causes structure to deteriorate after rain. A thin soil crust is easily formed. It dries up hard and is almost impermeable. In microdepressions, stagnating water stands for a long time on the surface. The soil surface in dry places turns gray, because dispersion of clay exposes many sand grains. The percentage exchangeable cations on the adsorbing complex indicated in the following table is given for a Dutch polder soil (marine clay soil reclaimed from the sea).

	Ca^{2+}	Mg^{2+}	K^+	Na^+
normal soils	88	8	3	1
soil in equilibrum with seawater	21	36	10	33
temporarily inundated with seawater	48	25	6	21



Salt content and chemical composition of the salt in an Internal Solonchak.

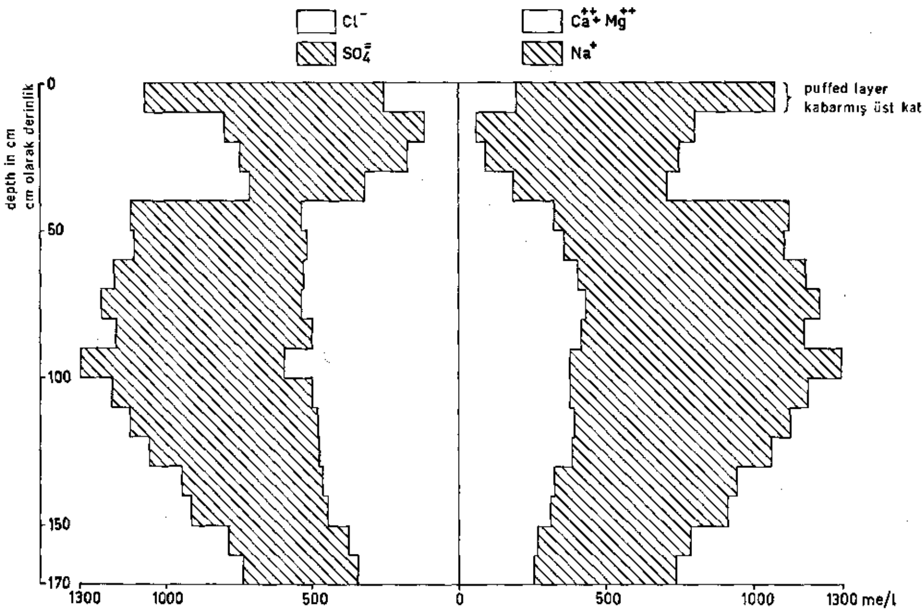
3.4 Some characteristic soils

By the processes of salinization, alkalization and solodization, the soil gradually develops specific chemical, physical, biological and morphological characteristics. The important soils are discussed below.

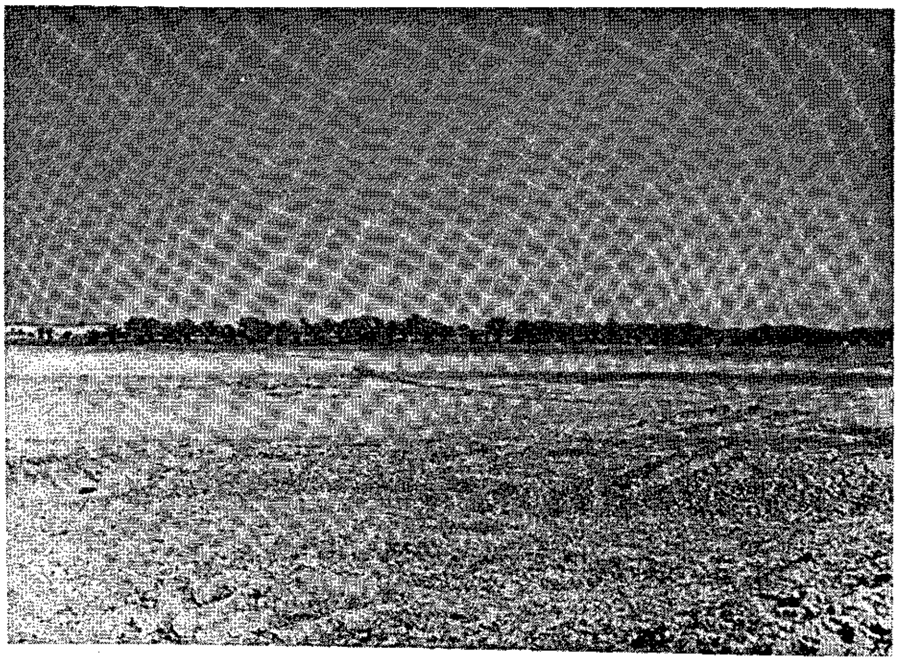
Solonchak (salt marsh or saline soil in Russian) are soils with many salt crystals, which give the soil a loose granular structure. In dry soils salt crystals can be observed.

There are two main types:

Internal Solonchaks, which are saline and have salt crystals only in the lower part of the root zone, mostly more than 80 cm below the surface

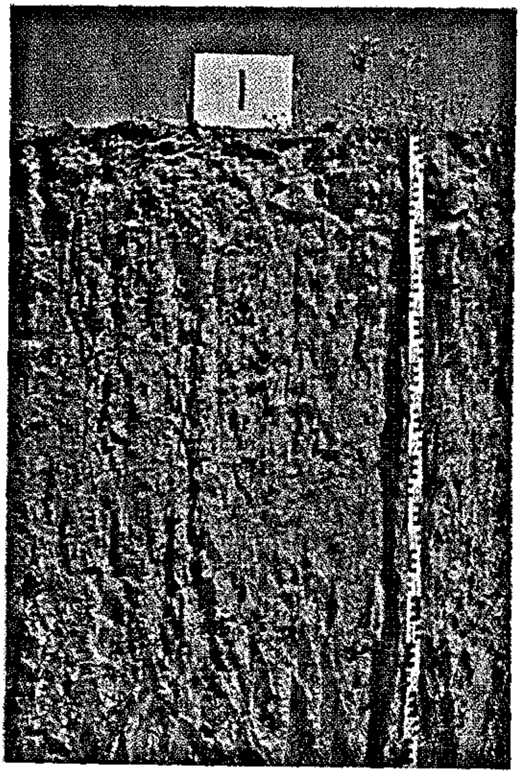


Salt content and chemical composition of the salt in an External Solonchak.



Flooded Solonchak near Babylon, Iraq. The soil is covered with a white crust of salt.

Profile of a Red-Yellow Podzolic soil, Venezuela. There is a clear A_2 horizon near the surface, and clay particles, leached from the upper horizons, have accumulated in the reddish subsoil (argillic horizon).



Profile of a Red Mediterranean soil, Terra Rossa, in Spain (Palexeralf). There is an ochric epipedon and an argillic subsurface horizon. The surface horizon consists of mixed material as a result of sheet erosion.

External Solonchaks, which are saline and have salt crystals throughout the root zone, up to the surface. The following types of External Solonchaks may occur:

— *Dry Solonchaks* (sometimes Crusty Solonchaks), which are dry, without influence of groundwater, often with salt crystals on the surface

— *Puffed Solonchaks* (Puffy or Fluffy Solonchaks), which are dry and whose surface is very loose and fluffy because of rather long needles of sodium sulphate ($Na_2SO_4.10H_2O$) which separate the soil particles

— *Sabakh soils,* which have the colour of moist soil (and are wet at the surface early in the morning) because of calcium and magnesium chlorides, which are hygroscopic and attract moisture from the air.

— *Flooded Solonchaks,* which are under water for part of the year and which have a layer of white crystals on the surface when dry

— *Wet Solonchaks,* which have a high watertable, at least in the root zone, often close to the surface.

Solonetz, which are non-saline alkali soils with a natric horizon.

The A horizon is often thin (5 to 10 cm), and the B horizon has an angular-blocky or prismatic structure. Important types are:

Steppe-Solonetz (sometimes Chernozem-Solonetz), a Chernozem or chestnut soil with Solonetz characteristics

Sierozem-Solonetz, a Sierozem soil with Solonetz characteristics

Meadow-Solonetz, a hydromorphic soil (with gley in root zone), with Solonetz characteristics

Eroded Solonetz, a Solonetz occurring patchily with the B horizon at the surface.

Soloth (Solod), with an albic horizon tonguing into a columnar B horizon. Soloths occur patchily on older terraces, and are quite rare. Some types are:

Typical Soloth, with the typical characteristics

Eroded Soloth, with the columnar B horizon at the surface. The eroded bleached sandy material accumulates in the surroundings

Solodized Solonetz, a soil intergrade between Solonetz and a Soloth, with characteristics of both: a weakly developed A_2 horizon, bleached grains on the columnar peds of the B horizon, which is usually still alkaline.

3.5 Soil classification

These soils can be classified in the light of pedogenesis, chemical composition, agrophysiological behaviour or soil morphology.

Pedogenetic classification In all pedogenetic systems of soil classification the Saline and Alkali soils are grouped in one general taxon, because these soils do not occur in specific climatic zones. In many systems they are placed in the order Intrazonal soils and the suborder Halomorphic soils, with the great soil groups: Solonchak, Solonetz and Soloth.

Chemical classification The basis of classification is the presence of various types of salt. The principal soils are: Chloride soils, Sulphate-Chloride soils, Chloride-Sulphate soils (the last mentioned salt being the most important component), Sulphate soils, Soda soils and Borate soils.

Agrophysiological classification Most attention is given to the quantities of soluble salts in the root zone. Chlorides are more harmful to most crops than sulphates. Salt content is evaluated by plant growth. The tables given in Section 3.3 are examples.

Systematic classification This is a classification based on morphometric characteristics of the soil profiles as used in CSSC. The classification is based on the presence of salts, distributed throughout the soil (halic group) and on the presence of a salic or natric horizon (salic and natric groups).

The great groups are:

In the Inceptisols: *Halaquepts;*

In the Ardisols: *Natrargids, Nadurargids* and *Salorthids;*

In the Mollisols and Alfisols various great groups with the prefix Natr- or Natri-.

The main differences from the pedogenetic systems are that:

a. There is no specific Holomorphic group of soils
b. The specific Solonchak and Solonetz characteristics are introduced in the third category and not in the first or second one. This is done, because various soils with specific diagnostic characteristics, may later become saline or alkaline, and inherit the specific characteristics of salinity, alkalinity or solodicity in a later phase of development.

3.6 Some intergrades and related soils

There are many intergrades from Solonchak to Solonetz and in particular from Solonetz to Soloth but there are also intergrades to normal great soil groups, in particular those occurring in arid, semi-arid and subhumid regions, for example to Alluvial soils, to Arid soils and to Vertisols. Some other soils are as follows.

Potential Solonchak, weakly saline soils, that do not have the morphological characteristics of the solonchak. They can be recognized only by analysing soil samples. Very often failure to recognize them in the field has led to big mistakes in the prediction of their agricultural potentialities.

Potential Solonetz, being young alkali soils with no or very weak characteristics of a solonetz. These soils occur mainly in alluvial landscapes. They often contain sodium carbonate and bicarbonate.

Pseudosolonetz, soils with morphological characteristics similar to those of a real Solonetz, but which prove to be non-alkali after analysis of soil samples. They mostly result from variation in sedimentation.

3.7 Agricultural evaluation

Some information on agricultural evaluation has already been given; the influence of salts on crop production has been explained and critical values have been indicated. It is evident that saline and alkali soils are poor agricultural soils and that measures can be taken to make such soils non-saline, and non-alkali. As leaching and draining of soils are important, the soil permeability, the quality of irrigation water and the hydrological conditions (groundwater, seepage water) are extremely important. Soil with bad natural physical properties, in particular with a very slow permeability, are always poor, if salinization and alkalization are likely to occur.

Some alkali soils without a natric horizon can be improved by applying gypsum. The sodium ions on the adsorbing complex are replaced by calcium ions of the gypsum. Some real Solonetz soils are improved by deep-ploughing (a metre or more), to bring a gypsiferous layer from the substratum to the surface.

In many countries with salt-affected or potentially saline and alkali soils, good irrigation water is scarse. Hence irrigated agriculture ought to be concentrated on soils with good physical properties, in particular those with high permeability, deep watertable (good drainage), a flat surface, a high water-holding capacity and deeply penetrable by roots.

3.8 Regional distribution

Saline and alkali soils mainly occur in arid and semi-arid regions and in regions with long dry and warm summers, especially when groundwater in the root zone is saline. Therefore large areas of saline, saline-alkali and alkali soils are found in all countries where such conditions occur, in particular in the subtropics. They also occur in low-lying regions along coasts, where land is submerged by seawater.

3.9 References

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4 Ferrallitic soils

4.1 General introduction

The zonal soils of the humid tropics (equatorial regions) are the Ferrallitic soils. These soils are very old, deeply weathered red to yellow clayey soils, almost uniform throughout the profile, without distinct horizons. They are rich in sesquioxide, and have poor chemical and good physical internal soil properties. They are characterized by the presence of 1:1 lattice clay minerals of the kaolinite group, the CEC is low, V is low too, and $SiO_2/R_2O_3 < 2$.

The Ferrallitic soils occur in undulating, rolling and hilly landscapes and are well drained. In the past they have had various names (e.g. Lateritic soils) and the definition was rather vague. Formerly the only criterion was $SiO_2/R_2O_3 < 2$. In 1950 the name Latosols was introduced with more precise definition. Now these soils belong to the order Oxisols and some to the Ultisols of CSSC. In this chapter the name 'Ferrallitic soils' will be used, including a great variety of tropical soils, as will be explained later.

In the literature on tropical soils there is much confusion on diagnostic characteristics and often quite different names and definitions have been used for Latosols, Lateritic soils, Ferralsols, Kaolisols, Ferrallitic soils.

Buchanan (1807) first described such soils in India, where the moist soil was cut into lumps of brick size and then dried in the sun. These lumps became hard on drying by irreversible dehydration and they were used as bricks to build walls, houses and temples. The soils were therefore called Laterite or Lateritic soils, from the Latin 'later', meaning a brick or tile.

Although there are various types of Ferrallitic soils, formerly indicated by their colour (Red, Brown, Yellow Latosols), they all have in common a lack of weatherable minerals, and consequently are infertile. Yields of agricultural crops are generally low.

In recent years research on Ferrallitic soils has been intensified; international co-operation, better and more widely accepted methods of description and soil analysis have considerably extended knowledge of them.

Ferrallitic soils occur in all wet tropical regions, e.g. Indonesia, South-

Plinthite layer in a soil profile.

