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Changes in soil pore-space distribution following deforestation and revegetation: An example from the Central Amazon Basin, Brazil

A. Chauvel[a], M. Grimaldi[b] and D. Tessier[c]
[a]*INPA/ORSTOM, C.P. 478, 69060 Manaus AM, Brazil*
[b]*ORSTOM, Centre de Cayenne, B.P. 165, 97323 Cayenne, French Guiana*
[c]*INRA, Station de Science du Sol, CNRA Route de St-Cyr, 78000 Versailles, France*

ABSTRACT

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Deforestation of the Central Amazon is leading to a dramatic modification not only of the chemical composition of the clay latosols, but also, and maybe more importantly, of the relative distribution of their pore size. The use of machines reduces the volume of micro- and mesovoids ($1\ \mu m < \phi < 100\ \mu m$) and results in homogenization of the spaces between the clay particles (characterized as 'cryptovoids' $< 0.1\ \mu m$). This size is crucial for determining the amount of water available to plants. When plants such as *Pueraria* (Kudzu bean) are introduced, their roots further modify the relative pore distribution, this time reducing the volume of cryptovoids through increasing the volume of micro- and mesovoids, thus freeing for plants even more water than in the original soil. This study, using mercury porosity analysis in addition to usual methods, shows the importance of measuring variations in porosity and water availability before deciding on cultivation and reforestation. Water availability may vary to a large extent depending on how the soil is cleared and what root action is allowed to develop. (Certain types of deforestation – heavy machinery, no cover plant such as *Pueraria* – may result in a completely unproductive soil although the chemical composition remains unchanged).

INTRODUCTION

Participants in this Symposium stressed the dramatic increase in deforestation in the Amazonian rain forest of Brazil which, in turn, has resulted in a deterioration in soil quality. This paper looks at selected examples of soil transformation resulting from such deforestation and subsequent developments following the establishment of new plant cover in the clay 'latossolo' of the region north of Manaus. This type of latossolo accounts for more than 10% of the surface area of the Amazonian rain forest in Brazil, and is particularly suitable for this type of research. To evaluate the effects of these changes on the ecosystem, the following approach was adopted: an analysis of the ef-

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fects of forest clearance at different levels of soil structure from soil profile to soil constituent scale; and an examination not only of the immediate effects of clearance work, but also of the subsequent evolution and potential reversibility of the soil deterioration process.

BACKGROUND

The climate is tropical rain forest. Annual rainfall varies widely from one year to another between 1200 and 2400 mm year^{-1}, the average being 2075. For 2–4 months of the year, sometime between June and October, rainfall is less than 60 mm/month^{-1}, i.e. less than moisture lost through evaporation and transpiration. This negative hydrological balance checks the growth of more-demanding plant species, such as oil palms, if not counter-balanced by soil reserves. The soil (Camargo and Rodrigues, 1979; Chauvel, 1982; Lucas et al., 1984) of the lower plateau is 'latossolos amarelos, álicos, textura argilosa' which may be characterized as being highly desaturated in B 'ferralitic' soils (according to the French classification system) or Oxisols (according to USDA Soil Taxonomy; Chauvel et al., 1987). The mineralogical composition is kaolinite (80%), iron and aluminium hydroxides, and between 5 and 15% quartz, the proportion of which increases from a depth of 1 m to the surface. This characteristic enables the matching of soil at surface level after clearance with the initial pedological profile under primary forest, irrespective of the degree of soil removal, digging and refilling caused by clearance work. Comparisons may be made between samples containing the same proportion of quartz, i.e. coming from the same horizon of the pedological profile. Furthermore, the soil is acid, varying from pH 4.3 at the surface to pH 5 at 40 cm depth, very poor in nutrients, with a porosity range of 50–80%.

The vegetation is known as 'floresta de terra firme': dense, humid, evergreen rain forest,

MACRO- AND MICROSCOPIC FABRIC OF THE SOIL

Three main stages were compared : under primary forest; following mechanical clearance; and two years after the establishment of a legume (Pueraria) as ground cover.

Under primary forest

The vegetation is dense and rich in palms (Fig. 1a) and the surface of the soil, covered by litter 3 cm deep, is so permeable that water rapidly percolates through, even after heavy rainfall (Chauvel et al., 1987).

The humic A horizon is porous, and rich in soil fauna and roots (Fig. 1b,c).

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SEM shows the predominance of biological aggregates and voids, and mycelia (Fig. 2a).

