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Environmental Characterization of Acid Tropical Soils

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Summary

Environmental characterization of acid tropical soils deals not only with the pedon, but also with the three-dimensional soil mantle organization, at the scale of eco- and agrosystems. Every time lateral and vertical differentiation is taken into account, it has been shown that most physical properties are ordered in the landscape. These properties appear to be particularly important considering that many of the driving forces governing pedogenesis and fertility depend on the rates and vectors of chemical and water transport. Under these conditions, sequential testing seems to be the most appropriate approach for obtaining a direct correlation of soil properties with plant response.

Introduction

According to Glinka (1927): "Soils are conceived to be independant natural bodies, each with a unique morphology resulting from a unique combination of climate, living matter, earthy parent materials, relief, and age of landform. The morphology of each soil, as expressed by vertical section through the differing horizons, reflects the combined effects of the particular set of genetic factors responsible for its development."

This approach leads logically to the concept of the pedon, defined as "the smallest area for which we should describe and sample the soil to represent the nature and arrangement of its horizons and variability in the other properties that are preserved in samples" (Soil Survey Staff 1975).

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It is thus implied that there is a one-to-one connection between the environment and a pedon or a group of pedons representing a given soil series (polypedon). According to this approach, environmental characterization allows us to determine within which limits the knowledge acquired by the study of a pedon or polypedon may be extrapolated to a landscape surface. In an environment that is supposed to be homogeneous, the polypedon thus represents a soil that is within the limits of physical, chemical, and mineralogical variability of a given soil series.

This definition of the soil in relation to its environment seems to allow an extrapolation to be made of the knowledge acquired through agronomic experiments on a group of polypedons to all the surfaces containing a similar group of pedons represented as a mapping unit. Therefore, soil maps appear to be very useful for those who manage agricultural development projects.

The environmental characterization of acid soils of tropical regions may be summarized as follows:

- Rainfall appears to be crucial: the limits of acid tropical soils in IBSRAM documentation nearly coincide with the 1000-mm isohyet;
- Mean annual temperatures are in the range of 20 to 27°C;
- Water balance for these soils is usually positive for at least part of the year;
- The soil moisture regimes may vary greatly depending on the nature of the soil. They range from aquic to ustic;
- The soil temperature regimes are usually isothermic and isohyperthermic;
- The natural vegetation is evergreen forest, deciduous subtropical forest, or savanna. When this vegetation is destroyed for cultivation, the surface soil moisture and surface temperature regimes are altered;
- Soil fauna is extremely dependent on vegetation and on the soil climate;
- Parental materials are diversified (sediments, weathered crystalline rocks);
- Landform and geomorphic elements are specific to the tropics; it has been shown that these elements are closely related to the distribution of different soils in the landscape.

Such environmental characterization requires an interdisciplinary approach, mainly based on the study of the interactions and interdependences of dynamic processes in physical surroundings (Kilian 1975).

Whereas all these environmental characteristics relate to lower categories in Soil Taxonomy (family, series), this paper deals with the problem of spatial and temporal variability at the much smaller scale of eco- and agrosystems. Specific examples are presented.

To describe the dynamics of key fertility parameters, Sanchez et al. (1983) chose three fields, ranging in size from 1 to 2 ha, and approximately 300 m apart from each other, having the same soil (classified in the same family, series, and phase), and the same geomorphic position and standing vegetation. They noticed that "the time at which nutrient deficiencies appeared and the amount of fertilizer or lime needed to correct them, varied substantially between the three fields." For instance, aluminum toxicity (more than 60% Al saturation in the topsoil) was apparent after 1 month in field I, after 45 months in field III, and has not yet appeared in field II, after 8 years. Having established this site variability, the authors concluded that "These differences are probably related to the longer time between cutting and burning in fields II and III, and perhaps to the quality of the burn itself, depending on when it rained last." It is therefore necessary to consider not only the intrinsic properties of the pedon but also the management history.

