Scientific registration number : 1099
Symposium n° 2
Presentation : Poster

Changes in pore-space and microstructure of 1/1 clay soils : examples from Brazil and Africa
Evolution de l'espace poral et de la microstructure de sols mis en culture en régions tropicales : exemples au Brésil et en Afrique

TESSIER Daniel [(1)], HARTMANN Christian. [(2)], TAVARES-FILHO Joao. [(3)]

(1) INRA, Science du Sol 78026 Versailles, France
(2) ORSTOM, BP n°8006, 97259 Fort de France Cedex, France
(3) UEL, Department of Agronomy, BP 6001, 86051-970 Londrina, Brazil

Mechanical deforestation in tropical areas is leading to dramatic modification not only of the chemical composition of the soils, but also, and may be more importantly, of the relative distribution of their pore size. The use of machines reduces the volume of micro- and mesovoids (1 µm to 100 µm) and results in homogenization of the pore spaces between the clay particles. This size is crucial for determining the amount of water available for plants.
Similar conclusions can be drawn from oil palm plantations after mechanical uprooting. Yield dropped as a result of the use of heavy machinery, accompanied by decreased soil porosity and increased hardness, especially in intermediate horizons (40-50 cm).

Thin soil sections, allowed the description of the porosity and the organization of the soil constituents. In non-degraded soils, clayey aggregates juxtaposed to the quartz grains were clearly shown. In degraded sites, the plasma covered quartz grains, giving a continuous solid phase. By taking steric parameters into account in the mineralogical characterization of oxisols, it allows a better understanding of granulometric results and a more comprehensive analysis of the structural stability factors. Transmission Electron Microscopy (TEM) observations indicated that the clay crystal arrangement was also associated with the location of organic matter. Under initial permanent vegetation cover, organic matter filled up the pore space of the clay matrix while in sites degraded by mechanical up-rooting organic matter mainly disappeared.

In oxisol developed on basalt, the degree of weathering of the mineral constituents and their geochemical environment have to be taken into account to understand and predict their physical stability.
When the pH was acidic (Cascavel) and the exchange complex was highly saturated, cohesive forces between very fine constituents (clays, oxides and organic matter) maintained the physical stability of the soil. When the pH was close to neutrality, like in Palotina, the absence of cohesive forces between the constituents (clays, oxides and organic matters) led to the physical unstability of the soil. The conclusions drawn in Cascavel no longer seem appropriate in Palotina because the soil presented a potentially unstable behaviour due to its structure and its geochemical environment.
Consequences for the management and rejuvenation of oxisols are discussed

Keywords : oxisols, structure, compaction, acidity, cultivation
Mots clés : sols ferrallitiques, structure, tassement, acidité, mise en culture

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(3) UEL, Department of Agronomy, BP 6001, 86051-970 Londrina, Brazil

Introduction

In the humid tropical areas, soils were generally covered until recently by permanent vegetation. When cultivated, those soils may be subject to rapid modifications, not only of their chemical composition but also, maybe more importantly, of their physical properties. For instance, the use of machinery can reduce the volume of pores and result in soil and yield deterioration. Such soil degradation was clearly shown on oxisols containing high amounts of kaolinite associated with iron oxides (Chauvel et al., 1991). For sandy oxisols, a relative resistance to compaction is generally expected and appears to be due to the presence of a rigid skeleton. Nevertheless, this low compaction can induce huge changes in soil properties (Hartmann et al., 1994). The aim of this paper is to identify the various changes in oxisol properties due to cultivation in order to understand better the modifications in soil functioning due to cultivation. The approach will based on a comprehensive study of the physical, physico-chemical and mechanical properties.

Experimental sites and methods

This paper will be based on the results obtained on different situations in South America and in Africa. The deforestation was generally carried out by mechanical uprooting and the soils were examined after 20 to 30 years cultivation. Among the situations described in this paper, a particular reference will be made on the influence soil properties and practices with, when possible, a comparison with native forest.