Observation with a light microscope reveals that the overwhelming mass (90%) of clay (or 'plasma'), occurring near the biovoids, is a grey-brown colour dark in natural light (Fig. 2b) and with slight anisotropy in polarized light (which makes it seem lighter in Fig. 2c). This optical anisotropy shows that kaolinite particles tend to have a common orientation. More compact islands, mainly isotropic, demarcated by a fringe which is dark in natural light and pale in polarized light, account for less than 10% of the total volume (Figs. 2b and 2c).

After mechanical clearance

The passage of machines had denuded the soil (Fig. 1d).

The upper horizons are very compact with a horizontal lamellar structure, and fine vertical and horizontal fissures may be observed (Fig. 1c).

A thin section from a magnifying glass (Fig. 1f) shows that porosity is reduced to a network of horizontal and oblique fissures, which delimit centimetric, polyhydronal aggregates. Compact islands, defined by a fringe as in soil under primary forest, can be detected but the proportion of these volumes is between 50 and 90%, compared with 10% under primary forest.

From SEM, the lamellar structure and sub-horizontal slickensides are clearly visible (Fig. 2d).

Using the optical microscope, two types of plasmic structure can be identified, but with very different properties. As above, an anisotropic structure is found near pores, but porosity is less well developed (Figs. 2e and 2f).

It has been noticed that a soil mechanically cleared eight years previously and left without ground cover has a microstructure identical to that observed in soil four months after clearance. Therefore, no regeneration of the soil structure occurs in deforested areas uncolonized by new vegetation.

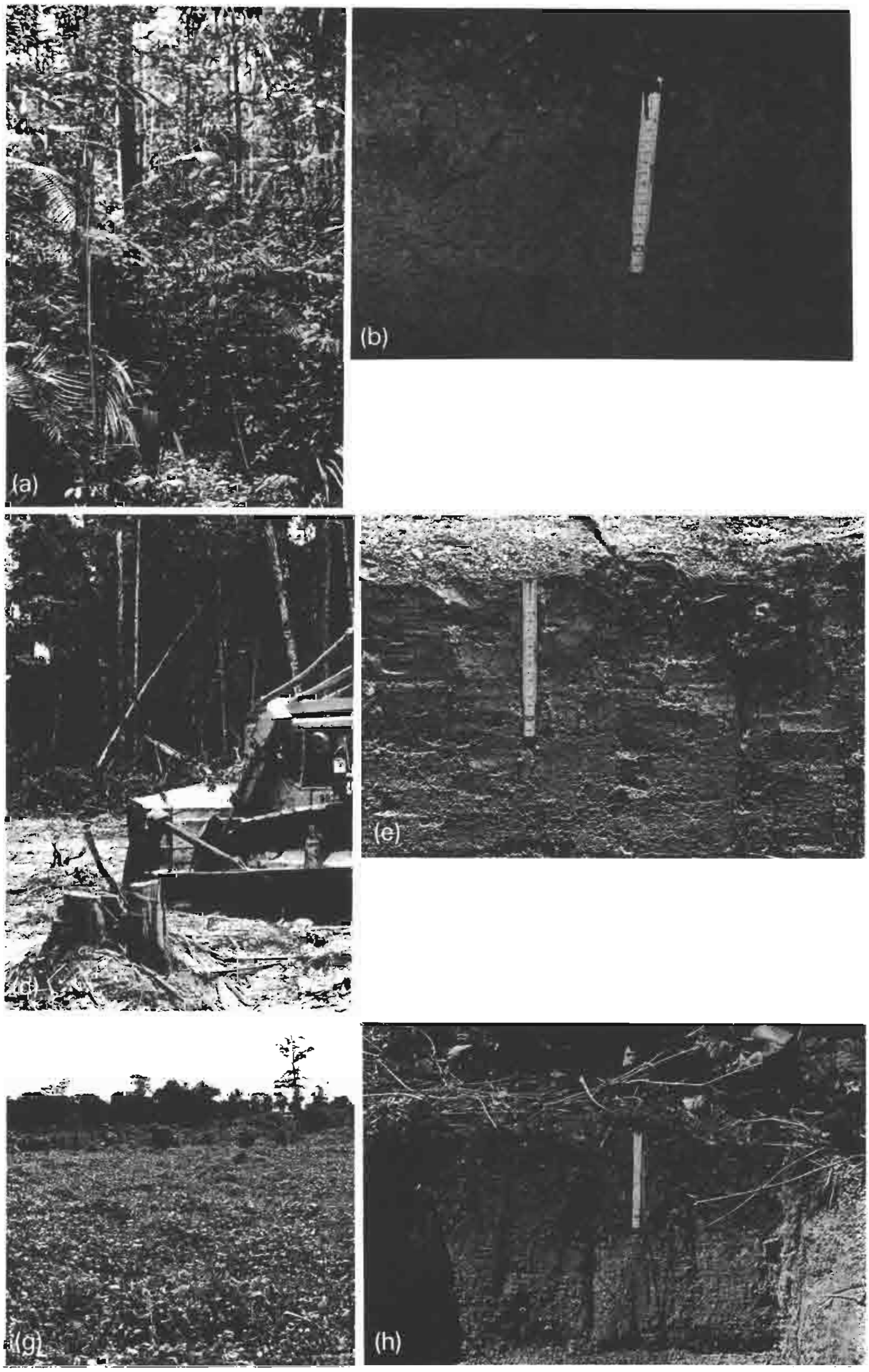
Two years after the establishment of leguminous ground cover (pueraria, planted six years after clearing)