East Asia, Central Africa, Brazil and various islands (Hawaii, Cuba). Before World War II, investigations in Indonesia (Mohr & van Baren, 1954; Dames, 1955), Hawaii (Cline, 1955), Cuba (Bennet, 1928) and Puerto Rico (Roberts, 1942) were the most important. After the War, Belgian (Bayens, 1938; Sys, 1960; d'Hoore, 1954), French (Aubert, 1954; Maignien, 1964), Portuguese and British soil scientists have extended knowledge by research work in Africa. Brazialian soil scientists (Camargo, Lemos) have done much work in co-operation with Bennema (1963) and Sombroek (1966).

During recent years various new proposals for classification of these soils have been made; these systems are still being revised and improved.

4.2 Soil-forming processes

The processes of soil formation are complicated and still only partially known. This is because all soils are very old, often polygenetic in character, developed from diverse parent materials, most of them weathered elsewhere, before being transported to their present site, where again processes of soil formation have acted upon this mixed and already altered, old material (French: roche fille).

The main soil-forming process is ferrallization, formerly also called laterization, lateritization, kaolinization or latosolization. Plinthite is formed in older tropical soils with hydromorphic characteristics (high watertable or stagnating percolation). with alternating dry & wet periods

The ferrallization process is rather complicated. Generally the process consists of:

a. An intensive continuous weathering, with hydrolysis of silica
b. A leaching of bases and silica, resulting in a relative accumulation of sesquioxides
c. The formation of 1:1 lattice clays of the kaolinite group (kandoid clays).

The weathering is an irreversible hydration, oxidation, solution and hydrolysis, which vary according to the composition of parent rock material. The high rainfall causes an almost continuous percolation of water through the soil and leaches the bases and silica. This results in a very low base-saturation V <35 %, a low pH (4.5 to 5.5), a low SiO_2/R_2O_3 (<2) and a low SiO_2/Al_2O_3 (<2). The chemical changes are active and vigorous throughout the year. Organic matter is often rapidly mineralized. The conditions for ferrallization are continuous moistness of the soil with an almost continuous percolation of water downwards. This is possible only with high rainfall, a very porous soil, rapid internal drainage, and deep watertable or none at all.

The kandoid clays are 1:1 lattice clays, consisting of one layer of silica tetrahedra and one layer of aluminium oxide-hydroxide octahedra; they may be kaolinite $Al_2(Si_2O_5)(OH)_4$, halloysite or metahalloysite. A general condition now accepted for many Ferrallitic soils is the presence of at least 15% clay of which more than 90 % is 1:1 lattice clay; no argillation should have taken place. The clay particles are usually cemented by iron, so that the content of natural clay or water-dispersible clay (shaking with distilled water) is low. The silt content is low too. The quotient fine silt/clay <0.25. French soil scientists determine the quotient L/A, where L is the content of 'limon' (fine silt fraction 2 to 20μm) and A is that of 'argile' (clay), which quotient should be <0.15.

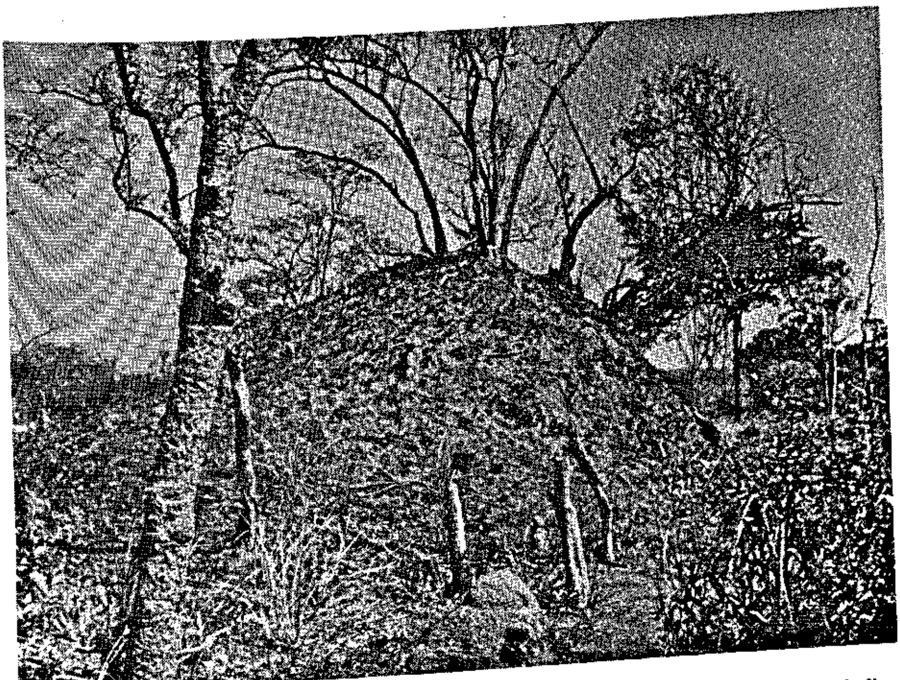
Another process that may occur in soils with hydromorphic characteristics (high watertable or no internal drainage) is plinthization, the formation of plinthite or mottled clay, formerly called 'laterite' (Fr. argile tacheté; Ger. Fleckenzone). This is the soft or hard clayey material, rich in sesquioxides, poor in organic matter, mottled often with red or reddish or purple mottles in a blue-gray matrix in or below the solum, and produced by change in redox with fluctuations in watertable. Plinthization is the mobilization, transport and final accumulation of iron compounds. In permanent moist conditions, plinthite is soft but when it dries (e.g. by fall in watertable or upheaval of the land) the material hardens irreversibly by dehydration, and hard plinthite or indurated ironstone forms. The hard plinthite may occur in various types, such as concretions, cemented concretions and hardpans (Fr. cuirasse; Ger. Panzer). Formed in situ, the hard plinthite overlies soft plinthite and there is a gradual transition. Hard plinthite concretions, however, can also be transported, and in colluvial material a layer of hard plinthite can sometimes be seen. In such soils there is no soft plinthite. If the soil has been eroded as far as the plinthite horizon, a real hardpan may occur at the surface. If a landscape is uplifted by tectonic movement, a really thick hard plinthite crust or cap may occur on hills and low mountains. Soils with plinthite were formerly called Groundwater Laterite.

Plinthization is a similar process to gleying in temperate soils but gleying also occurs in other tropical soils, e.g. alluvial soils. Plinthization is not confined to Ferrallitic soils; it may also occur in all older iron-rich tropical soils with recent or former influence of groundwater. It also occurs in various Tropical Ferruginous soils, dealt with in Chapter 5.

In many Ferrallitic soils a stoneline or stone pavement (Du. keienvloertje) can be observed at a depth of one to five metres in the soil profiles. It consists of a thin layer of hard plinthite concretions or quartz pebbles. Often such a stoneline indicates that the material above it has been deposited on top of a former soil, which had been eroded. Such a soil then has to be considered as a two-layer soil. Sometimes the stoneline seems to result from biological activity in the soil, especially of termites, which bring fine soil material to the surface and concretions or quartz gravels are buried to the depth, to which the termites have influenced the soil.

There are other processes connected with ferrallization, such as the lateral movement of water through the soil. Furthermore the water, that has percolated through the Ferrallitic soils, contains silica. The deep ground-water, containing silica, may seep to valleys, producing 2:1 lattice clays or smectoid clays (montmorillonite), forming Vertisols (Chapter 7).

Biological processes cannot be neglected, because the moist and warm soil conditions in well aerated Ferrallitic soils promote a very high biological activity. Soils are homogenous to a great depth; they are highly porous and vegetation has a deep and extensive root system. There are many organisms, both large and small. Termites are active in many soils.



A termite hill in the Congo. The hill is several metres high and consists of fine-textured material that is collected by termites. Termites are active in many tropical soils.

4.3 Soil-forming factors

The soil climate in the wet tropics is characterized by a continuous rather high soil temperature, about 24° to 27°C for the whole year. In mountainous regions, the temperature drops 0.5° or 0.6°C with every 100 metres altitude, so that the climate is temperate or sometimes even arctic. This explains why Ferrallitic soils occur at lower altitudes, with true wet equatorial climate.

The rainfall is generally evenly distributed and the annual average varies from 3000 to 6000 mm (sometimes even over 10 000 mm). There may be some really heavy tropical showers, daily maximum of 500 to 700 mm! It is estimated that about 70 or 80 % of total rainwater reaches the soil.

Ferrallitic soils are formed in various parent materials. The clay mineral formed from most acid materials is kaolinite and from basic materials gibbsite. The iron content of the parent material largely determines the sesquioxide content.

The natural vegetation of the Ferrallitic soils is dense tropical rain forest, with deep-rooting vegetation, producing much organic matter.

The topography is characterized by an undulating and rolling terrain in old land surfaces, leading to a good natural drainage of the soils, because without the natural internal drainage no Ferrallitic soils would have formed. In flat areas and depressions the watertable may reach the solum, so that plinthite has formed in the subsoil.

4.4 Some characteristic soils

The Ferrallitic soils, in particular very old ones are deep to very deep ABC soils, with diffuse horizons, a stable friable soil structure, a clayey texture, a low content of silt; they are very porous, not shrinking nor swelling, and very resistant to soil erosion. The A horizon is a bit darker than the B horzizon but contains little organic matter; the B horizon is uniform, porous, permeable and contains many roots. The C horizon often occurs at a depth of some metres, while the hard parent rock material may occur at a depth of 10 to 40 m below the surface; the upper part of the rock is rotten.

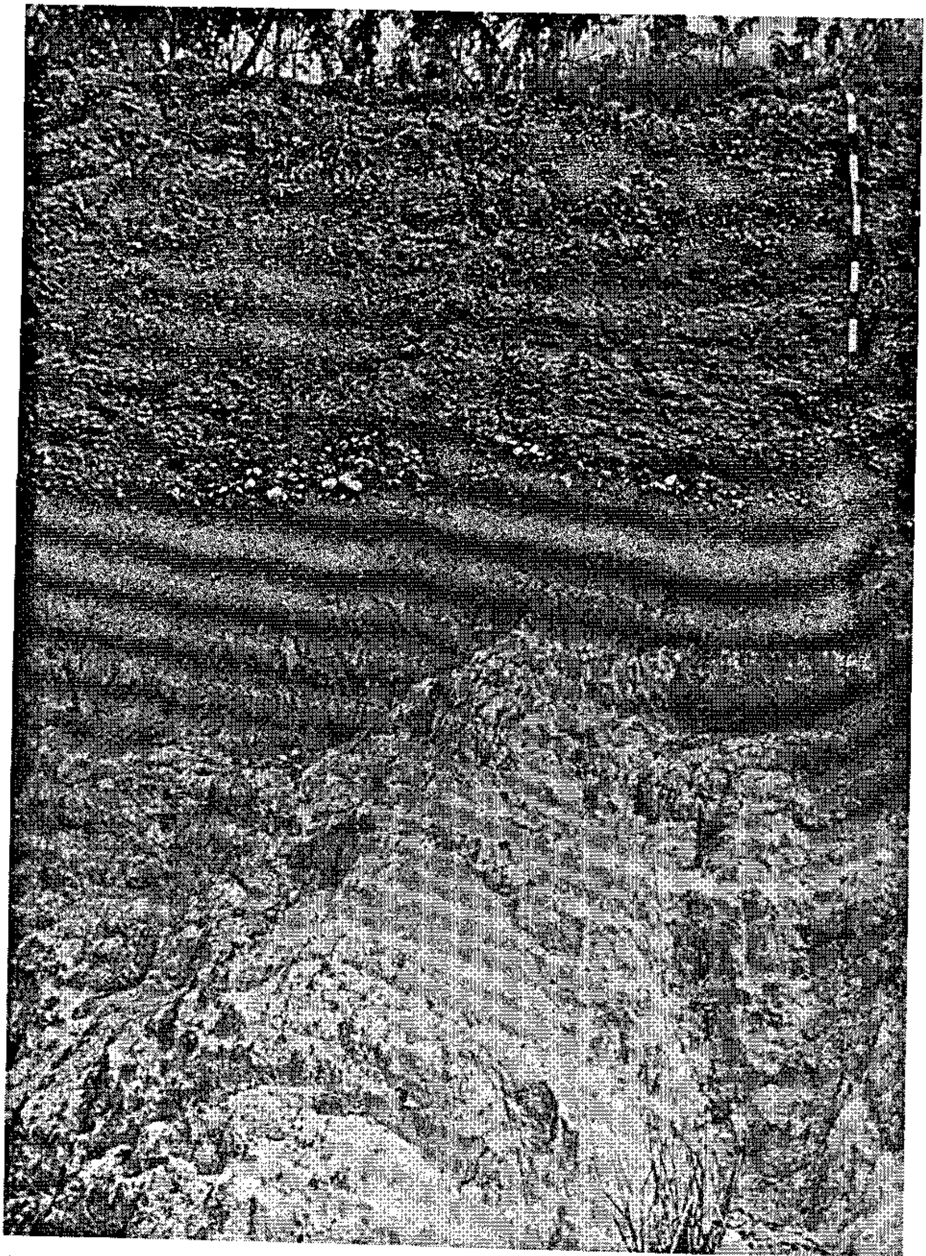
Chemically and mineralogically, the following characteristics are most important. The clay minerals are the 1:1 lattice clays, kaolinitic, with a low CEC; weatherable minerals are <1 % (by some other definitions <4 %), pH 4.5 to 6.0, $SiO_2/R_2O_3 \leqslant 2$ and $SiO_2/Al_2O_3 \leqslant 2$ (often even $\leqslant 1.7$). Morphologically the deep profiles are almost uniform, even in colour. There is an ochric, sometimes an umbric epipedon; the subsurface diagnostic horizon is an oxic horizon. In some classifications, it is called a ferrallitic or a latosolic B horizon. It is an altered horizon, consisting of a mixture of sesquioxides and 1:1 lattice clays; its main characteristics are thickness of more than 30 cm, retention by the fine earth of ⩽10 meq of bases per 100 g clay (with 1*N* NH_4Cl) and an apparent CEC of ⩽ 16 meq/100 g clay (NH_4OAc), only traces of weatherable minerals, some traces of water-dispersible clay, clay content (< 2μm) more than 15 %, gradual and diffuse soil horizon boundaries; less than 5 % of the soil volume has a rock structure. As the subsurface horizons are often thick, the lower boundary of the oxic horizon is usually set at 2 metres (for details, see CSSC, 1967 Supplement).

