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BROWN SUBARID TROPICAL SOILS OF WEST AFRICA

As understood by French scholars, the brown subarid tropical soils form in tropical regions in an environment of considerable aridity. This group of soils is characterized by an AC profile, and by deep penetration of organic matter along the profile — mainly by the effect of grassy vegetation of the steppe type under normal conditions of natural drainage.

As early as 1923, Shantz and Marbut reported the occurrence of brown soils in the Pou district (Senegal), but in fact these were tropical black clays. Only in 1946 did Aubert and the present author have occasion to observe brown soils of steppe type — from the south of Senegal to the north of Mauritania, along the line Dakar—Saint Louis—Nouakchot.

From 1947 to 1956, I was able in various papers to establish and clarify the factors determining the genesis of these soils.

While referring the brown subarid soils to the extensive class of steppe soils, I was nevertheless forced to classify them at the level of a [special] group, because the tropical climate confers specific traits upon them.

From 1959, surveys become more extensive in Mauritania and Nigeria,* especially in connection with soil mapping at various scales. We are now able to give more details on the morphological and analytical characteristics of these brown soils, and the processes of their formation.

Especially noteworthy are the studies by Gavot, Dugaine, Audry, and Bauquier.**

In 1962, Dommergue described the dynamics of microbiological activity in the subarid zone.

The group of tropical brown subarid soils includes two subgroups, differing in the nature of organic matter: 1) brown soils proper, and 2) red-brown soils.

The b r o w n s o i l s are thin, with a profile of the AC type (less than 100 cm); they are dark, with brown tinges; the upper horizon is only a few centimeters thick; it is structured, slightly foliate; lower down there appears a granular and prismoidal structure; usually, from 30 cm there is calcium carbonate in varying amounts; the total amount of organic matter is quite inconsiderable (1%), but is uniformly distributed in all horizons. The ratio C/N = 8. There is a considerable amount of free iron, reaching 70 or 75% of the total Fe content. Iron coloring is masked by organic matter. Soil solutions have a good buffer capacity. The pH value varies from neutral to alkaline.

* [Possibly a mistranslation for the Niger region within the former French West Africa.]

** [All these French spellings are uncertain; they are rendered in Cyrillic as G a v o, D y u g e n, O d r i, B o k 'e, respectively.]

There are often conspicuous variations in the soils' carbonate content, depending on texture. The process of "carbonatization" is nearly always well-marked on a clayey substratum. As a rule, soils are more highly carbonate at the foot of slopes than on divides, which seems to point to some translocation by lateral flows. Conversely, on sandy substratum there are usually no separations of $CaCO_3$, whereas on strongly clayey substratum on terrain where the slope becomes gentler there is quite often a transition toward tropical black clayey soil (vertisol). Moreover, sliding surfaces develop in the soil, the structure becomes coarser, cubic, and large inclusions of lime appear. Transitional forms of soil are possible.

With the deterioration of natural drainage, the sandy brown soils give way to hydromorphous soils with spots. The hydromorphous soils have a higher C/N ratio.

The red-brown soils have a much thicker soil stratum (up to 2 m), with two well-marked horizons: a) a humus horizon at least 50 cm thick, gray-brown or brown; b) underlying reddish horizon, >100 cm thick. There is a slightly foliate structure in the upper horizon near the surface, but lower down it is often inconspicuous and unstable. There is a high proportion of free iron (80—85% of total). The C/N ratio = 8. Bases are partly leached out. Soil solutions often have a limited buffer capacity. The pH value varies from neutral to weakly acid.

The principal variations are connected chiefly with natural drainage and with transition toward brown soil. Occasionally there are red-brown soils with spots of carbonates.

Finally, considerable modifications are observable in the transition toward tropical ferruginous soils. In such cases, the humus horizon becomes grayer and much thinner (25—30 cm). The reddish coloring of the deep horizon becomes a pure red, and a more faintly colored horizon which is already leached (between the lowermost and the surface horizons is conspicuous.

At the border between subarid soils and tropical ferruginous soils there is usually a zone of young soils which may be referred both to the steppe and to the ferruginous tropical soil types. They occur on younger topographical features or on ancient soils deprived of their upper horizons by water erosion. Their steppe transformation is still incipient, their humus horizon thin and underdeveloped. Carbonatization in depth is superimposed on ferrugination. Kaolin clays in the upper horizon are of the type 2:1. Moreover, such soils often show hydromorphous traces, which are sometimes very conspicuous. These contradictory data make interpretation difficult. The degree of development of these soils is not such as to indicate their basic soil-climatic characteristics. However, two preliminary remarks should be made: the young, underdeveloped soils are lithologically similar to the parent material. Hydromorphous action affects the profile much more rapidly than do soil-climatic influences within a tropical subarid zone (such influences as steppe transformation within the dry tropics).