The extreme vigour of pueraria, which entirely covers the ground, is evident (Fig. 1g).

The upper horizons of the soil are loose and porous. However, the presence of compact clods, light in colour and identical to those in recently cleared ground, may be observed (Fig. 1h).

Once again, a thin section with a magnifying glass, shows that porosity is due to fissures, now colonised by roots and fauna (Fig. 1i).

SEM images show the traces of a root near which the clay packing has been transformed; it would seem as a result of root penetration effect (Fig. 2g).


(a)
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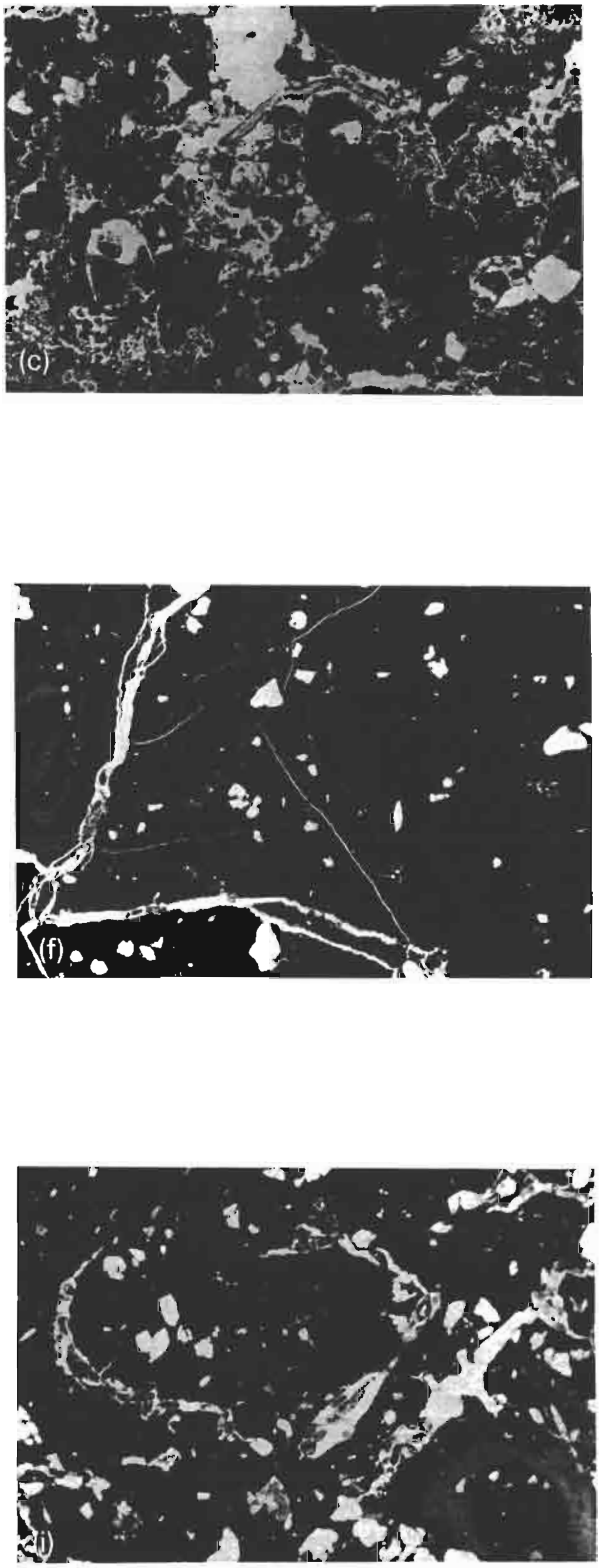

Fig. 1. Observations of vegetation and surface appareances, soil profile and thin sections under primary forest (a,b,c), following mechanical clearance (d,e,f) and two years after the establishment of a legume (Pueraria) as ground cover (g,h,i).