In some other definitions, other characteristics are mentioned too; e.g. $SiO_2/Al_2O_3 \leqq 2.0$ or <1.8; CEC <20 meq/100 g soil; a clay content of more than 11 %; L/A<0.25.

By differences in colour of the soils, a number of Latosols have been distinguished since 1950, e.g. Red Latosols, Dark-Red Latosols, Yellow Latosols, Earthy Latosols, Brown Latosols. Later some other Latosols have been added, e.g. Humic Latosols, Low-Humic Latosols, Hydro-Latosols, Latosols. Most of these soils, however, are no longer called Ferrallitic soils. Soils with hard or soft plinthite within 2 m of the surface have been called Groundwater Laterite; soils with less than 15 % clay are often called Psammentic Latosols, Latosolic Regosols or Areno Latosols.

4.5 Some intergrades and related soils

Intergrades may occur between various Ferrallitic soils and other great soil groups, e.g. Alluvial soils, Regosols and Litosols. A group of soils similar in morphological characteristics to Ferrallitic soils but with more than 4 % weatherable minerals is called Ferrisols. They are younger, or are mixed with colluvial material from less weathered places such as hill slopes. In the transitional areas, where the truly wet equatorial climate is changing into a tropical climate with a pronounced dry season there are intergrades towards another group of soils, the Tropical Ferruginous soils, sometimes also called Fersiallitic soils (Fr. Sols Ferrugineux Tropicaux, Sols Fersiallitiques), that are slightly leached with a weak A_2 and a textural B horizon. The Ferruginous soils will be dealt with in Chapter 5.



A hard plinthite or ironstone crust in a road cutting in southern Venezuela.

4.6 Soil classification

There always has been much discussion on the classification of the Ferrallitic soils. There are various systems, but they are almost completely incongruous. Even now most systems are not complete and they are still tentative. Some general remarks on the most important recent systems of soil classification will be made.

In Congo, Belgian soil scientists have subdivided Kaolisols into:
Hygrokaolisols of the forest regions
Hygro-Xerokaolisols of savanne regions
Xerokaolisols of dry savanna regions
Hydrokaolisols, the hydromorphic kaolisols.

These are each subdivided into Ferralsols (normal Kaolisols), Ferrisols (with more than 10 % weatherable minerals in the sand fraction) and the Arenoferrals (with less than 20 % clay, the sandy Kaolisols).

In the French system of soil classification, that is widely used in various African countries, the Sols Ferrallitiques are subdivided in the groups:
Sols Ferrallitiques typiques ($SiO_2/A_2O_3 < 1.7$)
Sols faiblement ferrallitiques ($SiO_2/Al_2O_3 < 1.7$ and $\leqslant 2$)
Sols Ferrallitiques lessivés (V is low, soils are more acid in the surface layer and there is an argillic horizon)
Sols Ferrallitiques humifères (7 to 8 % organic matter in the A horizon).

In Australia such soils are called Krasnozems (Russian for red soils), those with plinthite are Lateritic Krasnozems. (These Australian Krasnozems should not be confused with soils in Russia and Israel that are called Krasnozems, which are Ferruginous soils (Chapter 5). In German literature, the tropical soils under discussion are called 'Roterde, Braunerde'. The 'Nipe clay' developed on serpentine rock in Cuba and Puerto Rico is a real Red Latosol. In Brazil the Terra Roxa Legitima (pronounced rosha) is a well known Ferrallitic soil (Terra Roxa not to be confused with Terra Rossa from Italian (Chapter 5).

The British soil scientists, who introduced the term Ferrallitic soils, also used the name Red Earth that is subdivided according to the character of the parent rock. In some English-speaking countries of Africa the soils are called Ochrosols.

In CSSC most soils indicated as Ferrallitic soils belong to the order Oxisols, some belong to the order Ultisols. The Oxisols are those with an oxic subsurface horizon. The Ultisols do not have an oxic horizon, but have $V < 35\ \%$ at 1.25 m depth and an argillic horizon. In 1967, the Supplement introduced the following suborders of Oxisols:

Aquox (with groundwater influence)
Torrox (usually dry, polygenetic)
Ustox (dry for more than 60 consecutive days)
Humox (always moist, soil temperature <22 °C)
Orthox (as Humox but mean annual soil temperature >22 °C, no dry season).

It seems peculiar that some former Latosols are now classified as Oxic subgroups of Ultisols. The main reason is that until recently no good definition of a diagnostic horizon was available. Originally various often entirely different red and reddish soils of the tropics have been called Lateritic soils or Latosols, often the ratio SiO_2/R_2O_3 <2 being the only soil characteristic. As a result of recent investigations in many tropical countries, various suborders can now be distinguished (CSSC, 1967 Supplement). But the classification of these tropical soils is still insufficient and it may be expected that the classification of the Oxisols will be changed drastically in the coming decades, when more thorough and detailed investigations have been completed. The weaknesses and shortcomings in the classification of real tropical soils demonstrate clearly the present lack of knowledge of these soils.

4.7 Agricultural evaluation

The low V and CEC values, the low organic matter content and the high phosphate fixation (high free iron content) of Ferrallitic soils are factors raising difficulties for agriculture. Sometimes the rather high content of Al has a toxic effect on plant growth. Virgin soils, just reclaimed from the dense tropical forest, may produce good crops for some years but then yield drops to a low level. In newly reclaimed soils more organic matter and various ions for plant nutrition are available. Under natural forest a limited amount of ions circulate in the soil and vegetation. As soon as the soil is cultivated and crops are produced, the ions are released from this natural system, the mineralization of organic matter proceeds very rapidly and soil fertility becomes extremely low. It is difficult to build up a reasonable fertility status in these soils. However, due to the favourable physical soil condition, much more can be produced on many Ferrallitic soils if soil and agricultural management systems are improved. The system of shifting cultivation is often well adapted to present living condition of the rather poor farmers and is probably still the best. In future all soils have to be fertilized but it seems hardly possible to transfer knowledge of fertilizing soils in temperate regions to the Ferrallitic soils. Much research is still needed. Unfortunately there are only a few soil research institutes in the tropics studying these problems (Moss, 1968).

4.8 Regional distribution

Ferrallitic soils are known from all continents with tropical conditions. The new soil maps of Africa (d'Hoore, 1964) and of South America (Beek & Bramao, 1968) show the distribution of Ferrallitic soils and their relation to similar soils in the tropics. Some small general maps showing the distribution of Latosols are published too (Prescott & Pendleton, 1952). New soil maps on a small scale of all continents will be published soon by FAO and UNESCO. Many soil maps of countries or special regions show various types of Latosols. But there is a shortage of really detailed soil maps showing the soil series and types that form the various groups and subgroups. Most soil maps are only general, the descriptions are often too superficial with insufficient analytical data. The present French investigations (ORSTOM) are often the best for Africa, those in Brazil for Latin America.

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5 Ferruginous soils and tropical podzolic soils

5.1 General introduction

In tropical and subtropical regions with a prolonged dry season, many soils have a typical red or reddish colour caused by dehydration of iron compounds. These soils lack the typical characteristics of the Ferrallitic soils of the wet tropics (Chapter 4). Like Ferrallitic soils, they are rich in sesquioxides and 1:1 lattice clays but, unlike them, they also have 2:1 lattice clays.

In most of these soils, some argillation has resulted in a textural B horizon (B_{2t}) or argillic subsurface horizon. Most soils are oldish and have an ABC soil profile, unless they have been truncated by erosion as a consequence of deforestation. The alternating wet and dry seasons cause a contrasting soil climate, thus restricting the agricultural potential. The soil-forming processes are similar to those of Ferrallitic soils. Ferrallization is often the main process. Soils with hydromorphic characteristics contain also plinthite. In the subtropics rubefaction (Fr. rubéfaction; Ger. Rubifizierung) may become important.

Various soils in the tropics, often with a diverse range of internal soil characteristics, belong to the Ferruginous soils; they are often called Tropical Ferruginous soils (Fr. Sols Ferrugineux tropicaux) or Tropical Podzolic soils.

In Africa various soils classified as Sols ferrallitiques by the French soil scientists come within the scope of this chapter. Other soils have been called Sols fersiallitiques. Another important group of soils to be discussed in this chapter is the group Red and Yellow Podzolic soils, sometimes called Lateritic Podzols or Tropical Podzolic soils. In the literature on soil science, there are a great variety of such soils, which have been given special names. Since more has become known of tropical and subtropical soils and since soil classification has progressed, it has become easier to recognize characteristics common to these soils.

The main representatives in the subtropics are Red and Brown Mediterranean soils occurring in various countries around the Mediterranean Sea. They include the red soils on hard limestone, formerly called Terra Rossa.

In the following sections, reference will be made mainly to Red and Brown Mediterranean soils, Tropical Podzolic soils, and to Tropical Ferruginous soils. There are related soils, intergrades to Ferrallitic soils of the wet tropics or to semi-arid soils of the tropics and subtropics, while the Red Mediterranean soils have also intergrades to soils of temperate regions.

5.2 Soil-forming processes

The main processes are decarbonation, rubefaction, argillation, ferrallization (Section 4.2) and erosion.

Decarbonation (leaching of carbonates) results in carbonate-free A and B horizons. Sometimes some carbonate concretions may occur in the lower part of the B and in the C horizon.

Rubefaction (Fr. ferrugination, rubéfaction; Ger. Rubifizierung), mentioned in Section 2.3, is a process acting upon iron-rich parent material, forming hydrated ferric oxide, that by dehydration and crystallization in the dry season is transformed into bright red haematite. This process is active in soils of subtropical regions with a cool moist winter and a dry hot summer (Mediterranean climate). In forest soils that conserve moisture and are rich in organic matter, rubefaction is less thorough than in non-forest or cultivated soils, which dry out much more completely so that mineralization of organic matter is more rapid. In the clay fraction, illite is the most important clay mineral in subtropical soils, although some kaolinite is often present. In particular in the tropics, kaolinite may be more important but 2 : 1 lattice clays are still present.

Argillation (Fr. lessivage d'argile; Ger. Tonauswaschung) is a type of podzolation, in which fine clay particles (<1 μm) are leached from the A to the B horizon which becomes a textural B horizon (B_{2t}) in most of these soils. Finally a real argillic horizon is formed with clay skins (coatings or cutans) on the often blocky or prismatic peds. Ferrallization (Section 4.2) is one of the processes.

The total effect of these processes is a clear ABC soil profile, sometimes even with an A_2 horizon. Soils have often been eroded; such truncation may expose the B horizon or even the paler C horizon or rock. Much eroded material is deposited in valleys and depressions. In this colluvial material (Fr. Roche fille) a new ABC profile develops by the same processes. Stone lines or stone pavements have often formed. Various soils in the subtropics also have vertic characteristics deeper in the subsoil, e.g. slickensides.

In the tropics, similar processes to those of Ferrallitic soils have caused the formation of Tropical Ferruginous soils but a true dry season and argillation become important. Often there are weatherable minerals left and unlike Ferrallitic soils 2:1 lattice clays occur, besides the 1:1 lattice clays and high value for sesquioxides (SiO_2/R_2O_3 >2) characteristic of Ferrallitic soils.

In hydromorphic soils, plinthization (Section 4.2) occurs, in particular in the tropics. In some subtropical soils, plinthite may have been formed in a former geological period.

5.3 Soil-forming factors

Important factors are similar to those in Ferrallitic soils (Section 4.3). In the tropics, the natural vegetation is mostly a semideciduous or deciduous forest or savanna.

The real subtropical Ferruginous soils, the Red and Brown Mediterranean soils, are mainly formed on hard crystalline limestone, which retains little water and is readily permeable through cracks. However, some soils have formed on other rocks, e.g. schists, basalts, granite. There is a typical alternating soil climate which is hot in the dry season. The cool moist winter (8°-10°C) alternates with a hot dry summer (25°-35°C). The annual precipitation is about 600-900 mm, the effective precipitation much less. During the dry summer, the soil is completely dry for more than two months, often 3 or 4 months. Deforestation has often reduced the vegetation to a few shrubs and grasses, or land is cultivated and often severely eroded. The 'garrigue' on limestone parent material, and the 'maquis' on non-limestone parent material in southern France are well known. The topography of the land is mostly undulating, rolling or hilly; erosion is severe. Therefore most soils are rather shallow, stony and rocky.

Tropical Ferruginous soils have mostly formed on granite and gneiss. They do not often occur on ultrabasic, volcanic or lime-rich material. Here too there is an alternating climate, with an extreme dry season lasting at least some months. The annual precipitation is usually between 500 and 1200 mm. There is hardly any natural vegetation. Forest-savanna is often overgrazed and grasses are often burned; shifting cultivation is normal.

All Tropical Ferruginous soils and Tropical Podzolic soils are old and well developed. Many are polygenetic through changes in climate during the Pleistocene Era.

5.4 Some characteristic soils

Red Mediterranean soils

The main characteristics are the brick-redness of the whole soil and the paucity of organic matter in the epipedon (often no more than 1 or 2 %). The soil consist of decarbonated heavy clay. Below a rather uniform red A horizon (ochric epipedon), there is a red argillic horizon with distinct clay skins. Most Red Mediterranean soils, particularly in undulating or rolling landscapes, are truncated and a new ochric epipedon has formed in the upper part of a former argillic horizon. Other Red Mediterranean soils are very stony or rocky and have a rather shallow profile. In valleys and depressions, the soils are deeper, consisting mainly of mixed colluvial material. Although the soils are thoroughly decarbonated, the base saturation (V) is mostly over 40 %. The bright red of the soil has a high chroma.

The Red Mediterranean soils have a hue 2YR or redder; those with a hue 5YR or browner (sometimes 7.5YR) are called Brown Mediterranean soils.

A shallow Red Mediterranean soil with a thick lime crust, that is often at the surface. An area south of Aleppo, Syria.

In some countries, the 5YR soils are considered to be red too. In general these soils are referred to as Red and Brown Mediterranean soils (Fr. Sols rouges et bruns méditerranéens lessivés). The new name recently proposed by FAO soil scientists is Red and Brown Argilluvic soils. A typical soil is the Terra Rossa (Italian name) studied in various countries; it occurs under various conditions. Often quite different types of clayey soils, all typically red, have been called Terra Rossa, obscuring the meaning. In karst areas, relict soils occur in often severely eroded hard limestone. These soils are very shallow, stony and rocky; sometimes wide and deep cracks in the limestone are filled with red clay. Such soils are considered to be the real Terra Rossa soils of the southern France. In other Mediterranean countries, the deep red colluvial soils are also called Terra Rossa. In Israel the red sandy soils along the coast, there called Hamra soils, also belong to the Red Mediterranean soils. Similar Red Sands occur also along the east coast of South Africa.

