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Rehabilitation processes under fallow and pasture of a compacted Vertisol in Martinique (FWI)
Mécanismes de réhabilitation sous jachère et prairie d'un vertisol compacté de la Martinique

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This paper aims at precising the part of physical and biological processes in rehabilitation of a weakly craking Vertisol located in Martinique (FWI). Soil structure of a long-term compacted market-gardening plot (M: annual ploughing and low biological activity) is compared to two long-term grasslands installed after previous soil compaction. One is a long-term fallow (F) with a low biological activity; the other one is a long-term intensive artificial pasture (P) with a high biological activity. The changes of specific air volume (Va) are monitored at two structural scales (undisturbed samples of 5 and 500 cm^3, respectively Va (5) and Va (500)), from the 0/10 to 50/60 cm layer. Those measurements are completed with a description of solid phase and pore characteristics on thin sections (0/10 and 30/40 cm).

Despite the high level of mechanical constraints which were applied to the M plot, the structure did not become completely massive: a structural porosity still exists at both investigated scales. Under fallow (F) the rehabilitation is weak; it concerns much more the fabric of solid constituents than the pore volume. Under pasture the high root and earthworm activity is associated with a huge developement of Va(5). The rehabilitation concerns the stuctural pore at lower organisation scale, down to a depth of 30 cm. Our analysis indicates that earthworms do not play a major role neither in pore formation nor in solid constituent rearrangements. The repeated wetting/drying cycles induced by irrigation seem important to determine pedal development and consequent porosity. The root development in the whole profile and the cumulative effects of deep wet/dry cycles during more than one decade explain the deep rehabilitation.

It is concluded that, even in those weakly cracking Vertisols, shrink/swell processes are responsible for the rehabilitation. That is only possible through the use of of irrigation and plant water pumping which increase the natural drying/wetting cycle.

Keywords : vertisol, structural pores, biological activity, shrinkage, swelling
Mots clés : vertisol, porosité structurale, activité biologique, gonflement, retrait

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Introduction

The pore volume of Vertisols can be divided into three compartments: cracks, structural pores and matric pores. The structural pores are filled with air in a large range of soil moisture (McGarry & Malafant, 1987). In the field, they can be filled with water during several days after a rainy event or after irrigation (Cabidoche & Ozier-Lafontaine, 1995); that water is easily available, has a fast transmission rate in the soil and thus satisfies cultivated crops requirements (Ozier-Lafontaine & Cabidoche, 1995). Thus it is important to understand how the structural pores are formed and how they evolve so as to find cultivation techniques which preserve or rehabilitate them.
It is assumed that those structural pores are mainly interpedal macropores depending on the fabric of solid consituents which are hierarchically organised; in addition, there are also biological pores depending on the nature and level of biological activity (Kutilek, 1996; Cabidoche & Voltz, 1995). When Vertisols are tilled in dry conditions, those structural pores are preserved; if they are tilled in wet conditions (above plastic limits) a decrease can be measured in the specific air volume, even after only one tillage (McGarry & Daniells, 1987). That degradation is usually attributed to clay rearrangement at microscopic level with consequences on the macroscopic level (ped structure and interped porosity) (McGarry, 1989).
Once compaction occurred, a profile rejuvenation is rarely obtained using implements: the plots are left under fallow and a natural amelioration of soil by shrinking and swelling is sufficient. The physical processes involved in such a reorganisation have been clearly described by Tessier (1989); they seem so efficient that Ahmad (1996) noticed that it is unusual to find Vertisols degraded beyond rehabilitation anywhere in the world. That can certainly be explained by the fact that until now, the cultivated Vertisols are mainly those with 'deep cracking' properties. Recently, mechanization of agriculture has permitted cultivation of less favourable Vertisols, i.e. Vertisols with lower cracking properties. Therefore the natural swelling/shrinking processes are insufficient to obtain a rehabilitation of the structural porosity and complementary conservation and rehabilitation techniqeus have to be developed.

In Australia, irrigated cotton fields on a sodic Vertisol led to soil physical degradations. Subsoiling with gypsum application were used to create aggregates and stabilize them, but the improved porosity just lasted one season (Wild *et al.*, 1992). In Martinique, calco-magneso-sodic Vertisols supported sugarcane during more than two centuries; 20 years ago lands were changed to food crops and soil structural degradations were quickly observed (Turenne, 1982). Subsoiling (without gypsum application) has been unsuccessfully tried in order to rehabilitate them. Rather than ameliorating the deep tillage techniques at increasing costs, it would be better to improve the natural rehabilitation and develop the conditions for a more sustainable agriculture. A better understanding of the biological processes of rehabilitation of structural porosity on the profile level is necessary to propose well-suited management .