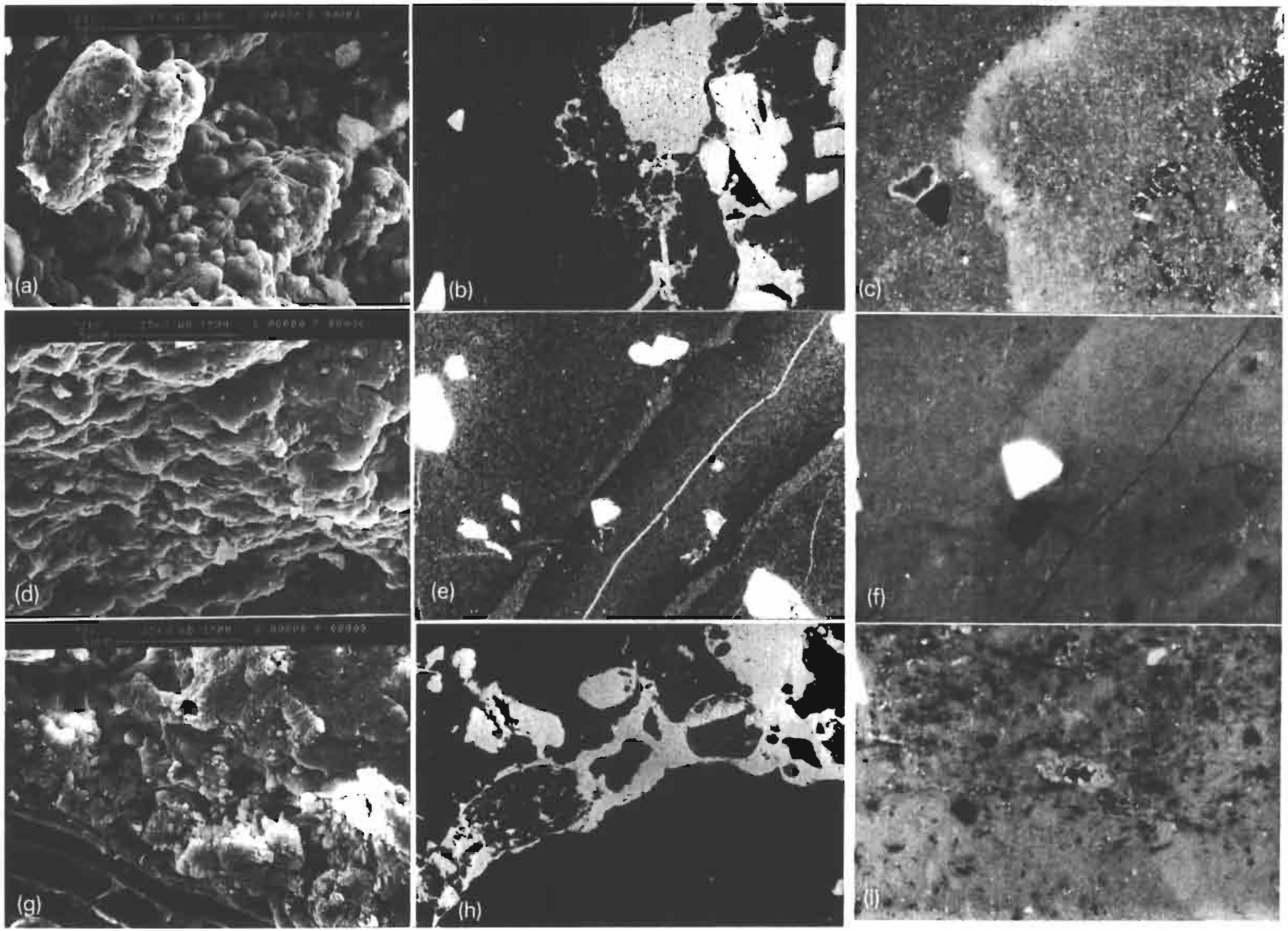

Fig. 2. SEM images, and light-microscope observations under primary forest (a,b,c), following mechanical clearance (d,e,f) and two years after the establishment of a legume (Pueraria) as ground cover (g,h,i).