In South America, the situations in Parana state of Brazil at Cascavel and Palotina will be presented in detail (Tavares Filho, 1994). Because similar conclusions were obtained in French Guyana (Tandy et al. 1990; Robain et al., 1990) some results will also be reported. Those situations will be compared to experiments carried out in Africa on sandy oxisols of the R. Michaud's plantation at Dabou, 60 km West of Abidjan in Ivory Cost (Hartmann, 1991). The results will be completed by the work of Kilasara et Tessier (1991) in Tanzania.

In each case, comparative studies were made between A and B horizons particularly those affected by external mechanical stresses from tillage or traffic (Tavares-Filho, 1995) or mechanical uprooting for oil palm plantations (Hartmann, 1991).

Undisturbed blocks, of about 500 cm^3, were collected in the field. They were put in plastic bags in order to preserve their humidity. Coarse fragments of the blocks of ~ 10 cm^3 were gently cut and were placed in a filtration apparatus for water retention measurements (Tessier and Berrier, 1979). The samples were fully rehydrated and brought at equilibrium at various initial matric potentials. For that purpose, a gas pressure was applied to the filtration apparatus in order to prepare the samples at y values of -1.0, -3.2, -10.0, -32.0, -100.0, -320.0 and -1000.0 kPa.

For compaction experiments aggregates of 5 mm and less were kept. Samples of 40 cm^3 of those aggregates were prepared in the filtration apparatus for water retention measurements and for mechanical compression (Sala and Tessier, 1993). The different pressures applied range from 50 to 1000 kPa. Water was able to drain out of the filtration apparatus during the compression experiments, equilibrium was reached when no more drainage was observed.

The main wetting-drying curves of the compacted samples were obtained by using pressure cells for matric potentials up to -1.6 MPa, and dessicators for a range of matric potentials between -2 MPa to -100 MPa. The specific bulk density of each sample was measured at every step, and the volumetric water content corresponding to the matric potential at each step determined with accuracy.

Undisturbed samples of different horizons were air-dried and impregnated with a polyester resin containing a fluorescent dye (Uvitex, Ciba-Geigy). Thin sections were examined using transmitted visible light and incident UV light simultaneously for studying the soil fabric (Hartmann *et al*., 1992).

Fragments were taken from the plasma (clay + OM) and embedded in an epoxy resin (Tessier, 1984, Kim et al. 1995). Ultrathin sections, 50 nm thick, were ultramicrotomed with a diamond knife. Electron micrographs at low (10,000 x) magnification were obtained using a Philips Model 420 scanning/transmission electron microscope.

Clayey oxisols of Brazil

Under primary forest the vegetation is generally dense and the soil is so permeable that water rapidly percolates through, even with heavy rainfall (Chauvel et al., 1987). By contrast, after 20 years cultivation a considerable increase of the bulk density was observed. It was noticed that the degree of compaction for Palotina was considerably higher than in Cascavel. Also, an experimental study was designed in order to understand better the soil degradation due to compaction of the Cascavel and Palotina sites (table 3; Tavares et al., 1994; Tavares, 1995). Their main physico-chemical data are reported in table 1.

Table : The physical and chemical properties of the soils of Cascavel and Palotina under forest (from Tavares, 1995).

Soils	clay g/g	silt g/g	sand g/g	CEC* Cm/kg	pH	O. M. g/Kg	ρs Mg/m^3	Exch.Al Cm/kg
Cascavel	0.81	0.17	0.02	4.6	4.9	8.0	2.88	1.6
Palotina	0.83	0.11	0.06	6.6	6.5	4.0	2.94	0.2

*measured with cobaltihexamine at soil's pH.

We can observe that the soils have similar mechanical analysis. By contrast, their geochemical environment was different particularly CEC, pH but also their exchangeable aluminum which is null in Palotina, about 40 % of the CEC in Cascavel.
An example of the relationships between the bulk density, and the water potential, y was depicted (table 2). Initially, the two soils are approximately at the same bulk density. After experimental compaction, the maximal bulk density of the Cascavel soil is lower than that of the Palotina soil.
To understand better the soil behaviour electron micrographs were carried out. They showed that the clay particles (kaolinite and oxides) are thinner in Cascavel than in Palotina. It has been shown elsewhere that the thinner the clay particles, the larger is the surface area in contact between soil constituents, thus inferring a higher stability to the fabric (Tessier, 1991; Van Damme and Ben Ohoud, 1989). It is concluded that the differences in stability measured from compaction experiments can be partly attributed to the dimension of clay constituents.