Tropical Podzolic soils

These soils are rich in iron, often low in organic matter, red or reddish; they often have an argillic horizon and base saturation (V) is sometimes above or below 35 %. The process of argillation is often so clear that a much lighter reddish A_2 horizon, much lower in clay and much higher in sand, is clearly visible. The argillic horizon often has a prismatic structure, with clay coatings, that can best be observed during the wet season. The soil profiles are characterized by various horizons, in particular the A_2 and B_{2t}.

The Red and Yellow Podzolic soils of the former USDA classification are typical representatives. French soil scientists call these soils Sols ferrugineux tropicaux lessivés if there is a clear argillic horizon and iron oxides have been redistributed. If there is no clear argillic horizon, often because they are too young so that argillation has only resulted in a weak textural B horizon, they call them Sols Ferrugineux Tropicaux non lessivés. In various soils with a pronounced and almost impermeable argillic horizon, pseudogley occurs in the upper part of the B horizon.

Tropical Ferruginous soils

In the tropics there are many soils, called Tropical Ferruginous soils (Fr. Sols Ferrugineux Tropicaux), similar to Ferrallitic soils (Chapter 4). Some may have an appreciable amount of weatherable minerals or of 2:1 lattice clays, or a higher value for V. Most soils are less deep, e.g. 1 or 3 m. They lack a real oxic horizon. There may be some argillation and there often is a textural B horizon and horizon boundaries are rather distinct. These soils often are less permeable, more susceptible to soil erosion and often more fertile than Ferrallitic soils, through the higher V and CEC.

5.5 Some intergrades and related soils

There are various soils in the tropics and subtropics forming transitions to Tropical Ferruginous soils, Tropical Podzolic soils or to Red and Brown Mediterranean soils. First there are many variations within the broad groups, secondly there are intergrades towards the wet tropical Ferrallitic soils, to the soils of arid tropical or subtropical regions and to soils of the temperate regions. Important intergrades are those with characteristics of Vertisols in the subsoil, in particular slickensides at various stages of development. Intergrades towards Lithosols in mountainous regions and towards Hydromorphic soils in depressions and valleys are common too. In the tropics, various types of intergrades between Ferruginous soils and Ferrallitic soils occur. Most soils discussed in this chapter are oldish, so palaesols of typical red can be observed in various countries with a past climate suitable for formation of Ferruginous soils. The Red soils of Japan are an example. Those soils, that have formed in a cooler climate, e.g. mountain slopes or plateaus, mostly have a more pronounced and darker A horizon with more organic matter than the tropical soils.

5.6 Soil classification

Most of the soils in this chapter have only been closely studied in the last decades so that they can now be better classified than earlier. However, the various new classifications still have deficiencies. In countries with real Red and Brown Mediterranean soils (France, Italy, Spain, Portugal) these soils are classified into a special great soil group. In Portugal they are subdivided into soils derived from calcareous or non-calcareous rocks. CSSC assigns the Red and Brown Mediterranean soils, in particular the typical representatives, mainly to the order Alfisols by virtue of their argillic horizon. In 1966 the suborders were drastically changed, therefore the typical soils are now Xeralfs, because the soils in the typical Mediterranean climate are dry in the layer 18 to 50 cm for more than 60 consecutive days, the dry summer season. The Rhodoxeralfs are the typical red ones (redder than 5YR) whereas the Palexeralfs and the Haploxeralfs are less red or browner.

The Tropical Ferruginous soils and the Tropical Podzolic soils are classified into two orders: Alfisols (those with V >35 %) and Ultisols (those with V <35 %). In both orders they fall mainly into the Ustic suborder, because the soil in the layer 18 to 50 cm is dry for more than 90 cumulative days; the mean annual soil temperature is 22° C or higher, the difference between soil temperature in winter and summer is less than 5°C, indicating tropical conditions, and there is a pronounced dry season. Here too there are Rhodustalfs and Rhodustults for the really bright red soils and Paleustalf or Haplustalfs and Paleustults or Haplustults for the browner soils with an abrupt or gradual argillic horizon. Various soils in regions with a real dry season (more than 60 consecutive days of dry soil in the 18 to 50 cm layer) and with a base saturation less than 35 % have to be classified as Xerults, in the groups Palexerults and Haploxerults. The well known Terra Roxa Estruturada (coffee plantations) in Brazil has a medium to high value for V in the B horizon and is fertile.

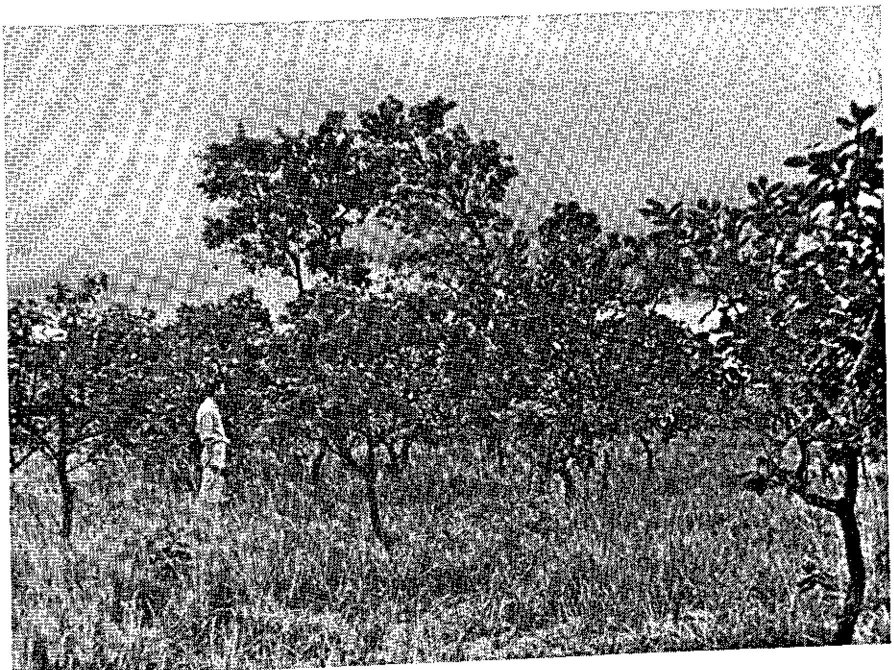
The classification of soils described in this chapter has always been difficult, whatever the system. The introduction of CSSC has made the assignment of many of them to classes much easier.

5.7 Agricultural evaluation

All Ferruginous soils share a pronounced dry season, during which no moisture is available for plant growth. Furthermore phosphate is a problem, because free iron fixes much of it. The Red and Brown Mediterranean soils are often very shallow, stony and rocky, poor for grazing. The deeper colluvial soils and soils on man-made terraces are often used for growing olives, pistachios, apricots or grapes. Although most soils are too dry in summer, they are often too wet in the rainy winter because of a poorly permeable argillic subsurface horizon. Deep soils in a favourable position should benefit from irrigation in the dry season but reservoirs are difficult to make in a karst landscape.

Salinization is not a problem, because red soils always have a free drainage to the Alluvial soils and the Vertisols in the valleys and depressions, which are mostly rather saline. If enough deep clay-filled cracks occur, reforestation is possible.

The Tropical Ferruginous soils mainly form bush savanna in regions where shifting cultivation and extensive grazing, including burning of grass, are practized. There too the possibilities of irrigation are often limited, because of shortage of water. Cropping during the rainy season depends mainly on total rainfall and the distribution of rainfall in the rainy season. Often soils with high base saturation are better than those with low V. Fertility depends on content of weatherable minerals.



Bush savannah in Venezuela: a type of vegetation that is typical for tropical regions with a pronounced dry season.

5.8 Regional distribution

The Red and Brown Mediterranean soils are well known from Mediterranean countries (Greece, Italy, southern France, Spain and Portugal, Morocco, Algeria, Tunis and southern Turkey). They also occur in some Balkan countries. Their distribution is shown on the soil map of Europe (1966) and on special maps published by Durand (1959).

Tropical Ferruginous soils and Tropical Podzolic soils occur in Africa and South America. In Africa they have been particularly studied by the French soil scientists of ORSTOM. In Latin America studies have been in Brazil. Red and Yellow Podzolic soils are well known in the southern United States.

For Ferruginous soils the most important characteristics in agricultural evaluation and consequently in soil mapping is the depth of the solum and the rootable volume; also important are the presence and depth of the argillic horizon, erodibility, stoniness and rockiness, V, and the reserve of weatherable minerals.

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6 Tropical Alluvial soils

6.1 General introduction

Alluvial soils are very important for agriculture. They occur all over the world in river plains, estuaries, deltas and low coastal regions. Alluvial soils of temperate regions are well known and closely studied, in particular in the Netherlands (Edelman, 1960).

Despite many similarities of Alluvial soils of the tropics and subtropics, there are also some important differences from those of temperate regions.

Alluvial soils are azonal, usually defined as young soils of recent and

Aerial view of the Orinoco Delta, Venezuela.

subrecent sedimentary deposits, without horizons or with only weak ones. The concepts Alluvium and Alluvial soils have various meanings. In geology Alluvium is a deposit of the Holocene Period. In sedimentology Alluvium often refers to sediments deposited in recent flooding, whereas in geography Alluvial plain means a flood-plain or river valley.

In this chapter Alluvial soils are soils with the following general characteristics. They are very young or young often stratified mineral soils in recent or subrecent sedimentary material, which has been carried in suspension, transported and deposited by water. They have a heterogeneous mineral composition and are permanently or seasonally wet, often with groundwater influence. They form flats in the lowest parts of a landscape and have hardly any profile; (A) C soils.

Alluvial soils occur mainly in:

a. River plains, seasonally flooded by rivers, often called flood-plain soils
b. Alluvial fans, deposited at the transition from highland to a valley bottom during short periods of heavy discharge by a small stream, often called fan soils
c. Deltas, seasonally flooded by rivers, low-lying soils with a permanent high watertable, often called delta soils
d. Estuaries, at the transition of flood plains to deltas with a mixture of fresh and saline water, influenced by tides. In most countries estuaries are in the brackish zone, whose soils are often called estuary soils
e. Former lake bottoms, originally underwater sediments, often called lacustrine soils
f. Old irrigated regions, where a thick layer of fresh material has been deposited during irrigation, called irrigation deposit soils or irrigational soils
g. Coastal plains, deposited in seawater, influenced by the tides, often called coastal or marsh soils.

Deposition can take place:

a. Under water (mud clays), e.g. in lakes or the sea
b. During flooding of a river with a high discharge in specific seasons, e.g. in river plains, the higher parts of deltas and in fans
c. During twice daily floodtides, e.g. in coastal regions and estuaries.

In some regions there are no longer floods, because the land is protected by dikes and drained, because the river has cut a deeper bed, or because man has built dams and barrages.

The water that transports the material in suspension (diverse organic materials and minerals) or in solution (carbonates, gypsum, chlorides, sulphates and other salts) may be fresh, brackish or saline. The young sediments may consist of mixtures of various unweathered, partly or completely weathered minerals depending on the lithological composition of the catchment areas (watersheds) and the cycles of erosion and deposition in soil development that have taken place in geological periods. In wet and humid tropical regions, sediments often consist of almost completely weathered material (base-leached material) that forms the rather infertile parent material of many Alluvial soils. Kaolinite clays, sometimes mixed with some illite and montmorillonite are the most important clay minerals. In volcanic regions, some fresh minerals may be present, producing a much higher natural fertility (Java, Indonesia).

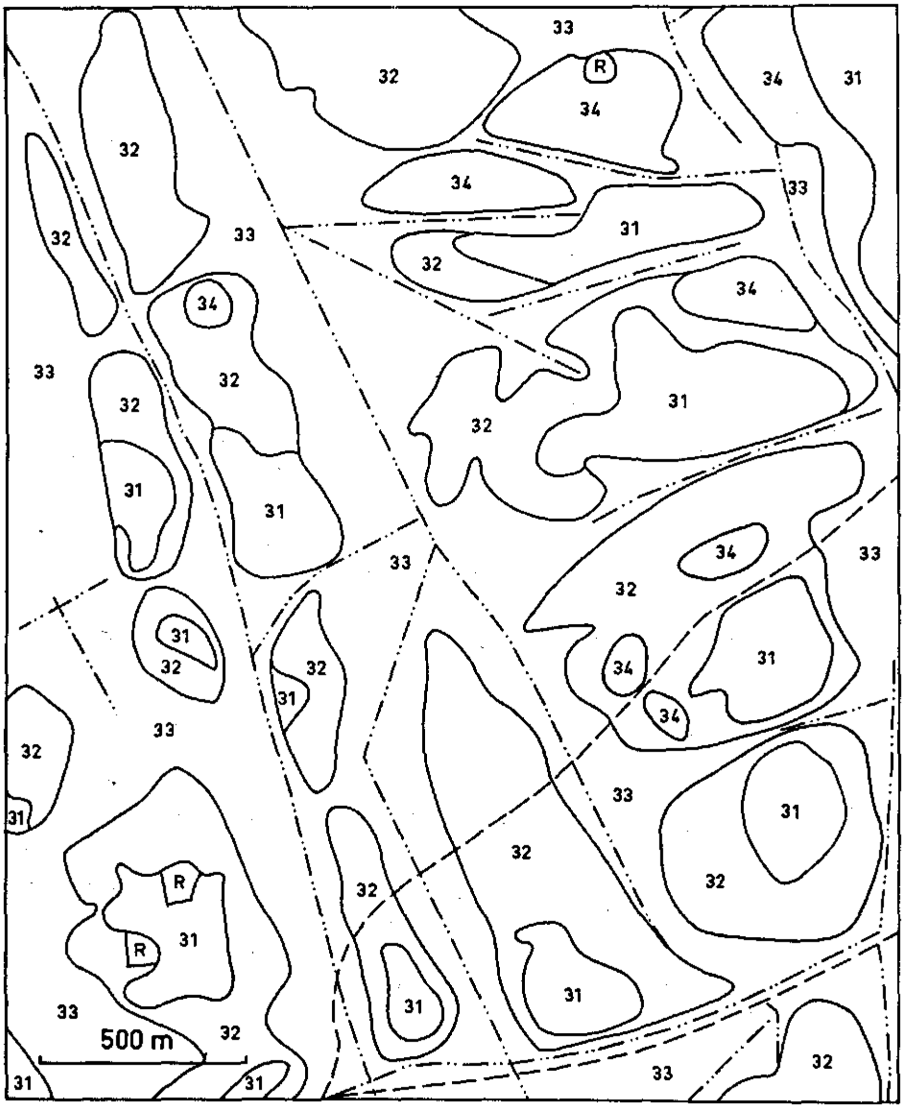
The usually low natural fertility of tropical Alluvial soils is an important difference from the often fertile Alluvial soils of temperate regions, where sediments are relatively young as they have mainly been deposited during recent glacial periods. In arid and semi-arid tropical and subtropical regions, sediments often consist of less weathered minerals, often high in carbonates and gypsum; illite is the main clay mineral. Marine sediments usually contain weatherable minerals.