Using an optical microscope, the development of dark brown plasma near to those fissures colonized by biological activity may be detected (Fig. 2h). In highly magnified polarized light, numerous opaque organic particles may be identified in the mainly anisotropic plasma (Fig. 2i). Taken together, these observations suggest that soil transformation, related both to mechanical and biological action, affects not only porosity as visible to the naked eye and to the optical microscope (i.e. above 1 μm) but also ultra-microscopic porosity found between clay particles with measurements of less than 1 μm. In this context, it should be recalled that the smaller the pores, the greater the energy needed to extract water. Below 0.1 μm, this energy is such that water is no longer available for the use of the majority of plants (pF > 4–10 bars).

MERCURY POROSIMETRY ANALYSIS

In order to quantify the fine-pore space, the pore-size distribution was measured using the mercury injection technique (Lawrence, 1977; Grimaldi, 1986; Grimaldi and Tessier, 1986). It should be noted that: (a) this method does not account for pores larger than 100 μm; thus total pore volume may be substantially greater than indicated by cumulative void ratios.
(b) The radius at the point which fluids penetrates into the pore is identified.
(c) The samples are dehydrated and degassed prior to analysis. However, results obtained by this method conform to those one might expect from water-retention curves; they are presented in two ways:

- a graph showing the cumulated void ratio (from the smallest, 0.0035 μm, to the largest, 100 μm). It should be noted that the void ratio (*e*) is the ratio of volume of pores to the volume of solid; thus the value is independent of soil particle density.
- a histogram showing pore size distribution, i.e. distribution by detailed pore class, defined by constant growth in the decimal logarithm of *r*.

Pore space of the 'Latosol' under primary forest

The pore size distribution (Fig. 3) was made on the basis of samples of undisturbed structure taken from depths of 10, 30, 50 and 80 cm. For each depth the pore size distribution is clearly bimodal, indicating two types of pore: the smallest, 0.01–0.03 μm, were due to the formation of pores inside compact clumps of fine kaolinite particles; the largest, which are biological in origin or due to fine fissures (0.1–100 μm), account for less than one-quarter of the total volume of pores studied.

Pore size distribution varies as a function of depth. There is a progressive increase in the volume of small pores (0.01 μm) and their size distribution is wider. This increase in volume is correlated with the clay content to 30 cm

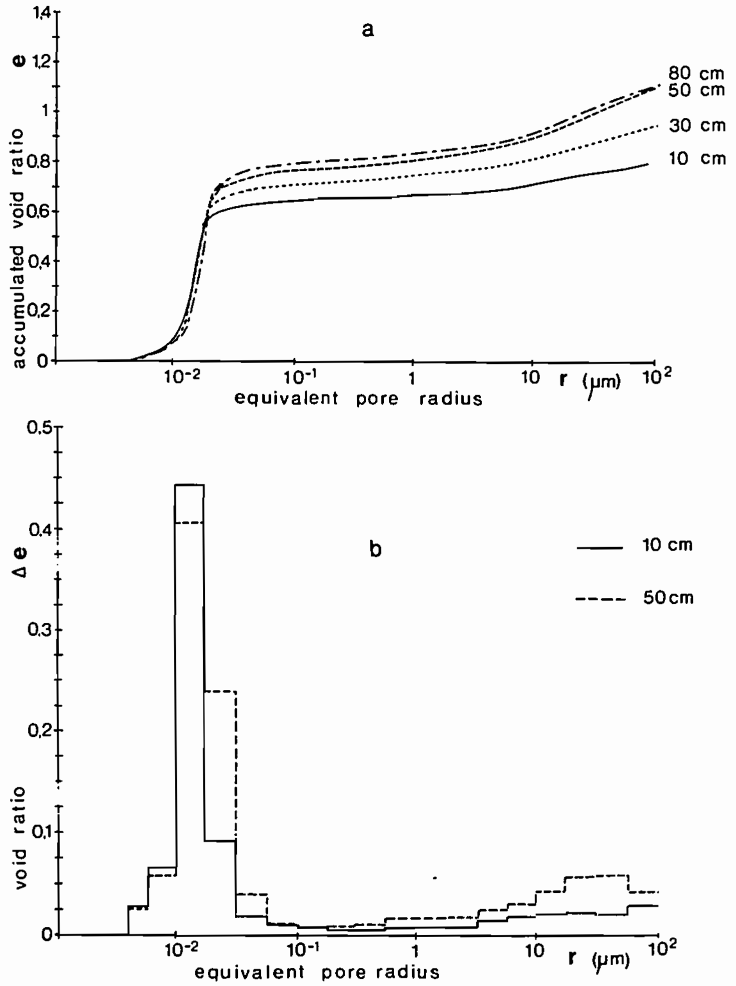

Fig.3. Mercury injection curves on latosol under primary forest showing the pore-size distribution at different depths. (a) cumulative void ratio; (b) pore-size frequency distribution.