Wilding and Drees (1984) write the following: "Landscape variability is the very essence of pedology" and "Inability to adequately cope with spatial variability remains a major obstacle to interpretation of field research." According to them, "Spatial variability can be grouped into two broad categories, random and systematic. Random variability includes changes in soil properties that cannot be related to a known cause. When the soil system is investigated in greater detail, a part of the variation considered random may be recognized as systematic. Systematic variation is a gradual or marked change in soil properties as a function of landform, soil forming factors and soil management by man." They add that in many agronomic experiments, "Variance due to soil parameters is extracted as blocking or as replication error and given little attention. Under these conditions, sequential testing appears to be more appropriate to direct correlation of soil properties with plant response." However, the topography is not a sufficient criterion to explain variability of crop behavior. It is necessary to know the spatial pattern of the soil mantle and its dynamics.

Let us now turn to our main example, a description of the soil mantle on old offshore bars. The chosen site is situated on prelittoral bars at the border of the Guiana Shield. These old offshore bars have flat or rounded tops, are 200–500 m wide, and are parallel to the seashore. They are composed of Pleistocene marine sediments. Their soils range from Oxisols to Spodosols, yielding considerable variability in the soil mantle (Turenne 1977; Boulet et al. 1982, 1984). Given the extensiveness and agronomic interest of these soils, and in spite of their variability, we have studied selected sites and carried out agronomic experiments.

Analysis of the Three-Dimensional Structure of the Soil Mantle

The aim of structural analysis is to determine spatial variability in three dimensions of the soil mantle of elementary landscape units, so that pedogenesis and soil behavior may be easily visualized.

The elementary landscape unit, in this case, is a section of the old offshore bar. It has been studied by means of transects oriented perpendicularly to changes in soil patterns following landscape features, changes that depend on the orientation of the bar. By drilling bore holes it is thus possible to recognize and compare the main pedological materials. After the limits of the various pedological volumes encountered in the bore holes are included in topographical maps, the inventory of

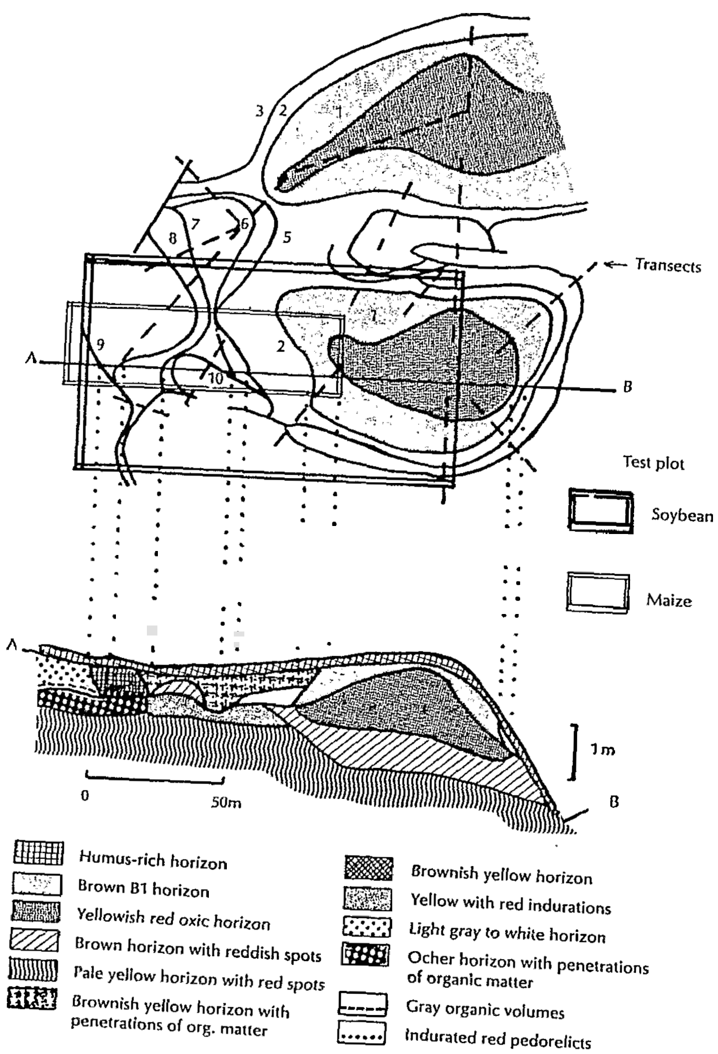

Fig. 1. Section and map of the experimental site showing transects and the location of test plots.

these samples is then set up by using simple descriptive terms (color, texture, porosity, moisture at a given time). By making additional bore holes as needed, it is thus possible to draw the accurate geometry of the various soil bodies that have been observed.