When examining the profile of soils that are transitional toward ferruginous soil, the formation of two horizons with clear hydromorphous traces should be stressed: 1) the upper horizon is strongly ferruginated, and its development is due to the intake of moisture from atmospheric precipitation, rich in oxygen; this favors liberation of iron, leaching of bases, kaolinization and hardening of the soil, with a tendency toward a cubic structure; 2) *the lower horizon, transitional* to parent material, shows features of excess moistening in a reducing environment (gray-olive coloring). Such environmental conditions are conducive to neo-synthesis of clays of the type 2:1 and to the separation of $CaCO_3$ in nodules.

On the basis of these two types of temporary hydromorphousness, two trends of soil evolution may be noted.

1) in the transition toward tropical ferruginated soils, with improvement in the conditions of intra-soil drainage and a sufficient intake of atmospheric moisture, saturation with iron arises and iron concretions form;

2) in the transition toward soil with coarse structural units, sometimes even toward tropical black clay, when soil permeability decreases, a clay develops of the type 2 : 1 which takes over the [entire] soil stratum.

These two trends of soil development manifest themselves much faster and earlier than any zonal processes and may often overlap. However, after sufficient time has passed, the soil-climatic processes assert themselves and predominate more or less markedly, giving rise to a series of transitional soils.

All these phenomena do not preclude the existence of past influences, further complicating the above scheme.

Distribution and limits of the brown soils. In West Africa, the brown tropical soils develop between isohyets 500 mm in the south and 200 mm in the north. The limits are well marked in the south, where the brown soils border upon the tropical ferruginous soils. East of Lake Chad the southern limit is deflected southward, toward isohyet 700 mm. However, further clarification is required here, since there might be some confusion between brown subarid soils and brown "eutrophic"* soils.

Northward, toward the Sahara, the brown subarid soils give way to gray semidesert soils, which have a poorly developed profile due to the very arid climate. The gray semidesert soils** have a profile (A)C in which the surface horizon is thin (10—15 cm) and light-colored, due to the negligible amount of organic matter (0.1—0.2%) which remains almost undecayed. There are often coarse mineral soils, forming on redeposited material (sand, clay) or on ancient red soils which had evolved in the past, in a moister climate.

Between isohyets 500 and 350 mm, on loose acid rocks, in an environment of good drainage, there are exclusively red-brown soils. On any other parent material, especially on clay or on material rich in alkali-earth minerals, brown soils develop.

Between isohyets 350 and 200 mm there is an entire series of brown soils of various texture which are often very sandy. Toward the north, such soils give way gradually to gray semidesert soils. It is therefore quite difficult to establish a limit here. Brown soils evolving on ancient red formations should not be confused with red-brown soils. The criterion for their differentiation is the red noncarbonate underlying horizon. Indeed, in brown soils proper, the red underlying horizon may be very rich in carbonate.

* Brown soils on bedrock. (Ed.).

** *Such soils in the USSR are termed "desert soils".* (Ed.)

Yet it should be remembered that such distinctions are rather subtle. The age of the soil should be estimated by studying the relative situation of the various topographic levels. Soils of the steppe type are usually the older ones, and are situated on ancient surfaces. Halomorphism phenomena are very limited, except within the Chad Basin.

Factors of soil formation. We have indicated limits determined by rainfall. Brown subarid tropical soils occur between isohyets 500 and 200 mm. Rainfall, varying greatly from year to year, is restricted to 1—3 months of the humid season, and comes in short strong showers.

Mean annual temperature is 27—28°C, with absolute minimum in December—January and a maximum in April—May, when the temperature usually rises above 45°. Except for a few days following rainfall, atmospheric humidity is extremely low, of the order of a few per cent.

The climatic rhythm is characterized by an exceedingly short rainy season, followed by a very long dry season. This is typical of a tropical climate, which northward becomes more and more arid.

The nature of parent rocks is of rather limited significance in the formation of brown and red-brown soils. However, it influences the amount of organic matter, the saturation of soils with alkali-earth cations, and especially the presence of carbonates. The composition of rocks in West Africa is actually unfavorable to halomorphism.