depth; below this depth volume is more dependent on the size and shape of the clay particles (these vertical differences enable the identification of reference points for the initial profile under primary forest). To a depth of 60 cm, there is an increase in the volume of large pores.

Effects of mechanical clearance

Mechanical clearance compresses the soil, which destroys most of the pores with an equivalent size >0.1 µm, i.e. the biological spaces and fissures (Fig. 4). The structure becomes bulky due to the coalescence of clumps. The pore size distribution is almost unimodal (due to the disappearance of the second mode described above) i.e. 0.1–100 µm. The end result is a fall of three-quarters in pore volume containing water available for plant life.

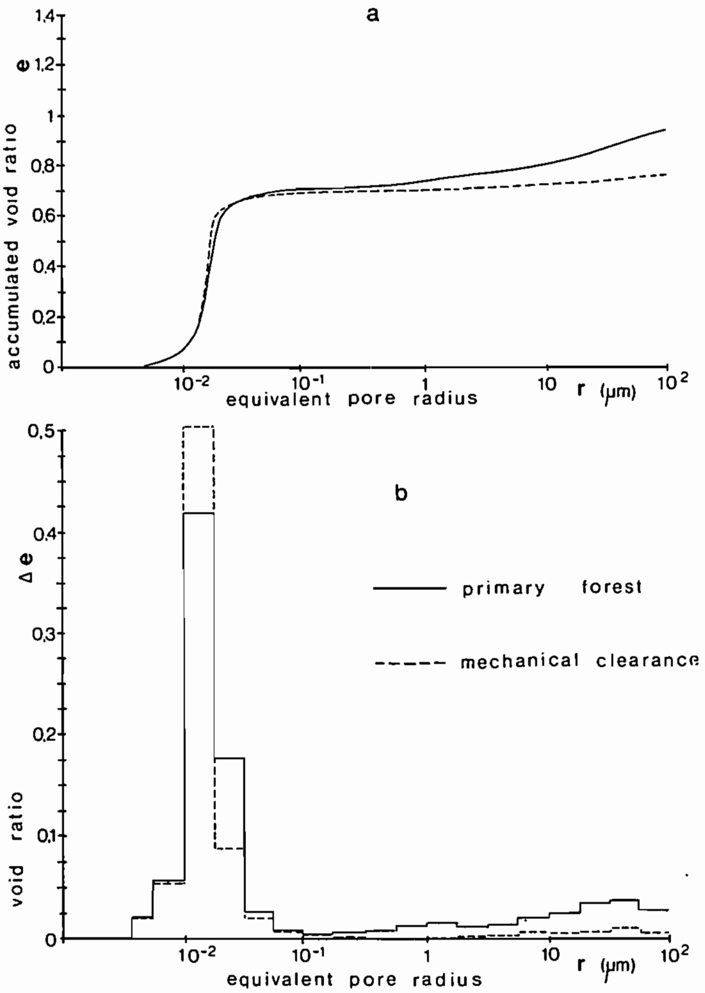

Fig. 4. Mercury injection curves showing the effect of mechanical clearance. (a) cumulative void ratio; (b) pore-size frequency distribution.

The volume of smaller inter-particle pores does not vary significantly, thus there is no compression at this scale. Nevertheless, there is a change in the size distribution of interparticle pores, shifting the mode from 0.10 to 0.18 μm. This can be interpreted as a homogenization in the arrangement of clay particles. The state of the soil after mechanical clearance is relatively stable; it remains unchanged for terrain deforested eight years previously if left unplanted. It is also observed in compact clods conserved in loose material from under pueraria cover of two years' standing (the cumulative void-ratio curve is almost identical to that for compact soil).