6.2 Soil-forming processes

Although Alluvial soils are young, there are still some processes that influence soil conditions. These processes are influenced by various environmental conditions. In arid regions rainfall is low and vegetation is sparse, whereas in wet and humid regions rainfall is high or extremely high and vegetation is dense. The flatness and lowness of Alluvial soils make most of them wet with a high watertable, permanently or during specific periods. Such soils are called Hydromorphic soils.

Sedimentation

Sedimentation (a geogenetic process) of material in suspension or solution depends on the velocity and turbulance of the water transporting the material, on the size of the particles and on the chemical composition of the water. Particles up to about 50μm (sometimes up to 100 μm) are carried in suspension, larger particles are dragged along the river-bed. The suspended material is deposited in sedimentation patterns, common throughout the whole world. Alluvial soils are often classified by such characteristics related to their physiographic position.



Detailed soil map of an area in Central Iraq. All soils are Alluvial soils in irrigation sediment. The saline irrigation levees (33) are about a metre higher than the heavier-textured saline-alkali irrigation depression soils (31); the transitional soils are partly saline (32), and partly leached (34). The map shows a typical pattern of sedimentation that is related to the position of the irrigation canals (dotted lines).

In flood-plains of meandering rivers, the most important physiographic units are natural levees and basins (backswamps). Other features are silted-up former river-beds and meander belts. The silting up of the plain or valley may change the river's course, build up new levees and basins on top of former ones, and form layered soils consisting of layers of varying thickness and texture.

In braided river-plains, there is a specific braided gully pattern consisting of course-textured soils.

In cultivated areas, where irrigation has been practised for centuries (e.g. Mesopotamia), several metres of irrigational sediment have been deposited over the former valley bottom. Along the irrigation canals and ditches, irrigational levees and at some distance irrigational basins or depressions are found. The soils are often silty or clayey. The pattern of deposition is closely related to the pattern of canals and ditches made by man.

In deltas the pattern of deposition is similar to that of the flood-plain but the rivers have many branches. There are small levees and large backswamps. Soils are often flooded for much longer and the watertable is almost always near the surface.

The estuary pattern of sedimentation is similar to that of the deltas; often there are sharply curved creeks, and the water is brackish.

Near coasts there are former beachwalls (sand, gravel or shells) and coastal flats with saline clayey soils.

The lacustrine pattern of sedimentation is less distinct. Usually soils are uniform and clayey (underwater deposits, mud clays), often mixed with organic material, very soft with a very high water content. Sometimes beach-walls occur, indicating former beaches of the lake. In flooded regions with dense forest or a swamp or papyrus vegetation, the water moves much slower than over bare soil or short vegetation of grasses only. The type and density of vegetation therefore influence the pattern of deposition.

Initial soil formation

Young sediments deposited under water contain much more water than normal soils. The packing of the particles is very loose and the material is reduced. Such clayey material is called mud-clay. The process by which these mud-clays change into normal oxidized soils is called initial soil formation or ripening (Pons & Zonneveld, 1965). It has physical, chemical and biological aspects.

During ripening the physical characteristics of the clays change. Water drains off or evaporates and the mud-clay loses water and dries out. Horizontal shrinkage causes clay to crack, often into a polygonal pattern.

There is also a gradual vertical shrinkage as drainage and evaporation continues. This causes a gradual subsidence. The clay material may lose more than half its water. When moistened, it can never take up so much water again.

The chemical process is mainly oxidation and decarbonation. On drying, air penetrates the soil through the many cracks; organic matter oxidizes rapidly. The bluish-gray of the reduced mud-clay changes to brownish by oxidation of iron compounds. In brackish mud-clays containing pyrite, this is also oxidized, removing the commonly blackish colours. In various clays, particularly marine clays, the cations ratios of the clay complex change too; Ca^{2+} increases and Na^{+} decreases.

Biological processes start as soon as plants grow. Roots penetrate the clays; evapotranspiration rapidly increases; various microbes and larger organisms can live in the clay.

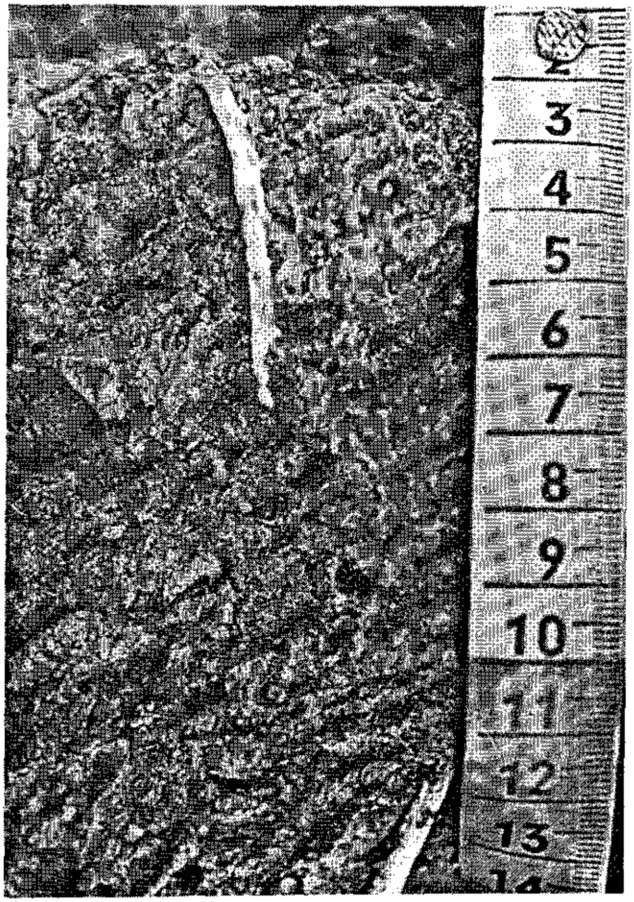
The initial process of soil formation or ripening, the transformation of mud-clay into soil material, is irreversible. A soil once ripened can be partly reduced by submerging it again, but it never takes up all the lost water. There are various stages in soil ripening. The process is not only important for agriculture but also for land reclamation and road construction. Mud-clays have a much lower load-bearing capacity than normal oxidized clays. The ripening factor or n value indicates the stage of ripening.

$$n = (A - 2) / (L + 3H) \quad \text{or} \quad n = (A - 0.2Z) / (L + bH)$$

in which A = % water, L = % clay, H = % organic matter, Z = 100 — H — L and b is a factor of about 3. In the field, the clay can be tested by squeezing it between the fingers: if $n \gg 0.7$, the clay flows easily; if $n > 0.7$, the clay flows with difficulty; if $n < 0.7$, the clay does not flow between the fingers. A very unripe clay soil often has an n value of 3 to 5.

Decarbonation starts if there is excess rainfall and the soil dries. The rainwater, that becomes acid when it takes up humid acids in the upper part of the soil, percolates through the soil. There is a leaching of carbonates which may be about 1 % per century in temperate regions and humid subtropics, and somewhat higher in the tropics.

Biological homogenization is another important process. It is the mixing of the fine stratified sediments by plant roots and by microbes and larger fauna and flora. Worms mix the soil material thoroughly. This mixing, cracking and penetrations of roots make the soil porous. The pores vary in diameter and length, and form a heterogeneous system very favourable for crops. Most crop roots penetrate only the homogeneous upper soil layer. Some soil animals, in particular worms, eat soil and thoroughly mixe it with organic material to form a dark mull. In the tropics the action of termites and ants can be very widespread in somewhat drier soils.



Surface soil with very high biological activity (many holes and pores) from a tropical forest in Venezuela.

Gleying

A fluctuating watertable causes alternate oxidation and reduction in soil layers above the groundwater. Bluish-gray reduction (gley) and reddish oxidation (rust) mottles form. The rust spots, mainly orange-brown in temperate regions are often more reddish or yellowish in the tropics, through warmer soils and some dehydration. Rust occurs particularly along cracks and root channels; sometimes there is a tendency to form concretions (not plinthite). In highly calcareous soils of arid regions there are almost no rust spots or mottles, and redox potentials have to be measured in order to find the status of the soil.

Cat clay formation

Although cat clays (acid sulphate clays) are best known from temperate regions, where marine clays have been deposited in acid brackish water, there are even wider and more extensive areas of acid sulphate clays in the tropics, in particular in coastal regions. These marine clays contain pyrite, often in large amounts. The soft mud is not ripe, its pH is 7 to 8 and it is completely reduced. Oxidation produces acid sulphate clay (pH 2 to 3), especially if the soil contains little or no lime. The final stage is the formation of straw-yellow mottles of basic ferric sulphate. Such a clay is called cat clay.

Sulphur and sulphates come from seawater; reduction forms insoluble iron sulphide (FeS) which is finally transformed into polysulphide or pyrite (FeS_2). This reduction of sulphate is a biochemical process. Reduction is most complete when some organic matter is present (mangrove, reed). Reduction of sulphates by micro-organisms forms hydrogen sulphide (H_2S), which produces various compounds with iron, such as $FeS.nH_2O$ which changes into $FeS_2.nH_2O$ (cryptocrystalline pyrite). Both are black, giving the reduced soil a blackish tinge. Oxidation forms $FeSO_4$ and H_2SO_4; more oxidation forms ferric sulphate ($Fe_2(SO_4)_3$), which hydrolyses to the yellowish basic ferric sulphate ($Fe(OH)SO_4$) (van Beers, 1962).

Peat formation

When soils are poorly drained, very wet, or submerged, the decomposition of organic matter produced by the dense vegetation is slow and stagnates. A partly decomposed organic layer is formed on the surface of the mineral soil. In Surinam this organic layer is called pegasse, in Nigeria chicoco. Sometimes organic matter is formed during deposition and a mixture of organic matter and clay, containing much water, forms. Such soils have a low load-bearing capacity, a weak surface and cannot carry grazing cattle or farm machinery.

Some other processes

Lateral movement of groundwater from higher surroundings can transport diverse compounds in solution to the lower Alluvial soils and cause specific characteristics. Iron-rich underground layers (plinthite) may form (plinthization: Section 4.2). Other soils may acquire vertic characteristics (e.g. slickensides, see Chap. 7). In other regions there may be lateral movement of acid, highly calcareous or gypsiferous groundwater.

In the humid tropics, soil-forming processes continue throughout the year because of the warm soil, the high precipitation and leaching; hence normal soil-forming processes take effect much earlier than in cooler and temperate regions. Alluvial soils with very little or no evidence of soil formation therefore change rapidly into zonal or intrazonal soils. In temperate regions progressive soil formation consists mainly of a browning (Ger. Verbraunung), the formation of a coloured B horizon (a cambic horizon) with specific structure. This process also occurs in the subtropics and tropics, although colours are more reddish because the process intergrades to ferrugation.

6.3 Soil-forming factors

The composition of the parent material, that consists of a mixture of various often base-leached material, depends closely on the mineral composition of the soils and weathered or unweathered material of the catchment area. In catchment areas with Ferrallitic soils, the parent material of the Alluvial soils consists mainly of kaolinitic clays, quartz, and highly resistant minerals, low in natural fertility. In arid and semi-arid regions, the often unweathered minerals are mixed with lime and gypsum, and natural fertility is much higher. Clays of heavy texture in natural basins may contain 30 to 40 % lime, that gives these arid clays much more favourable physical properties (structure, porosity) than non-calcareous basin clays in temperate regions. In regions where volcanoes are active, unweathered volcanic minerals may form an important component of minerals in the Alluvial soils.

Some large rivers have a catchment area entirely in the equatorial region (Congo, Amazon); others rize in an equatorial region but end in the subtropics (Nile), or rise in temperate regions and end in the subtropics (Tigris, Euphrates) or in the tropics (Ganges, Mekong). The parent material of the Alluvial soils deposited by these rivers are obviously quite different. Marine clays often are more alike. They are richer, often illitic. However they are poor in calcium carbonate because of the higher, more uniform temperature of seawater and the thorough leaching in high rainfall.

The climate does not have an important influence, except for the leaching (decarbonation, desalination) of the young soils. Vegetation is an important factor, first during the geological process of sedimentation (decreasing the velocity of flood water) and secondly by producing organic matter, transpiring water (ripening), perforating the soil and encouraging microbes. Under specific conditions, a real O or organic surface horizon can form but normally the O horizon is only weakly developed. In some tropical grasslands with a shallow watertable 'kawfoetoes' (pronounce cowfooto) form, being microhills less than a metre high and consisting of wormcasts. Homogeneity is an important factor in Alluvial soils. Relief differences are usually limited to microrelief. In shallow depressions with poor drainage, organic matter or salts accumulate.

Hydrology is another main factor. Groundwater, floods and the effect of tides influence oxidation and reduction. Man's influence can be widespread. He can determine the type of vegetation, regulate rivers (dams, barrages), floods (dikes), make polders (areas of artificial drainage surrounded and protected by dikes), and determine the system of irrigation and the layout of canals and ditches. However man's influence is in general less important for Alluvial soils in the tropics than in temperate regions.

6.4 Some characteristic soils

The concept Alluvial soils is very broad, often including many diverse soils usually showing: a stratified (A)C or AC profile, with groundwater influences or characteristics of wetness often with strong gleying (g) in the subsoil, without diagnostic horizons, a flat topography, and lowness in the landscape. V, CEC, organic matter and natural fertility are normally lower than in Alluvial soils of temperate regions. Sedimentation takes place in specific patterns, producing typical physiographic units, characterized by differences in texture, topographic position, groundwater influence, stratification, vegetation and hydrology. Besides these differences, there are also important differences in mineral composition, clay mineralogy, thickness of layers, lime content, consistency, stage of ripening, decarbonation and homogenization.