Table 2. Bulk density (g/cm^3) of the Cascavel and Palotina soil aggregate beds prepared at y = -32 kPa after different mechanical compression (Assouline et al., 1997).

Mechanical compression (kPa)	Cascavel	Palotina
0	0.60	0.60
50	0.70	0.80
200	0.95	1.10
500	1.15	1.35
1000	1.25	1.55

The soils differ also in the organic matter (OM) content. It appears that when the clay texture is small, the pH acidic with higher O.M. contents. It must also be noticed that the pH of the 2 soils are largely different as Cascavel is 2 pH units lower than Palotina. In strongly weathered soils such as oxisols where kaolinite and oxides are dominant, the pH affects also the structure stability of (El-Swaifi, 1980; Mc Bride, 1989; Schwertmann and Taylor, 1989; Assouline et al. 1997). In the acidic conditions of the Cascavel soil, the surfaces of iron oxides are mainly positively charged, while kaolinite surfaces are negatively charged. The resulting attraction forces between the soil constituents impart some physical stability to the clay aggregates. By contrast, in the Palotina soil, the pH is close to neutrality, iron oxides have very low charges, and therefore a weaker fabric is obtained.

Because of the low pH of the Cascavel soil, the presence of free aluminum was found in this soil solely. Free aluminum acts as a ligant, and could be more effective than iron oxides in maintaining the stability of soil aggregates. Also, the effectiveness of the free aluminum and the iron oxides in stability is increased by the presence of OM (Edwards and Bremner, 1967). That means that the Cascavel soil, with fine clay particles, high organic matter content, low pH, inducing the presence of free Al is logically the most stable soil.

Similar differences in mineralogical constitution and behaviours were also observed in French Guyana (Robain et al., 1990; Tandy et al., 1990). On contact with saprolite in weakly weathered horizons, large kaolinite cristallites (10 µm to 20 µm), segregated from iron oxides were observed. In the oxic horizons of the soil, there were only small cristallites (10 to 20 nm) closely gathered face to face and intimately associated with iron oxides. It appears that steric parameters of *clay* cristallites can play a significant role in the cohesion of the clay organization. In oxic horizon, when the clay surface area is large, the intercrystals pores are small. Both surface tension between water and clay surface reactivity of clay ensure the cohesion of clay fabric. By contrast, the dominant organization of the weakly weathered horizons is totally dispersable and clay monocrystals themselves can reach the silt size. Finally, by taking clay texture into account in the mineralogical characterization of oxisols, it allows a better understanding of the structural stability.

Clay organization in sandy oxisols of Africa

Most of the soils in Western Africa are developed above sedimentary parent materials. Those rocks contain significant amount of quartz as observed in the mechanical analysis of the soils. Data concerning the profiles are reported in table 3. We compared the soils during a first oil palm plantation (FP) and after re-plantation (RP). During the first plantation, few changes of the soils were observed compared to that of the natural vegetation (Savannah). After uprooting of the first plantation, a change in soil properties was observed, particularly water deficit and hardness.

Physical measurements showed the evolution of the bulk density between 0 and 120 cm, in first plantation and replanted site (Table 4). It is clear that compaction affects the soil up to 120 cm. This compaction can be attributed to a mechanical compression due to heavy machinery, but to other factors as a loss porosity due to a change in bioactivity (roots and termites).

Observation with UV and visible light simultaneously (Hartmann *et al*., 1992) allowed to understand better the changes in soil microstructure from first to re-plantation. The thin sections of the original plantation showed a predominance of spheroidal clay micropeds, 50 µm in diameter. Clay did not embed the quartz grains. In the re-planted site the clay embedded the skeleton grains as a matrix. Contrary to the original plantation, the pore system was no longer continuous while the solid phase appeared mainly continuous.

Table 3. Particle size distribution and some physico-chemical properties of the soil from the original plantation (FP) and the re-planted site (RP) at Dabou in Ivory Coast (from Hartmann et al., 1994).