Effect of pueraria cultivation

The pore size distribution of fragmentary clods is clearly bimodal. The pore volume, in the range 0.1–10 μm, is even higher than that observed under pri-

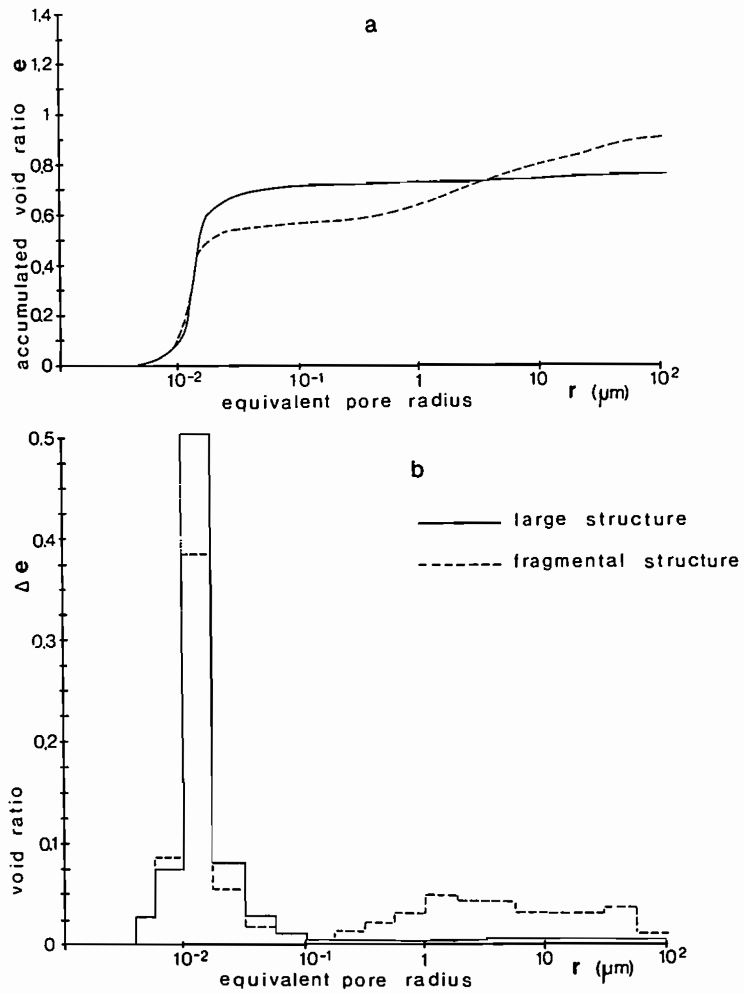

Fig. 5. Mercury injection curves showing *Pueraria* effects on pore size distribution. (a) cumulative void ratio; (b) pore-size frequency distribution.

mary forest. Furthermore, although the volume of small pores is still clearly in evidence (Fig. 5), it is considerably lower when compared with material looked at up to now. This reduction in the volume of small pores can be attributed to changes in the arrangement of clay particles on contact with *Pueraria* (Kudzu bean) roots. Thereby, the availability of solutions for living organisms is increased as much by an increase in porosity in the 0.1–10-µm range as by a reduction in very fine porosity found between clay particles (containing water which is mainly unusable by plants). This remark deserves verification by hydraulic measurement.

EFFECT OF CLEARANCE ON WATER-BEARING PROPERTIES OF THE 'LATOSOL'

The volume occupied by solids, water and air at a given time (13 November 1987) in profiles of the same soil type (two replications per treatment) are shown here. The measurements were made using a 100-cm^3 cylinder (nearly 5 cm in diameter). It can be seen that the proportion of volume taken up by solids, liquids and air varies considerably according to the treatment (Fig. 6).

In soil under primary forest, the quantity of water is less than 30% of volume. Larger pores occupied by air are mostly open to the surface. Many of these pores have a diameter above 100 μm, which could not be taken into consideration by the previous measurements. Their size explains the easy penetration of rain water.

Manual clearance does little to alter these proportions; however, there is some evidence of compression and a slight increase in the column occupied by gas.

Mechanically cleared soil has very different characteristics: a large increase in the volume of solids (+35%) due to compression; a sharp decrease in porosity occupied by gas in the upper horizon (by 3/4); and a significant increase in the proportion of water (50%).