6.5 Some intergrades and related soils

There are many intergrades towards other soils. First there are intergrades towards Saline and Alkali soils, Vertisols, and Organic soils or Histosols. There are intergrades towards other types of zonal soils, especially in older alluvial deposits, mainly on terraces of different age. Here one can observe intergrades towards Arid and Semi-Arid soils, Ferruginous soils, Ferrallitic soils and Andosols.

A specific tropical soil is the Sawah soil, a man-made rice soil. This is a typical hydromorphic soil, often artificial, continuously flooded during the growing season. The surface layer is thoroughly mixed by puddling; it is bluish-gray by reduction. Below an Ap horizon there is a more clayey plastic compact layer with complete reduction and a very slow permeability. Underneath is a horizon with rust and gley mottling, and a horizon with manganese accumulation. Both are oxidized and grade into an oxidized subsoil. The physical condition of such soils is poor for most crops. To grow good rice, the cropping season has to be followed by a dry season when the surface soil oxidizes slightly, and free iron oxidizes too. In the next period of reduction the oxygen of the ferric hydroxides becomes available for the rice. The pudding of the soil reduces permeability, and softens it in a way suitable for planting out rice.

6.6 Soil classification

In most systems of soil classification, Alluvial soils are a great soil group of the Azonal soils, together with the Regosols and Lithosols. Often little attention is paid to further subdivisions because most Alluvial soils are still subject to flooding by rivers, submerging by seawater of very poorly drained. Their potential is small until they have been protected and well drained, when, except for acid sulphate soils or cat clays, they may achieve high agronomical value.

In some Western European countries, where Alluvial soils are well protected and drained, a physiographic classification is adopted. The advantage of such a classification is the close relation to agricultural potential and artificial drainage requirements. Subdivisions of Alluvial soils are often based on soil texture, thickness and drainage classes or phases; however, it *should be realized that in particular the phases of ripening and homogeneity* in various depth classes of the stratified subsoil are often more important than textural classes.

Their classification on taxonomic principles has much advanced with the introduction of CSSC. Most Alluvial soils belong to the order Entisols. Since 1966, however, the characteristics of wetness, present in a great many Alluvial soils, are considered to form a special type of cambic subsurface horizon, and therefore such soils now often belong to the order Inceptisols and the suborder Aquepts.

In the order Entisols the suborder Fluvents is the typical suborder for Alluvial soils without clear characteristics of wetness. There is no specific diagnostic soil horizon and content of organic matter in the soil decreases irregularly with depth. The following groups are important for the tropics and subtropics:

Hydraquents: n (Section 6.2) > 0.5, clay > 8 % and organic matter > 3 %, typical unripened soils

Torrifluvents: usually dry, e.g. in arid and semi-arid regions

Ustifluvents: dry for more than 90 cumulative days, in tropical regions with

pronounced dry seasons
Xerofluvents: dry for more than 60 consecutive days and less than 180 cumulative days, mainly in subtropical regions with a long dry season
Tropofluvents: of the wet and humid tropical and equatorial regions.

In the order Inceptisols and the suborder Aquepts, that are saturated with water for some period of the year and that have characteristics of wetness, the following great groups must be mentioned:
Tropaquepts: of tropical regions, where the difference of soil temperature in winter and summer is less than 5°C
Humaquepts: with an umbric, mollic or histic epipedon
Plinthaquepts: with plinthite in the subsoil at a depth of less than 125 cm.

The classification of the many intergrades does not give serious difficulties, since many grade towards Inceptisols, or are an Entic subgroup of soils of various other groups, since the typical characteristics of the Typic subgroups are not well developed.

6.7 Agricultural evaluation

In many regions the productivity of Alluvial soils is low, partly because of low natural fertility or high acidity, but more through floods and inundation, because most low-lying Alluvial soils are not protected by dikes and there are no pumping stations that can drain the land. Very often the period in which Alluvial soils can be cultivated is short and only crops with a short growing season can be grown. In some regions there is salinization or alkalization, in others a dense vegetation or there are no roads. In many coastal areas soils are unripened clay soils, that become acid sulphate soils on reclamation. The special crop of Alluvial soils is rice, but sugar-cane, bananas and on better drained sites cocoa, coffee and citrus are grown too. Although tropical Alluvial soils are not considered to be as good as those in temperate regions, they still have great potential. However it is extremely difficult to reclaim such soils, not technically, but because of economics and sociology.

6.8 Regional distribution

Alluvial soils occur in almost all countries in the tropics and subtropics. Important rivers and deltas in the subtropics are the Nile, the Tigris and Euphrates, the Jordan, the Yangtse, the Murray, the Parana, the Mississippi, and in the tropics the Indus, Ganges, Brahmaputra, Mekong, Irrawaddy, Digul, Congo, Niger, Amazon and Orinoco. Coastal flats, often with acid sulphate clays are well known from Surinam (Pons, 1965; van der Eyck, 1957; van der Voorde, 1957), Guyana, Sierra Leone and South-East Asia (Moorman, 1961).

Irrigational sediments, now forming Alluvial soils, are best known in Mesopotamia (Buringh, 1960). Innumerable areas of Alluvial soils are scattered all over the world. Many villages are built on levees, shorelines and other natural elevations, where food and cash crops are grown often, under primitive conditions.

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Deep and wide cracks in a brown Vertisols in the Sudan.

7 Vertisols

7.1 General introduction

Vertisols are heavy-textured, often dark clay soils, that shrink during the dry seasons; they have deep wide cracks, that close during the wet seasons. Other features are gilgai microrelief or slickensides at some depth. The shrinkage and swelling is due to the presence of montmorillonitic clays, to an alternation of pronounced dry and wet seasons, and to a warm climate.

These soils occur in a great many tropical and subtropical countries and include a range of soils known as Regur (India), Grauwaarden or Margallitic soils (Indonesia), Black Cotton soils (India), Tropical Chernozems (Africa), Black Earths (Australia), Badobe soils (Sudan), Vlei soils (S. Africa), Tirs (N.Africa), Barros (Portugal), Smonitza or Smolnitza (Balkan).

Since 1951, when results of comprehensive studies in the United States (Texas) were published, they have been called Grumusols. This name was changed to Vertisols (Latin vertere = to turn) when CSSC (1960) was published. This name has been generally accepted in almost all countries. Even in the new French system of soil classification, the name Vertisols has been introduced. There are many more local names for these soils but not all soils belonging to a group with such a specific name are Vertisols as now defined.

A monograph recently published by FAO (Dudal, 1965) reviews present knowledge of these soils. For agriculture in the tropics and subtropics these soils are important but they have limitations because they are difficult to handle and internal drainage is poor.

Vertisols mainly occur in low-lying, large and flat areas where soil conditions are uniform. Their natural vegetation is often bush or grass savanna that can easily be cleared. They are AC soils with a deep often dark-coloured A horizon.

7.2 Soil-forming processes

The main processes of soil formation in these heavy clay soils are cracking and swelling, self-mulching, churning, and the formation of slickensides, gilgai relief and kankar, and development of the dark colour.

Cracking and swelling

Cracking and swelling are due to the presence of montmorillinitic or smectoid clays and to alternating dry and wet seasons. Montmorillonite is a 2:1 lattice clay that shrinks when dry and swells when wet, so that wide deep cracks open up in a polygonal pattern, each polygon having a horizontal diameter ranging from 1 to 4 metres. The cracks may be a few centimetres wide and 80 cm or more deep. Such soils with at least 30 % clay and cracks at least 1 cm wide 50 cm below the surface are Vertisols.

Self-mulching

Many Vertisols have a loose granular surface mulch 1 to 5 cm thick, sometimes even 10 cm. This mulching is the result of a natural process, similar to that of cracking and swelling but limited to a shallow surface layer. Here the cracking leads to granulation into small (3 mm) hard particles, mainly because there is no pressure of a soil layer. In the subsoil granulation would be impossible because of compression by the upper soil. Self-mulching is not an essential characteristic of Vertisols, although most Vertisols do have a mulch layer. Some years ago a subdivision was made into suborders Aquerts (with groundwater influence) and Usterts (without groundwater influence). These suborders have had two groups, the Grumic (Grumaquerts and Grumusterts), those with a self-mulching surface, and the Mazic (Mazaquerts and Mazusterts), those without a mulch but with a solid crusty surface. Recently it was realized that granulation of the surface can be influenced by tillage, and therefore other soil characteristics (Section 7.6) have been used in classification.

Churning

This process, sometimes also called self-swallowing, occurs in combination with self-mulching. It is a mechanical mixing (homogenization) of the soil material of the deep A horizon. During the dry season, the small soil aggregates of the surface mulch fall into the cracks, which partly or completely fill up. When the soil becomes wet again during the wet season, all the soil material swells. The former cracks cannot close, because they are filled with surface material that swells too. The high pressure in the subsoil pushes part of the material to the surface. In this way part of the subsoil material becomes surface soil. Later on it may become subsoil material again when it has fallen into the cracks. This churning is particularly important in the upper 30 cm. At greater depth it gradually becomes less important but extends to the whole depth of the A horizon, which sometimes has tongues of former very deep cracks into the C horizon.

Slickenside formation

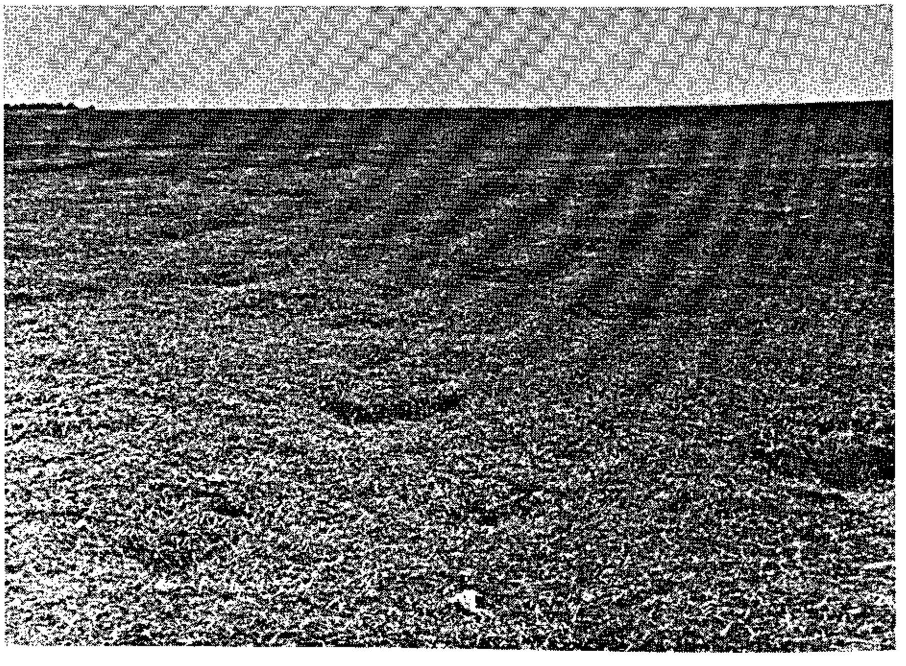
The internal pressure in the subsoil becomes very high when the clay swells; this causes the formation of polished and grooved soil aggregate surfaces, that occur mainly at a depth of 50 to 80 cm and that are tilted with an inclination of 20° to 60° to the horizontal plane. Often there are so

Close up of a slickenside in a Vertisols of Central Portugal.

many slickensides that they intersect, a characteristic of real Vertisols. Slickensides are sometimes called slickenfaces or slipfaces. Another phenomenon related to this process is the presence of wedge-shaped or of parallelepipedal structural aggregates, that also are tilted at 10° to 60°.

Gilgai formation

The gilgai relief is a result of the processes described before. Some subsoil is pressed to the surface so that some small (5 to 15 cm high) hummocks or mounds are formed and former cracks become small depressions. This microrelief is called gilgai. The higher parts are sometimes called puffs, the lower parts shelves or depressions. Besides this type of gilgai there are some other types too. Sometimes real holes, called crab-holes or melon-holes are formed.



Typical gilgai relief in the Sudan, characteristic for many Vertisols.

Kankar formation

Vertisols are often very calcareous and lime concretions occur throughout the A horizon. Pockets of powdery lime occur in the lower part of the profile below the influence of the churning process. There may be a horizon of lime accumulation or even a calcic horizon. Drying and combination with iron and manganese may harden the lime into small lime concretions (kankar) that may be bluish-gray or yellowish-gray. There is often a slight accumulation at the surface, although kankar occurs throughout the A horizon.

The dark coloration

The dark colour of the A horizon, often mentioned in local names (e.g. Black soils) is not due to a high content of organic matter but to a thorough mixing of organic matter (often not more than 0.5 to 1.5 %) with clay. The organic matter is adsorbed on the clay surfaces, forming a thin coating. This formation seems to be favoured by temporary anaerobic conditions in wet seasons. Some Vertisols are really very dark to almost black; others are dark-brown or dark-gray-brown. Those that are black usually occupy shallow depressions or are waterlogged for part of the wet season.

The formation of clay minerals

Montmorillonitic clay is formed when sufficient Mg is present and there is enough Ca to maintain a high pH. These conditions can be fulfilled when the parent material (Fr. roche-mère, roche-fille) meets these requirements. In regions with red tropical soils the percolating water that contains SiO_2 may accumulate in depressions and 2:1 clays are formed. Another important factor is the high density of the subsoil, that is almost impermeable to water. This prevents various components being washed out of the soil.

7.3 Soil-forming factors

The main factors are the typical climate, with alternating dry and wet seasons, and the heavy montmorillinitic clays as parent material. Without these two factors, no Vertisols would be formed.

The parent material of most Vertisols is transported material, although some Vertisols are formed in weathered material from basalt or limestone *in situ*. The clay content should be at least 30 % and is mostly 40 to 60 %, sometimes even 80 %. Those Vertisol-like soils with less than 30 % clay are called by the French soil scientists 'Para-vertisols'. The parent material is rich in Ca and Mg.

The climate is warm with alternating dry and wet seasons. The pronounced dry season varies from 4 to 8 months, the wet season from 2 to 7 months. The average annual temperature ranges from 15.5° to 26.5°C and there is a hot summer. The annual precipitation generally ranges from 300 to 1000 mm.

Vegetation is mainly bush or a tall-grass savanna. Man has often disturbed the vegetation (fire), therefore often only drought and fire-resistant grass and bush species remain.

Relief is not an important factor. Vertisols occur mainly below 300 metres above sea level. Some are developed *in situ* on lower slopes. Most Vertisols, however, form in depressions.

Real Vertisols are not recent. Most are probably Holocene, some Pleistocene.

Gravity is responsible for the filling of cracks with surface mulch.