The time factor plays a prominent part. The formation of a typical soil requires suitable conditions over several millennia (perhaps even more than 10,000 years). Yet the regions which we have surveyed have suffered climatic changes during the last 2000—3000 years, trending toward greater aridity. Various investigations suggest that rainfall has decreased during this period by 200 mm. The ferruginous tropical soils, and the levels with lateritic "shields," which usually form under conditions of greater humidity, are relicts from the past, and do not display very conspicuously the signs of present-day processes, such as the infiltration of organic matter which is a characteristic of subarid soils. Such ancient formations are usually reworked to some extent by water or wind erosion, giving rise to younger soils with temporary hydromorphousness, as we have explained.

Brown subarid tropical soils are characterized primarily by their vegetation, which consists of an association of sparse scrub formations of acacia with thorny arboreal formations, and with gramineous plants, with the predominance of annuals forming a thick, low cover (30—50 cm). Bush fires are very common in the dry season. The overground part of plants contribute a very inconsiderable amount of "biomass," since the plant residues are mostly eaten up by termites. In fact, the soil is enriched only by the decay of the root system.*

The role of the microbian flora is much more important than was believed until recently. According to Dommergue, telluric activity may reach pF 5.5—5.6. Various groups of microbes become active at different times. One of the more remarkable circumstances in this respect is that definite degrees of humidity favor definite processes. Thus, it has been observed that at moisture content close to wilting coefficient, hydrolysis of cellulose predominates over ammonification, and a partial fixing of mineral nitrogen occurs. Predominance of ammonification over nitrification occurs at pF > 4.2.

* In soils of tropical savannas, the increment of biomass due to roots reaches 650—700 q/ha (Bazilevich, Rodin, 1963). (Ed.)

These data explain the extent of processes of mineralization of organic matter during the dry season, when upper horizons of soils in subarid regions are capable of remaining for many months after the rainy period within an interval of pF 4.2—5.0. Telluric activity is mainly due to fungal microflora.

Processes of soil formation. The action of various factors enable us to gain a better understanding of the soil-forming processes characterizing the subarid soils in tropical regions. These processes may be listed in the following order of importance: steppe-transformation, carbonatization, ferrugination, neo-synthesis of clay, and leaching.

Steppe-transformation governs the development and accumulation of organic matter in subarid soils. In a tropical environment with a high annual mean of temperatures, conditions are not very suitable for the accumulation of organic matter, because mineralization is quite intensive even at low moisture content. Actually, the deficit of moisture is a factor enhancing some accumulation of organic substances. [On the other hand], such a deficit limits the intake of organic matter, since the vegetation itself is underdeveloped. The soil reaction (neutral to alkaline) favors a neo-synthesis of colloidal organic complexes which are sufficiently resistant to microbian action. These are mixtures of gray humic acids (rich in N, of rather low solubility in ordinary solvents, and strongly coagulated) with brown humic acids (poor in amino N and in synthesized quinonimine products), which bind them, though not firmly, with mineral colloids. The amount of such substances varies with the pH, abundance of Ca, and hydromorphous nature of soil.

The tropical environment renders the organic matter exceedingly unstable in brown and red-brown soils. However, organic substances decompose less readily in brown soils than in red-brown.

Carbonatization is of particular significance for the typology and development of subarid soils.

At more or less considerable depths there is often a horizon of $CaCO_3$ accumulation, even where the parent material is poor in Ca. The calcium may accumulate by leaching from upper horizons, which indeed are frequently deprived of carbonates. It is also possible that biological activity related to the growth and decay of root systems of grasses enhances the separation of $CaCO_3$ in subarid soils.

It is however more probable that the process of carbonatization of tropical soils is mainly connected with reduction occurring in deeper carbonate horizons, near the parent rock. In such case, Ca would concentrate as bicarbonate (hydrocarbonate, protocarbonate) and precipitate during the dry season, at a depth depending on drainage. Indeed, it is observed that the forms in which $CaCO_3$ separates are closely related to the conditions of intra-soil drainage. In an environment poor in bases and well aerated, the carbonates separate diffusely; if the texture is heavier, there form lime pseudomycelia. However, the concretions are usually in the form of nodules, 2—3 cm long, accumulating chiefly in the zone of contact with the parent rock. Colmatage enhances this phenomenon, and in extreme cases conspicuous concretions separate, sometimes of very considerable sizes (up to 5 cm).

The high temperature of soil solutions restricts any possibility of high content of CO_2.

The depth of the horizon of $CaCO_3$ accumulation is variable.

While carbonatization is quite usual in brown soils proper, it is much less common in red-brown soils.

Ferrugination. An important and quite specific peculiarity of tropical subarid soils is the considerable liberation of iron sesquioxide [= ferric oxide]. The process results in a reddish or brown coloration of the soil. A small amount of Fe is enough to color the soil profile, perhaps because of the very close bonds between organic matter and iron. More than 70% of total Fe in subarid soils is in free condition. When soils become more hydromorphous, the ferric oxides are easily redistributed; accumulations of such oxides arise, especially in an environment rich in oxygen. However, since the natural drainage is restricted by deficit of moisture, circulation remains weak: there is a certain upward shifting in brown soils, and incipient leaching in red-brown soils.