	<2 µm %	2-50 µm %	50-200 µm %	200-2000 µm %	Org. C.%	pH	CEC $Cm.kg^{-1}$	Exch. Al $Cm.kg^{-1}$
Ap (0-10 cm)								
FP	10.5	4.1	22.2	63.3	2.4	4.9	4.3	0.07
RP	11.1	3.4	26.1	58.6	1.2	5.0	1.5	0.75
AB (40-50 cm)								
FP	16.1	3.4	18.1	62.0	0.7	4.8	0.9	0.53
RP	16.5	2.7	21.0	59.8	0.7	4.3	1.1	0.75
B								
FP (150 cm)	19.3	4.4	24.7	51.6	0.5	4.1	1.0	0.75
RP (100 cm)	18.1	4.8	22.9	54.2	0.4	4.4	0.9	0.55

The arrangement of the clay particles of each thin section could be observed with TEM. In the original plantation, clay particles were randomly oriented and the intercrystal pore space was largely filled by organic matter. In re-planted site, the clay crystals were oriented face-to-face. The particle frequency, i.e. the amount of particles per unit area, increased sharply in the replanted situation.

Table 4. Bulk volume of soil samples (cm^3/g) in original plantation and re-plantation site. Note that the root zone is located between 10 and 30 cm (from Hartmann et al., 1994)

Depth (cm)	Replanted site	Original plantation
0-10	1.45	1.11
10-20	1.33	1.28
20-30	1.52	1.33
30-40	1.56	1.43
60-80	1.54	1.45
80-120	1.56	1.45

These results were used in order to interpret the changes in soil physical properties from original plantation to re-planted sites. In the original plantation, clay particles were organized in micropeds between quartz grains. Thin sections showed a continuous pore space which can explain the high permeability of the soil. The soil behaves like an assemblage of sand-like particles and is thus soft. In this case, all

constituents, i.e. quartz grains and micropeds, behave as individuals. As a consequence, the soil hardness does not increase very much during drying.
After replanting, there was a complete change in the organization of the microstructure. The degradation of sandy Oxisols involved a rearrangement of soil components from the microscopic to ultramicroscopic scale. At the microscopic scale, the quartz grains are embedded by the clay matrix, and the solid phase (skeleton and clay matrix) is mainly continuous. The soil cohesion, especially after drying, increases. Permeability decreases and root penetration is hampered.

Changes in soil physical properties cannot be related to clay content but rather to clay location and its local concentration around skeleton grains. After heavy machinery, when clay embbeds skeleton grains, the soil behaves as a clayey material with low macropore continuity, higher cohesion in dry state. On the other hand, its clay content is too low to induce shrink-swell phenomena and, therefore, to induce soil structure regeneration.
TEM revealed that in the original plantation, organic matter filled up the pore space of the clay matrix and the mean distance between clay crystal was considerably larger than in re-plantation where the clay particles were mainly on contact face-to-face. The presence of organic matter in the clay matrix seems to play a major role in determining clay particle arrangement, soil fabric and, as a consequence, soil physical properties.
As the soil physical properties are mainly related to the clay organization, the key to soil rejuvenation appears to be associated with the genesis of a micropedic microstructure. We can expect that deep cropping or subsoiling, as tested in the area of Dabou, are not suitable techniques for soil rejuvenation. Appropriate management of plant residues and high bioactivity level appear only capable of incorporating organic matter at the scale of the clay particle arrangement and of maintaining a micropedic structure (Feller et al., 1996).

Conclusions

Management of Oxisols must take into account changes at the smallest scale. In oxisols, soil compaction behavior is not determined solely by the mechanical analysis of the material. It is also affected by properties like pH and CEC, and by the presence OM, iron oxides and free aluminum, that, together, determine the nature of the resulting cohesive forces between the soil constituents. Oxisols presenting practically the same mechanical analysis can considerably differ in these properties. A description of the structure sensitivity to degradation can be done by establishing soil compression curves which can be compared to field observations in order to assess cultural practices.

Only appropriate management of plant residues and high bioactivity appear capable of incorporating organic matter at the scale of the clay particle arrangement and of maintaining a micropedic structure (Tisdall and Oades, 1982; Garnier Sillam *et al.*, 1986). Nevertheless, the weathering degree of the soil and its geochemical environment partly determine the soil behaviours.

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