7.4 Some characteristic soils

The main characteristics of all Vertisols are: they are (heavy) clay soils (> 30 % clay), with cracks (1 cm wide at a depth of 50 cm) in the dry season; they should have gilgai or slickensides (close enough to intersect) or wedge-shaped or parallelepipedal structural aggregates; many Vertisols are dark (mainly 2.5YR and 10YR) with a self-mulching surface layer and an AC profile (no distinct horizon) with kankar and a Ca horizon. The A horizon is often deep (50 cm or more) and may have some characteristics of a mollic epipedon.

In arid regions, where content of organic matter is often less than 0.5 %, the colour is never very dark, except when the soil is hydromorphic.

The chemical characteristics are favourable. Most Vertisols are fertile; V is almost 100 %, potassium is available although there may be some fixation; Vertisols are often calcareous and pH is high. Nitrogen and phosphate must be added for good yields of crops. The physical characteristics are partly favourable, partly unfavourable. Favourable characteristics are self-mulching and churning; unfavourable are the swelling and cracking, the extremely slow permeability of the subsoil, the absence of pores, the high density and the hardness. The clay soils have a high retention of water but little water is available to plants. The biological activity is low because of the long dry periods. The organic matter, however, is well mixed due to the churning process.

7.5 Some intergrades and related soils

There are various intergrades to other well known soils in the tropics and subtropics, in particular to Alluvial and to other clayey soils. Some intergrades do not have enough clay ($<30\%$, the French Para-vertisols), others do not have enough montmorillonitic clays. The result is often that slickensides occur but there are not enough to intersect, or the cracks are not very pronounced or not wide and deep enough.

There are also various transitions in areas with less pronounced dry seasons. In arid regions the surface layer often is of aeolian (sandy) origin. This sandy material is mixed with the A horizon, producing intergrades to Vertisols. In many regions, e.g. in regions of Red and Brown Mediterranean soils, subsoils with pronounced slickensides have all the characteristics of Vertisols but the upper soils layers not. Some intergrades are classified as a special subgroup in the order Vertisols; others having most characteristics of other soil groups are classified as Vertic subgroups of those groups.

In some regions there may be an effect of soil salinity or soil alkalinity; besides those there are also some with real hydromorphic characteristics.

7.6 Soil classification

Before 1960 the soils that are now called Vertisols did not occur in the various systems of soil classification. In 1951 the great soil group Grumusols was tentatively introduced in the older USDA system. In 1960 a special order Vertisols was introduced to distinguish all soils with the characteristics of Vertisols from all other soils. If a soil meets the requirements of this order, it is classified as a Vertisol, even for example if such a soil has a mollic epipedon (characteristic for the order Mollisols), it must still be classified as a Vertisol. The Vertisols, therefore, are not classified by diagnostic horizons but by diagnostic features. Four suborders are recognized (1967 Supplement):

Torrerts: usually dry throughout the year; the cracks remain open; in arid regions

Usterts: with cracks that open and close more than once a year, and that remain open for more than 90 cumulative days; in regions with some dry and wet periods, often in the tropics; no pronounced dry season

Xererts: having cracks that open and close once a year, and that remain open for more than 60 consecutive days; in regions with a pronounced dry and wet season

Uderts: usually wet, with cracks that open and close ~~more than once~~ once or more a year, and that open for less than 90 cumulative days; in humid regions.

In these suborders there are two groups with the prefixes: Pell(o)- with chroma <1.5, and Chrom(o)- with chroma >1.5, e.g. Peloxererts, Chromusterts.

In the new French system of soil classification the Vertisols and Para-vertisols are subdivided into 'Vertisols et Para-vertisols topomorphes' (without external drainage, mainly in depressions), and 'Vertisols et Para-vertisols lithomorphes' (with external drainage, mainly on lower slopes). Formerly similar soils were called 'Sols noirs tropicaux' (France) or 'Argillis noires tropicales' (Congo) or 'Pelosole' (Germany).

7.7 Agricultural evaluation

The Vertisols are important soils in the tropics and subtropics because of their high natural fertility, uniformity and occurrence in large flat regions. The vegetation can easily be cleared for cultivation. The favourable surface mulch looks promising but the poor physical condition of these heavy clays is a real drawback. They are too dry and too hard in the dry season and too wet and too sticky in the wet season. The low permeability makes soils often too wet and machines are difficult to move. Good tillage is only possible over a very short period when moisture content is favourable. During cracking of the soil many fine roots are broken and crops are seriously damaged. Even with irrigation the range of crops that can be grown is limited.

On sloping land there is always a danger of erosion. In depressions and during the wet season most Vertisols are waterlogged. Land drainage is almost impossible. In many countries, however, Vertisols are important agricultural soils. They are quite famous for cotton (Black Cotton soils), whereas also rice, wheat, sorghum, lucerne, sugar-cane or groundnuts can be grown. In some countries there are extensive irrigation projects on Vertisols. The most famous irrigation project is the Gezira Project in the Sudan, now more than 40 years old, where cotton is the main crop. It must be realized that not all Vertisols are suitable for agricultural development. Much depends on specific soil characteristics and climate, and on suitability for irrigation and drainage. There is often a great risk in developing Vertisols in agricultural projects.

For engineering purposes Vertisols are problem soils because the internal pressure often causes walls of houses to crack; poles, fences and trees tend to lean downhill; roads and lined irrigation or drainage canals may crack too. Vertisols endanger the stability of many structures. The change in volume of the soil with cracking and swelling is often 25 to 50 %. The clays are unsuitable for brick-making.

7.8 Regional distribution

There are three countries with very extensive regions with Vertisols: Australia (70 million ha), India (60 million ha) and the Sudan (40 million ha). Less extensive areas are found in almost all tropical and subtropical countries, especially in Africa. In Europe Vertisols are well known in Spain and Portugal (Barros) and the Balkans (Smonitzas). In the United States, Texas is the state with most Vertisols. These soils generally occur between 45°N and 45°S. Dudal (1965) has given details on small-scale maps of the distribution of Vertisols in various continents.

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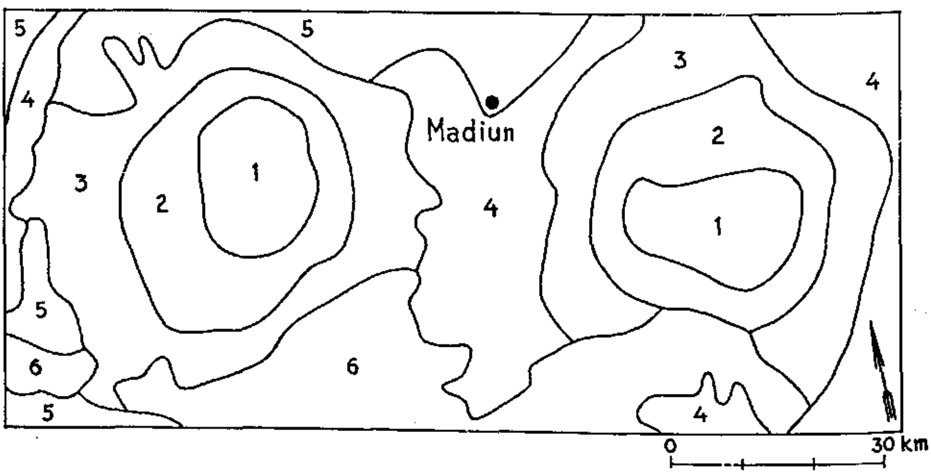
8 Andosols and other Volcanic ash soils

8.1 General introduction

In regions with volcanic parent material, various soils can be formed. Most soils are zonal because they are already rather old. However in more recent and fresh volcanic ash material, occurring in tropical regions with active volcanoes, specific soils are formed, called Ando, Ando soils or Andosols, which means dark soils in Japanese. These soils are intrazonal. The great soil group Andosols was introduced tentatively in 1948, after surveys in Japan by American soil scientists. In Indonesia these young volcanic ash soils (Du. Asgronden) were already known for a much longer period and were sometimes called Dark Dust soils (Du. zwarte stofgronden), Dark Volcanic Dust soils, Ash soils or Volcanic Ash soils. Some of these soils, called Regosols, are young soils, almost without profile development, and



Part of the exploratory soil map of Java (FAO, 1959), showing the relative position of some soils in two volcanoes in Central West Java. 1. Andosols; 2. Oxisols; 3. Red soils and Vertisols; 4. Tropical Alluvial soils; 5. Vertisols; 6. Tropical Mountain soils.

occur as almost unweathered fresh volcanic material near active volcanoes in the humid tropics (Java).

The Andosols are mainly AC soils with a thick (50 cm) loose granular, dark-gray to black A horizon over a yellowish-brown or brownish (B) or C horizon. The soil may be coarse or fine textured, and is very porous, has a low specific weight, a high content of organic matter and a high water-storage capacity. The clay is characterized by dominance of allophane (amorphic hydrated aluminium silicates of varying composition). In some coarse (sandy) volcanic soils a silica-cemented duripan (in Indonesia called Padas) is formed about 40 to 100 cm below the surface. On maturing Andosols in the humid tropics often become Ferrallitic soils or Vertisols. Sometimes when they occur in regions with other great soil groups (e.g. in mountainous areas), they are transformed into zonal soils of those regions. Andosols and most other volcanic soils are among the best agricultural soils in the tropics, because they have a high natural fertility and good biological and physical characteristics.

8.2 Soil-forming processes

Fresh volcanic material may be acidic (>60 % silica), intermediate or basic (<50 % silica). These differences in mineral composition make the final result of soil formation somewhat variable chemically.

The type and speed of weathering is slightly slower in acid material (e.g. dacite) than in intermediate (e.g. andesite) or basic (basalt) material. The weathering of dacite in Sumatra tends sligthly towards podzolization. The weathering of andesite and basalt is best known. It is the weathering of volcanic glass into amorphic hydrated aluminium silicates, which forms allophane, an amorphic gel of quite variable composition (often written as: $Al_2O_3.SiO_2.5H_2O$) with a SiO_2/R_2O_3 ratio >1 and a CEC of 35-54. Allophane is difficult to analyse physically (clay fraction) and mineralogically because it is amorphic and occurs in various phases of crystallization. The presence of allophane and the porosity of the pumice-like parent material cause the soils to absorb much water (high water-storage capacity) and they contain much organic matter (5-20 %). They may therefore become very sticky and are very dark to almost black. The subsoil is very often smeary (thixotropic). This type of soil formation can be called initial soil formation in volcanic ash material in the humid tropics. It is related to a soil climate that is warm and moist (humid tropics). Oxidation is easy due to the high porosity. A few years after the volcanic material has been deposited, there is a significant vegetation, producing organic matter. During this type of initial soil formation, very little real clay is formed. On maturing in the humid tropics, the various types of allophane are transformed into metahalloysite and finally into kaolinite.

Padas forms mainly in rather course (sandy) young andesitic soils. It is often about 25 cm thick, 40 to 100 cm below the surface and almost parallel to the surface. It is a duripan, mostly silica-cemented, very hard when dry, fragile when moist. It is slightly permeable to water and almost impermeable to roots. Soluble silica, produced during weathering of the upper layer, is probably leached down but not washed out of the soil.

8.3 Soil-forming factors

The parent material and its mineral composition is a very important factor. It consists of vitric volcanic ash (glass), pumice and other pyroclastic material. The soils are mostly formed in layers of varying thickness, texture and mineral composition. There are six types of volcanic parent material:

a. Lava-streams, over the volcano surface, formed by hot magma from a crater. After cooling, rainwater percolates quickly through cracks to underlying porous ash. Hence weathering and soil formation are slow.
b. Lahars, cold or hot mud streams, carrying debris from the summit down through gulleys. These catastrophic streams are hot when a crater lake is ejected during eruption, as occurs occasionally. Catastrophic cold lahars are commoner, as during the first heavy tropical rains after eruption, when there is much newly ejected debris near the summit. As the mud streams down, much material is eroded from the gulleys. Around the foot, there is a sorting of material, the coarser staying halfway down the slope, the finer at the foot.
c. Ash rains, consisting of very fine dry material, that is blown into the air, carried for a long distance (sometimes a few thousand kilometres) and deposited. Near the volcano an ash layer 40 cm thick may be deposited after one eruption. The ashes are finer and the layer is much thinner further from the volcano.
d. Volcanic sands, that are carried from the lower slopes of the volcano during heavy rains and deposited from wet sand streams. This sand is not quartz but weatherable volcanic glass (vitric volcanic ash).
e. Alluvial ash deposits, carried by the rivers passing the foot of a volcano and deposited in alluvial plains or in irrigated fields.
f. Ladus are dry hot pyroclastic stones and boulders, erupted from the volcano and occurring near the summit. They are not important for soil science or agriculture.

Ash rains may bring fresh minerals to old and very old soils and rejuvenate them in large areas around active volcanoes. This is, for example, very important for many soils in Indonesia and Argentina. In the study and evaluation of older zonal soils, such fresh volcanic material may be mixed with the upper soil layers in sufficient amount to raise their fertility.

8.4 Some characteristic soils

A typical Andosol has an AC profile, generally with the following properties and characteristics: A horizon, 20 to 50 or 100 cm thick, black to very dark grayish-brown (10YR 2/1 to 10YR 3/2) silty material (often 30-75 % silt and 10-40 % clay) rich in organic matter, often 8 % (varying from 5 to 20 %). The C horizon is yellowish-brown or brown (7.5YR 4/4 to 10YR 4/3) silty material, low in organic matter. All material is granular, very porous (pumice-like) and it has a high water-storage capacity. Allophane is an important component. The SiO_2/R_2O_3 quotient of the soil varies from 0.7 to 1.2, the CEC from 20 to 30, V from 20 to 40 %, plasticity is low and pH is 5.0 to 6.5 Some soils may be truncated; the C horizon may be at the surface through soil erosion. Sometimes there is a rather weak (B) horizon, with less organic matter and a brownish colour, which may be a cambic horizon.

8.5 Some intergrades and related soils

Soils with a Padas layer were formerly called Planosols. Recent loose volcanic ashes, still unweathered, are Regosols; the hard recent lavas belong to the Lithosols. Fine-textured volcanic materials are carried by streams and deposited in Alluvial plains to form Alluvial soils; sometimes they are similar to the fine-textured lahar soils.