This paper aims at precising the respective roles of physical and biological processes in rehabilitation of the Vertisol of Martinique. To reach this goal, a compacted plot is compared to two long-term grasslands after soil ploughing which differ in the biological activity level. The first one is a planted fallow with low biological activity (mainly roots); the other one is an irrigated, fertilized and grazed pasture with high root and earthworm activity. On the whole profile depth (0-60 cm), the changes in specific air volume at two structural scales will be measured, and the solid phase and pore characteristics will be described on thin sections of the upper layer (0-10 cm) and the layer at the bottom of the cultivated zone (30-40 cm).

Materials and methods

Climate and soil

The plots are located in an experimental station in the South of Martinique (14°25N, 60°53W). The mean annual rainfall is 1460 mm and mean potential evapotranspiration (Piche) is 1080 mm; the water balance is generally positive from June to December and negative from January to May. The Vertisol which were described as 'à structure large dès la surface' (Colmet-Daage & Lagache, 1965), could now be called 'weakly self-mulching'; in the US Soil Taxonomy they can be classified as Leptic Hapludets (Eschenbrenner, pers. comm.). The clay content is approximately 60 % on the whole profile (80 cm), the pH is ca. 6.5, the exchangeable sodium percentage (ESP) increases with depth (5% at 0/10 cm and 12 % at 30/40 cm).

Study plots

Three plots characterized by different managements in the last 2 decades were studied:

- M is a 16 years' old (1979/1995) irrigated market gardening plot. Preparations consist in a deep tillage (40 cm) using a one furrow plough followed by 2 or 3 secondary operations and completed from time to time by subsoiling (60 cm depth). It was usually ploughed between November and January, as soon as the tractor could enter the plots after raining events. After harvesting (April/May), irrigation was stopped and a natural fallow grew until the next cropping season.

- F: after 8 years in market gardening with deep tillage preparations (1972/1980), a grass (*Cynodon nlemfuensis*) was planted. That plot is now under natural conditions (no irrigation and no fertilization).

- P: after 4 years as a natural fallow, the soil of that plot was deep tilled and a grassland (*Digitaria decumbens*) was sown in 1979. Until 1995 that grassland was irrigated, fertilized and grazed by sheeps (150 kg living meat ha^{-1}).

Some biological and organic soil characteristics of the three plots are displayed in Table 1.

Table 1. Earthworm (*Polypheretima elongata*) biomass and density (means, standard errors in brackets), and soil organic carbon content (C) (means and confidence interval in the brackets, $P<0.05$) of the 3 experimental plots.

Treatments	M	F	P
Earthworm biomass ($g.m^{-2}$)	3.2 (8.0)	1.8 (4.5)	37.3 (35.0)
Earthworm density ($ind.m^{-2}$)	28 (30)	21 (26)	316 (244)
C 0/10 cm ($g.mg^{-1}$)	14.9 (1.1)	20.4 (2.1)	35.4 (3.8)
C 10/20 cm ($g.mg^{-1}$)	13.1 (0.4)	13.8 (1.3)	21.3 (2.3)
C 20/30 cm ($g.mg^{-1}$)	9.2 (0.7)	9.8 (2.0)	15.4 (2.1)
C 30/40 cm ($g.mg^{-1}$)	6.3 (1.3)	8.3 (1.7)	12.1 (1.4)

Soil analyses

Undisturbed soil samples (30 x 10 x 10 cm) were collected at 0/10, 10/20, 20/30, 30/40 and 50/60 cm depth on the wall of 2 (P) or 3 (M and F) pits. They were collected in December (wet soil without cracks) and stored in plastic bags in order to keep their moisture. In the laboratory, they were cut in smaller samples on which the bulk density was measured by liquid (kerosene) displacement (Archimede's principle) and on which the specific air volume (νa) was calculated (Voltz & Cabidoche, 1995) .

As the sample size influences the total pore volume and the specific air volume, the bulk density measurement was realized on two sample sizes:

- clods from 2 to 3 cm diameter and 1 cm high (volume ≈ 5 cm^3). Such clods enabled to measure the structural porosity developed at the centimetric aggregate level which involve the smallest interpedal and biological pores.
- clods of 8 cm side (volume ≈ 500 cm^3). Those samples involve the same small size pores than the previous samples as well as the bigger discontinuities which could be created by tillage or biological activity (as largest grass roots).