In the present case, a dozen materials may be distinguished on this section that differ by their color (yellow red, brown, yellow, light grey), their texture (from sandy-clay to sand), the presence of red volumes that are differently indurated, by penetration and accumulation of organic matter, and by ocher patches around the voids (Fig. 1). Soil pits are then dug at appropriate sites to observe in detail the materials and to sample the principal horizons that are specific to this pedological mantle.

To draw the map, one can use first the most important lateral variations that can be accurately determined, such as the appearance and disappearance of horizons and variations of some of the above characters. Then, back in the field, variations are checked along secondary transects. By appropriately placing additional bore holes, we can accurately determine the limits of the horizons and of their properties. On the map, points representing the same stage of pedological differentiation are then linked by a continuous line. These continuous lines are called "lines of isodifferentiation."

The principal features that can be distinguished in the present example (see Fig. 1) are:

- On the side of the shoulder is the unit characteristic of an oxic horizon that is clayey and most permeable; to the left are horizons that are progressively lower in clay content and which are deeply penetrated by organic matter; corresponding soils are delineated by unit 7 on the map.
- Starting with unit 5, the bottom of the same horizons have grey organic volumes; and we have seen that, during the rainy period, considerable moisture accumulated due to the decrease in internal drainage.
- To the left of unit 7 the soil in the upper horizons is a pale yellow color and extremely low and very sandy. The lower limit of these horizons is sharp; the bottom of these horizons, during the rainy season, has a seasonally perched water-table.
- Beyond line 9, the top horizons are bleached and permeability is very low.

Sequential Testing of Plant Response in a Given Landscape Unit

The experiments presented here were carried out by agronomists from IRAT and ORSTOM (Godon 1981; Worou 1983). The first trial involved two successive cycles of soybean. The test plot was rectangular and comprised most of the pedological variability that had been studied. Measurements were made according t