In tropical lowlands with alternating dry and wet seasons, allophane may crystallize to form kaolinitic clays, and soils finally become Ferrallitic. The first well developed stage is a Brown Latosol. Later soil formation proceeds to Reddish Brown and finally to Dark-Red or Red Latosols. These soils may all occur on the slopes of one volcano. In low-lying, poorly drained parts of the terrain Andosols may be transformed into Humic Gley and Gray Hydromorphic soils. Sometimes montmorillonitic clays form if enough silica is present to give rise to intergrades towards Vertisols. In regions with Gray-Brown Podzolic soils, Brown Podzolic soils or Arid soils, there are intergrade towards Volcanic soils.

8.6 Soil classification

In Indonesia the volcanic ash soils were formerly subdivided into a younger gray and an older, yellowish to brownish gray group. In both groups there was a subdivision into four textural classes.

Gravelly soils (particles mainly >2 mm)
Sandy soils (particles mainly 100-2000 μm)
Dust (fine sandy) soils (particles mainly >100 μm)
Silty or loamy (mainly silt particles).

In other countries the following names are used:

Black Andean soils (Colombia, Ecuador)
Paremo soils (Colombia, Ecuador)
Trumao soils (Chile)
Talpete (Nicaragua)
Hydrol Humic Latosol (Hawaii)
Brown Tropical soils (Congo)
Ando soils (Japan and former USDA classification).

In the Cameroons, Hasselo (1961) has classified three age phases (oldest, younger and youngest) is ash or lahar deposits and in lava streams.

CSSC (1966) classifies the Andosols into the order Inceptisols and into the suborder Andepts; those with characteristics of wetness from the great group Andaquepts into the suborder Aquepts.

The typical characteristics of the Andepts are a low density (in the fine earth) of less than 0.85 g cm^{-3} in the epipedon, the cambic horizon or both, and the exchange complex is dominated by allophane; or there is more than 60 % vitric volcanic ash, pumice or other pyroclastic material in the silt, sand and gravel fraction. The Andaquepts have the further typical characteristics of wetness.

8.7 Agricultural evaluation

In Indonesia, especially on Java, (andesitic) Andosols are the best agricultural soils. They are rich in minerals and have a high natural fertility. The deep fine sandy (dust or ash) soils are best and give high yields, especially of sugar-cane and tobacco. The deep silty or loamy soils are good too, but yields on the coarse sandy and gravelly soils are much lower because of a lower fertility and irregular texture. Padas layers, mainly occurring in the coarser soils are unfavourable for most crops except irrigated rice, because the Padas prevents irrigation water from percolating through the subsoil. In the coarse and sometimes also in the finer soils, there is often a shortage of available phosphate, although total phosphate may be rather high. Phosphate fixation is a rather normal phenomenon in these soils. There is usually sufficient potassium; it is least in the coarse-textured soils. Some N and P fertilizers are often applied to raise agricultural productivity. Important is the percolation of rainwater falling near the summit of the volcano and percolating through the coarse deeper layers. This water comes to the surface on the lower slope in the sandy region. It forms streams that may produce irrigation water for the good soils in the regions below their source.

8.8 Regional distribution

This chapter has dealt mainly with Andosols and some related volcanic soils in Java, Indonesia. They occur also on some other Indonesian islands, some islands in the Pacific Ocean (Hawaii), Japan, Philippines, Cameroon, some East African and Central American countries, as well as in Chile and Colombia.

Here, only Andosols developed in young volcanic material near active volcanoes in the tropics have been discussed. There are many older volcanic soils in the same countries, that have changed into other soils, discussed in previous chapters. Sometimes there are volcanoes in arid and semi-arid regions in the subtropics (Syria, Jordan, Turkey) with pumice-like granular parent material, without or with a slight Arid soil development. The rainwater occasionally coming down from such volcanoes often produces saline soils in the nearly flat regions. Sulphate is an important component and Puffed Solonchaks are common.

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9 Some other tropical and subtropical soils

9.1 General introduction

Besides the groups of soils discussed in the preceding chapters, there are still some other groups of soils, e.g. Lowland Podzols, Rendzinas, podzolic and other soils in mountain regions, and the Peat or Bog soils in coastal flats, in swamps and on mountain plateaus. Such soils only occur regionally. Most are unimportant for agriculture, except the low mountain soils developed in volcanic parent material as in Indonesia (Java, Sumatra) and Hawaii. Many soils have similar characteristics to the corresponding soils of the cool and temperate regions, although the pedoclimate of these soils is different, causing differences also in various soil-forming processes. In the past, such soils have been given the same names as those in temperate regions; later the word tropical was added, e.g. Tropical Podzolic soils, Tropical Gray-Brown Podzolic soils and Tropical Brown Forest soils. In CSSC (1966) the prefix Trop- has been introduced at group level for such tropical soils, e.g. Tropaquods, Tropudalfs and Tropudults.

9.2 Lowland Tropical Podzols

These soils are true podzols with A_2 and B_{2h} horizons developed in very poor (almost pure quartz) very permeable parent material in tropical lowlands ($<$1000 m altitude) with high precipitation. The differences from normal Podzols of temperate regions are the very thick bleached almost white A_2 horizons (albic horizons) that may be more than 3 m thick and the often rather thin (5 to 10 cm) B_{2h} horizon, that occurs at a great depth.

The soil-forming process is podzolization, in recent years also called silicization because leaching of bases and sesquioxides causes the proportion of silica to increase. Bases, sesquioxides (especially iron) and soluble organic compounds (fulvic acids) are leached in various complex combinations to a great depth by high rainfall or a fluctuating watertable. Silicization is intensive, because there is leaching with water of 22°-26°C, far different from temperate regions where the soil and water temperature is 15° or less.

Soil-forming factors are characterized by a very poor and very permeable parent material, mainly consisting of rather coarse sand, often pure quartz, very low in bases and clay (less than 2 %). The vegetation is sparse too, because of the absence of nutrients. It is often a grass savanna, scanty forest, or bush savanna, all producing acid organic matter. There is little mineralization and mainly humification of organic matter. Very often there is a layer of unchanged organic material; the pH is always low, about 4. A slight slope and high permeability encourages lateral movement of water. The parent material of inland Podzol soils is probably repeatedly decomposed, altered, eroded, transported and redeposited. In coastal areas the parent material consist of poor quartz sands of former beachridges.

A characteristic soil profile has an O_1 and O_2 horizon a few centimetres thick consisting of raw or partly decomposed organic matter, over a 10 or 20 cm A_1 horizon consisting of dark gray sand with many bleached grains, with 1 to 6 % organic matter, and a thick (50 to more than 300 cm) A_2 horizon of white bleached moderately coarse to coarse loose sand. Below is a thin (5 to 20 cm) dark-brown B_{2h} horizon in which organic compounds, some sesquioxides (however little iron) and some clay have accumulated. The B_{2h} horizon is often partially cemented and rests on a brown sand C horizon. These Lowland Tropical Podzols are often associated with dark water in streams coming from the podzolic regions. This water is dark-brown to reddish-brown and contains some aluminium, organic matter, more iron and less silica than clear-water streams; the pH is often about 4.

The classification of these Podzols is complicated. In the tropics they are intrazonal soils (Intrazonal Tropical Podzols), called White Sands, Bleached Sands, Bleached White Sands, Regosols, White Sand Regosols, Groundwater Podzols, Groundwater Humus Podzols and Gigant Podzols. A modern name would be king-size Podzols. If the spodic horizon, that occurs at a great depth, is not observed or is ignored, these Podzols are called White Sands, Regosols and would be classified as Quartzipsamments. If the characteristics of wetness are present, they should be classified as Tropaquods (the real Groundwater Humus Podzol), and if no characteristics of wetness are present as Tropohumods. Although Lowland Tropical Podzols have been observed in many countries, detailed studies are scarse and insufficient data are available to check the criteria for a spodic horizon.

The agricultural value of these podzols is low because of the low nutrient status, the high permeability and low water-storage capacity, the low field capacity, the acidity, and the low content of organic matter and clay. In future some of these soils in a favourable topographical position could probably be improved by manuring, green manure and if necessary by supplementary irrigation.

Lowland Tropical Podzols cover 7 million hectares in various tropical countries, mainly in limited inland areas or patches and only exceptionally (Surinam) in slightly larger regions. They frequently occur in poor marine coastal quartz sands in older beachridges. A complete review of the literature has been given by Klinge (1968).

9.3 Mountain soils

There are various mountainous regions, sometimes with very high mountains, having eternal snow on the summits. From the lowlands at sea level up to the mountain tops, there is a rapid decrease in temperature and often an increase in precipitation. Temperature at sea level is usually 26°C and decreases by 0.5° or 0.6°C for every 100 m altitude. At 1000 m above sea level the average annual temperature will be about 20°C and at 2000 m about 14°C. The conditions become similar to those of the temperate regions and soils become Forest soils, Podzolic soils or Podzols, with increasing elevation. The high rainfall and lower temperature mean that the soils contain more organic matter, mineralize less and humify more. The pedoclimate of these mountain soils has a specific characteristic: there are only slight differences in soil temperature throughout the year. The difference between the average winter and summer soil temperature at a depth of 50 cm is often less than 5°C. This difference is much greater in the temperate regions.

Another typical feature is that there are belts or zones of special soils at various altitudes. In close proximity (often within half a kilometre), there are different zonal soils. Especially on the lower mountains and mountain slopes below 1000 or 1500 m, there is still some tropical influence, often characterized by a higher percentage of 1:1 lattice clays. It is evident that such soils have different characteristics from similar zonal soils of the temperate regions in Europe, the Soviet Union or the United States. For soil formation, the type and mineral composition of the parent material is very important, although relief and vegetation are important too.

Most mountain soils are Lithosols or belong to Lithic (shallow) subgroups, or are very stony. Those developed in volcanic material (Indonesia, Hawaii) seem to be the best soils, because of the favourable mineral composition. Acid volcanic soils tend to podzolize more than Basic ones. Permeability is an important characteristic too. If it is low, peat may form, e.g. a peat layer on hard rock, even on hard basalt of a lava stream. Parent material poor in bases promotes more rapid acidification and leaching. The vegetation is also adapted to such conditions.

Mountain Podzols are known from Indonesia (Java, where they occur at an altitude of 1000 to 2000 m or more on acid parent material), West Irian, Tanzania, South Africa and India. The profiles are normal in thickness, about 70 to 100 cm with clear A_2 and B_{2h} horizons. There is often a peaty layer at the soil surface, the acid A_2 being almost without organic matter and sesquioxides. The soil-forming process is mainly silicization.

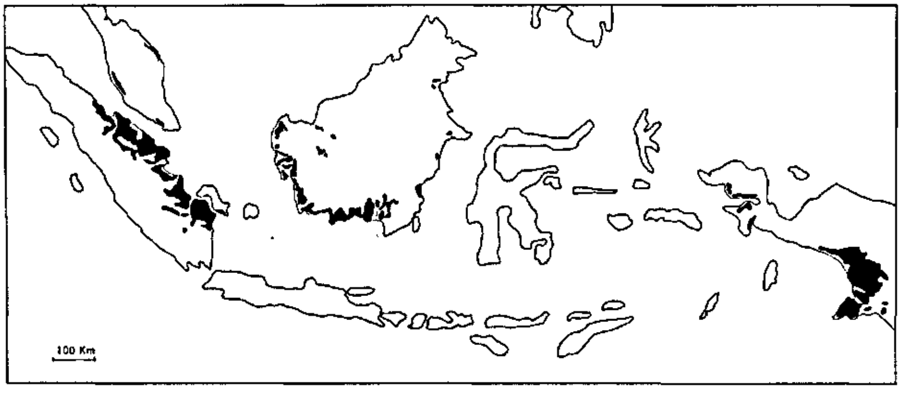
Below the Podzol belt there is a belt of Podzolic soils, often with Brown or Gray-Brown Podzolic or Red-Yellow Podzolic soils, and below this belt Brown Forest soils and transitional soils to the Ferrallitic soils, in particular Brown Latosols. These toposequences have been studied by van Schuylenborgh in Indonesia, especially on volcanic parent material, under different climatic conditions. In a monsoon climate, ferrallization extends a much higher altitude than in a humid tropical climate, at least in andesitic material.

Some mountain soils, in particular those at lower altitude and in volcanic parent material, may be important for agriculture if they are deep and favourable situated. Climate, parent material, soil depth and type of soil formation are the main determinants of agricultural value.

The mountains in more arid and in subhumid regions have similar soils as discussed in chapters 2 and 5. They are base-rich, often thin, stony and lithosolic. Desert soils, Sierozems and Reddish-Brownish soils occur, e.g. 2000 to 3500 m above sea level in Bolivia and Mexico. Many soils are very shallow and stony because of erosion, as in the Mediterranean Region where Rendzinas and Reddish Rendzinas are common. In the drier mountain regions, podzolization is very slow because of the low rainfall and the irreversible dehydration of iron. There organic soils are unknown.

9.4 Organic soils

Organic soils are formed in tropical areas with extreme hydromorphic conditions, e.g. in coastal regions, swampy inland depressions and in the mountains with high rainfall and stagnant water. Such stagnant water can occur on almost impermeable rock, e.g. hard lava on Hawaii. A blanket of organic soil is formed. In some tropical coastal regions, the peat layer may be several metres thick. The peat can be in various stages of humification. In Africa, various papyrus and phragmites swamps occur locally. The organic material is completely reduced almost to the surface. Large forest peat areas occur in some coastal regions, e.g. Kalimantan, Sumatra and West Irian (Indonesia). The Orinoco Delta also consists largely of peat. The organic



Map of Indonesia. The position of tropical peat soils (Sumatra, Kalimantan and West-Irian) is indicated in black (after Polak, 1952).

soils may be eutrophic, mesotrophic or oligotrophic as in temperate regions. There also may be much mineral sediment mixed with the peat, in particular in coastal and delta regions, sometimes in inland swamps too (erosion); these are often unripe soils.

Organic soils form the order Histosols in CSSC (1967 Supplement). Such soils must have a high content of organic matter: more than 30 % if there is more than 50 % clay, and more than 20 % if there is no clay. In between, the ratio should be proportional. Some scientists have classified Organic soils according to the different types of vegetation producing the organic matter, e.g. forest, bushes, papyrus, grasses, mangrove.

The Organic soils of the tropics are not important for agriculture, because they are wet and hydromorphic, and occur mainly in small areas. When drained they oxidize rapidly and subside tremendously. Various Organic soils in coastal regions, especially in the brackish zone may be transformed into acid sulphate soils when drained. In Africa, this may also happen to some papyrus swamps containing sulphur, derived from volcanoes or from the old intensively weathered and leached Ferrallitic soils.

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