This sharp decrease, following mechanical clearance, in the volume and

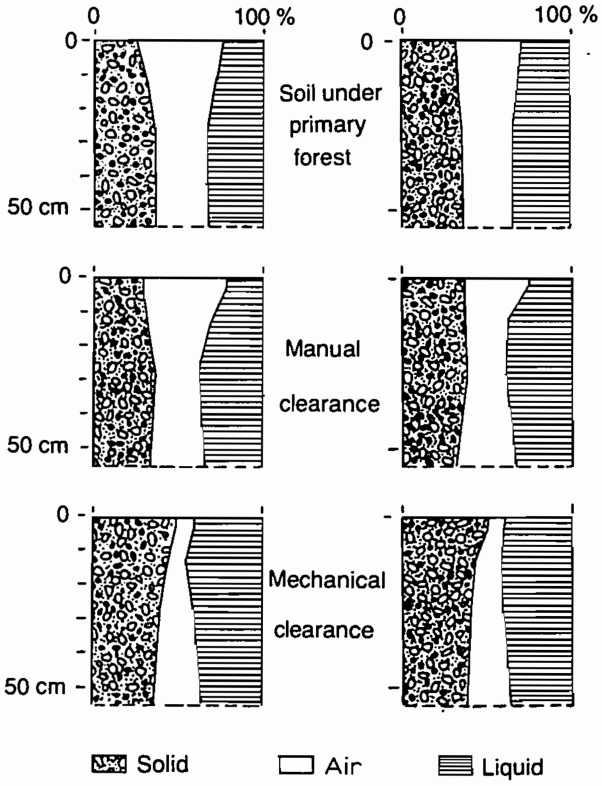

Fig. 6. Soil composition (solid, liquid and air) as function of depth for soil under primary forest, after manual and mechanical clearance (results were made using 100-cm^3 cylinders and repeated three times in two distinct stations).

TABLE 1

Water content as a function of matrix potential (pF) in clods with large and fragmented structure under pueraria

pF	1	2	3	4	1–4	2–4
Matrix potential (bar)	0.01	0.1	1.0	10	0.01–10	0.1–10
Clods with large structure	32.7	32.3	30.7	29.9	2.8	2.4
Clods with fragmented structure	40.1	34.2	29.5	28.0	12.1	6.2

continuity of larger pores (especially of a biological origin) must strongly affect hydraulic conductivity so that soil is saturated (hence the additional water content), reduce water transfer to plant roots, and limit evaporation from the bare soil.

A comparison of soil profiles after a dry spell (13 November 1987) also showed a much higher water content in layers affected by compression than under primary forest. However, this in no way means that the water is available for plant life, as already shown in the two examples considered above – clods with a large structure and clods with a fragmentary structure under *Pueraria*.

The gravimetric water content was measured in the laboratory on these samples, using ten replicates, for four values of matrix potential. These samples were rewetted to pF1 then progressively dried up to pF4. These values are considered in these soils as near to field capacity and wilting point respectively (Table 1). It can be seen that in the same range of water potential, i.e. between pF1 and pF4, the extracted volume of water is four times higher in soil with a fragmented structure than in compacted soil. When the same comparison is made between pF2 and pF4, the values are about two times greater (Table 1). These data underline the role of *Pueraria* in soil-structure transformation. The important modification in pore volume containing solutions available for plants can only be due to the beneficial action of *Pueraria* roots. It is not possible to draw a definitive conclusion on the mechanism at the origin of such a transformation. Nevertheless, mechanical effects due to root growth and clay particle-arrangement changes by strong drying (Tessier, 1984), seem to play a major role in soil structure changes.

CONCLUSION

Both water-retention and mercury-injection curves allowed us to conclude that soil pore size distribution and, consequently, water available for plants is strongly modified by *Pueraria* roots in latosols from Brazil. It would appear that two complementary types of action can modify the porosity containing water available for all living organisms in clay soil.

(a) Root action, as shown by the effect of *Pueraria*, improved 'useful capacity' (as much) by increasing macroporosity and by reducing cryptovoids volume (Brewer, 1964) between clay particles. These modifications in the plasma structure are certainly due to both a mechanical and a suction effect of roots. Thus, cohesion and stabilization of the structure could also be increased. It is unlikely that this is solely a characteristic of *Pueraria*, and microstructural soil changes due to other plants which might be cultivated in the Amazon should also be evaluated.

(b) The principal effect of heavy mechanical action is to reduce macroporosity. As a result of this, there is a sharp decrease in the amount of water available for plants.

Amazonian agriculture must use all the means available to manage and regenerate the soils. Soil/plant-relationship studies appear to be one at the best approaches to this purpose, and the clay soils of the region north of Manaus are well-suited to such studies.

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