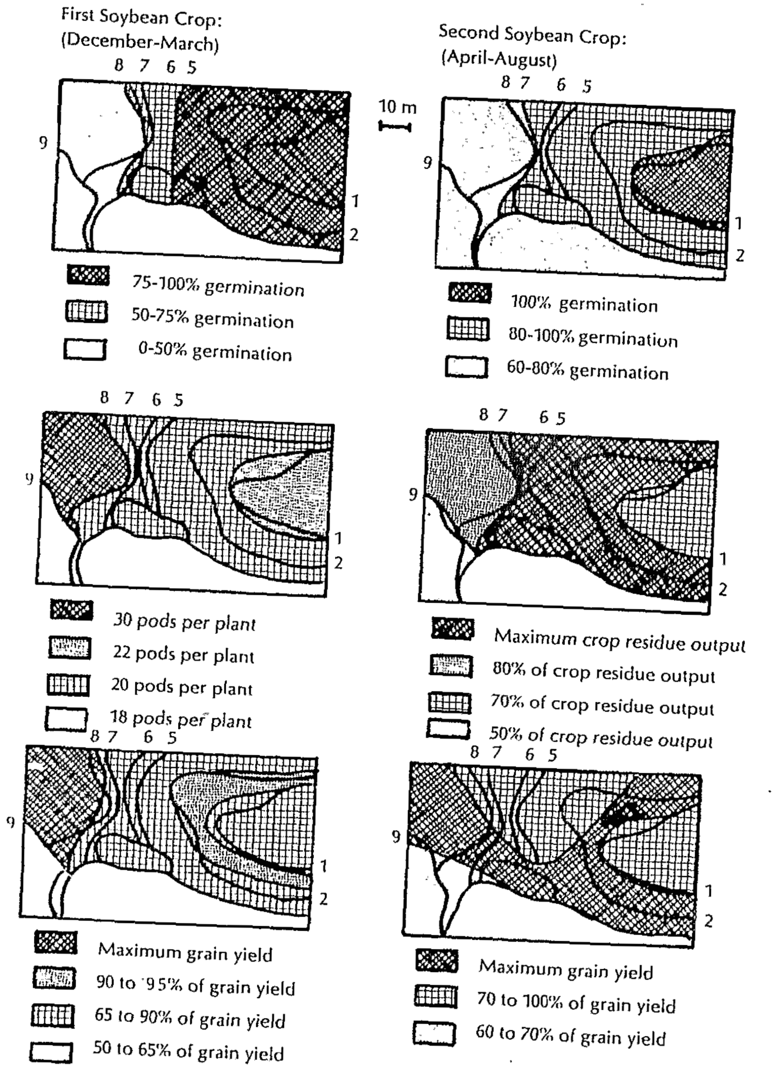

Fig. 2. Soybean behavior during two successive crop cycles.

a grid 1 m wide; they included number of seedlings per m^2 (percentage of maximum), number of pods per plant, volume of crop residues, and grain yield. The first cycle, from December to the end of of March, gave the results presented in Figure 2.

Germination occurred under favorable rainfall conditions. The best results were found wherever drainage was sufficient. An excess of moisture, linked to a decrease in internal drainage, was clearly visible to the left of line 7, precisely where the seasonally perched water-table was observed.

In some places, the number of pods per plant compensated for low plant density. In the area between lines 8 and 9, low plant density and the considerable water reserves (caused by the low permeability of the deep horizons) favored soybean pod development when a drought took place in March. On the other hand, to the left of line 9 an excess of water limited soybean production. To the right of line 7, the normal density of plants led to pod counts of lower than 20 pods per plant. Better water retention in the more clayey Oxisols delineated by line 1 accounted for the higher pod counts in this area.

As for grain yield, the high number of pods per plant between lines 8 and 9 largely compensated for poor germination and resulted in a maximum yield of 1.4 t ha^{-1}. The yield was lower on the right side of line 8 because of lack of water; nevertheless, it was a little over 90% of the maximum in between lines 1 and 2, where conditions were favorable at the end of the cycle. On the left side of line 9, the combination of low density and limited number of pods resulted in a minimum yield (0.7 t ha^{-1}).

The second cycle, from the end of April to the end of August, gave the results shown in Figure 2. Germination occurred during a period of heavy rains. The results are like those of the previous crop but shifted toward the better-drained soils (Oxisols, delineated by line 1). Nevertheless, maximum germination obtained in this trial was only 23 plants per m^2, in comparison with 41 plants per m^2 during the first cycle. The worst results occurred on the left side of line 8, exactly as in the previous crop.

The amount of crop residue (see Fig. 2) is once again in accordance with the soil properties. Better rainfall distribution explains why the maximum residue amount is attained, for this trial, between line 1, which delineates the oxic soil unit, and line 7, which delineates the area lower in clay content.

The grain output is maximum (2.1 t ha^{-1}) in the area limited by lines 9 and 1. Low germination was more than compensated by the number of pods per plant (data not shown). Grain yields overlap to the left of line 1, but do not correspond to any predictable soil limit. This may be due to an unknown event during maturation.

This field test demonstrated the importance of compensation phenomena that are so typical of soybean cultivation. Thus, it was necessary to carry out more experiments, with maize, which is less prone to compensation. In addition, to appraise soil resistance to root penetration, different types of tillage were compared:

with a heavy 60-cm disk harrow, with a tooth scarifier, and with a 4-disk plow. The limits of the field test are shown in Figure 1. The data are shown in Figure 3.

At the first stage of cultivation (28 days) the distribution of plant height correlates very well with the way in which the soil was prepared. This influence is clearly marked by the horizontal patterns. The tooth scarifier gave the best results through the whole pedological sequence.