Neo-synthesis of clay. Study of the texture of brown soils reveals considerable amounts of clayey products: mixtures of kaolinite, illite, and montmorillonite. So far, mineralogical findings are still few and do not provide adequate explanations for the rise and development of these secondary clay minerals. Nevertheless, it is of interest to clarify certain specific aspects of clay formation in the environment of arid tropics.

Although processes connected with the moisture regime are sometimes very limited in duration, they may proceed very intensively during these short spans of time. Under normal regime kaolinization predominates, while weathering provides products that are chiefly plagioclases. Illites are mainly a result of the weathering of shale and phyllite. They are merely an intermediate stage of development, but a rather stable one in a well-drained environment. Kaolinite and illite may also be inherited from ancient soils or sedimentary deposits.

If natural drainage is insufficient and pH varies from neutral to alkaline, a considerable amount of new formation of clay of the type 2 : 1 is observed. Such neo-synthesis results in the rise of montmorillonite, forming in the presence of Mg.

Kaolinite is exceedingly stable and is encountered in practically all soils. Illite and montmorillonite occur chiefly in young soils or within depressions without drainage. Here they concentrate within horizons formed by colmatage and are connected with the formation of alkaline soils, while kaolinite correlates with acid soils. Neo-synthesis of montmorillonite always takes place in an environment with excess moistening many months each year. This accounts for the occurrence of montmorillonite on low terrain where water stagnates, and where the concentration of cations increases by hydrolysis while evaporation is intensive. But as soon as an inner drainage arises, the process of kaolinization begins.

Leaching. Leaching processes are quite limited in the soils in question. Study of the water balance indicates that the periods of natural drainage activity are very short. During such intervals only negligible amounts of moisture circulate. However, study of profiles shows that certain substances are indeed redistributed between the various horizons: this actually points to some leaching, but only within the soil stratum itself (disregarding exceptional cases). Deep horizons thus develop with a high carbonate content.

On the other hand, eluviation of clay is never observed. Upper horizons are often lighter textured than deep horizons, due to sand admixture at the surface, or to a relative increase in the proportion of coarse material because of the removal of fine particles by sheet erosion. [However], the increase in clay content with depth is mainly due to neo-synthesis within a reducing environment in temporarily hydromorphous conditions.

Actually, leaching involves only the very mobile products of soil formation, especially iron: this is characteristic of the tropical subarid zone.

To sum up: considering the processes of soil formation as a whole, since they participate in the development of subarid brown tropical soils, it should be noted that they are closely dependent upon conditions of natural intra-soil drainage. They correlate as closely with temporarily hydromorphous conditions.

Thus, location governs the particular development of each type of soil within the soil group.

More intensive hydromorphous conditions result in the accumulation of residual organic products; in the increase of the C/N ratio; in the decrease of pH values; in the formation of clay with high swelling capacity (when the environment is rich in alkali-earth cations); in the liberation and redistribution of Fe and Mn oxides.

Of course these various processes are not independent: certain correlations between them may be established.

Excess moistening favors separation of $CaCO_3$ in a reducing environment. An oxidizing environment, which is less hydromorphous, limits such phenomena and enhances an acid reaction in the soil.

CLASSIFICATION

Within the French classification on which Aubert reported at the conference of Ghent (1962), the tropical subarid soils may be referred, according to their general properties, to the class of steppe, or "iso-humic" soils.

At the subclass level they belong to the saturated steppe soils, with considerable separation of ferric oxide. They form a group of subarid brown soils and include two sub-groups (depending on the degree of evolution of organic matter), namely: a) brown soils, and b) red-brown soils.

Further classificatory subdivisions are as follows:

at the "family" level, according to texture of the mineral soil constituent and the amount of alkali-earth minerals;

at the "series" level, depending on the character and forms of carbonatization and/or ferrugination in deep horizons.

We regard a distinction between tropical brown soils and subtropical (or Mediterranean) brown soils as being quite important. Indeed, it points not merely to the different properties of these soils, but also to the influence of a tropical climate, differing substantially from any climate of subtropical type, even from a continental one. For instance, the dormant periods in vegetation are not caused by the cold but solely by lack of moisture. The growing season is exceedingly short and occurs during a warm period.

Such conditions account for the feeble accumulation of organic matter, the intensive liberation of iron, and the limited formation of carbonates.