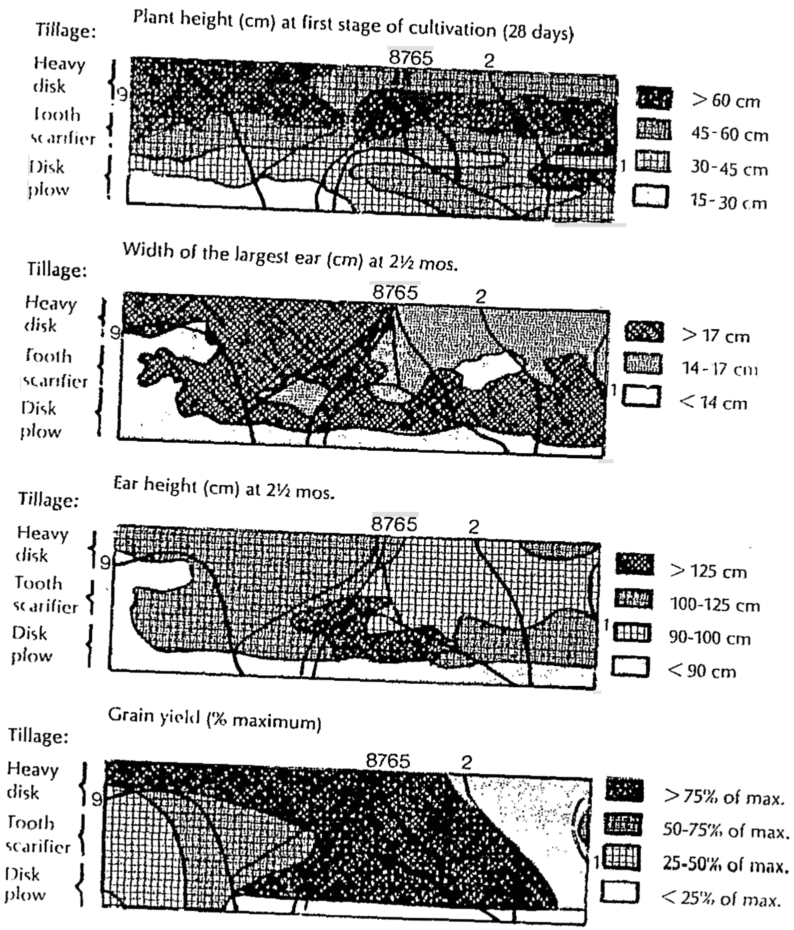

Fig. 3. Maize behavior as affected by soil mantle variation and tillage treatment.

As time went on, the influence of the pedological properties became increasingly important, as measured by the width of the largest ear and ear height at 2½ months. The soil that is low in clay, located between lines 7 and 9, which had produced the best results for soybean, appeared to be most favorable at this stage of maize cultivation.

Highest yields were obtained in the area limited by lines 2 and 9, that is, on the soils that have brown to yellow horizons, are low in clay, and are deeply penetrated by organic matter.

Concluding Remarks

Through these tests, marked changes in plant response appear directly correlated with pedological gradients. Thus, agronomic experiments have to take into account changes in soil properties linked to pedogenesis. These soil properties that are found on typical landscapes of old offshore bars (that cover hundreds of thousands of hectares), thus offer accurate and reliable guidelines for extrapolation of results of agronomic trials from the test site to similar sites.

Given the existing interactions between soil and climate, it is necessary to replicate these trials during different seasons, so as to derive partial but accurate predictions for each growth stage as a function of climatic condition.

Let us not forget that in these acid tropical soils, natural chemical fertility is low, whereas physical properties greatly vary from one site to the other. This is why we have stressed morphological and physical properties of these soils. These properties appear to be particularly important, considering that many of the driving forces governing pedogenesis and fertility depend on rates and vectors of chemical and water transport (Wilding and Drees 1984).

It should be clear that it is not only in the specific case of the old littoral bars that physical properties are ordered in the landscape, a fact understood by native populations, who prefer to locate their small fields in specific areas in close agreement with pedological patterns.

One final remark is worth adding: all variations in the environment, no matter whether they are caused by natural conditions (climatic, tectonic) or by human action (deforestation, cultivation), trigger transformations that show an orderly pattern in time and space. We simply have to discover this orderly pattern, instead of negating the existence of variations or regarding them as artifacts of the analysis.

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