The calculated specific air volume are respectively called: νa (5) and νa (500).

Those measures were completed by micromorphological observations in order (1) to describe the porosity and to assess its biological origin, and (2) to describe the changes in fabric of the solid constituents. Only 2 depths were compared i) 0/10 cm where the biological activity or the mechanical constraints of the tractor are intense and ii) 30/40 cm where biological activity is lower whereas constraints from the tillage implements are still intense. Undisturbed soil samples were embedded in a humid state (after water/acetone exchange) and observed as described in Hartmann *et al*. (1994).

Results and discussion

Long-term tilled plot

The specific air volumes $\nu a(5)$ of the upper horizons are identical to those measured in the deeper layers (ca. 0.030 $cm^3.g^{-1}$). That value can be considered as the minimal interpedal porosity value which can be reached for that Vertisol in field conditions. This porosity may correspond to the closest packing of peds. This is consistent with the observations of thin sections which exhibit a massive structure of the groundmass with

only few polyconcave pores. On thin sections, a lot of striated zones can be noticed in peds, corresponding to the rearrangement of clay minerals under mechanical constraints (McGarry, 1990).
A few larger structural pores can still be measured as $\nu a(500) > \nu a(5)$ (respectively 0.058 and 0.030 $cm^3.g^{-1}$ in the 0/10 cm). The pore volume of those big clods is slightly higher in the surface layers (0/20 cm) than in the bottom layers (0.041 $cm^3.g^{-1}$). That higher pore volume could result from the swelling and cracking processes which can occur under natural climate mainly in those upper layers.
Despite the high level of mechanical constraints which were applied on the M plot for 16 years, the structure did not become completely massive. However, the two profiles are homogenous with almost same values for deep and surface layers and with low confidence intervals.

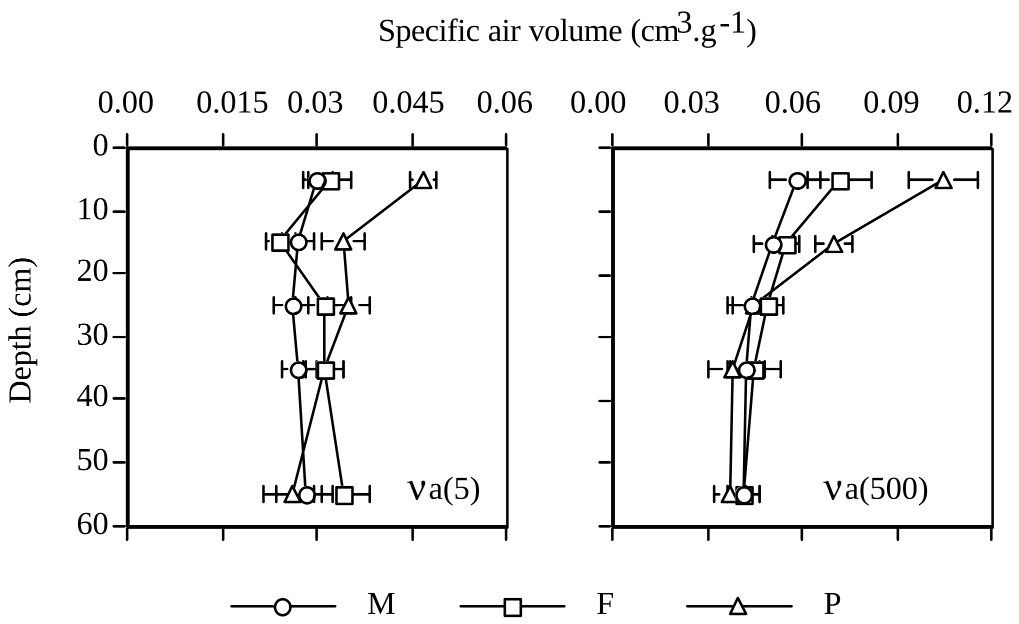

Fig. 1. Specific air volume (νa) in 3 plots at different depths for 5 and 500 cm^3 clods, respectively $\nu a(5\ cm^3)$ and $\nu a(500 cm^3)$ (mean and confidence intervals, $P<0.05$).

Rehabilitation under fallow
The specific air volume $\nu a(5)$ measured in the 0/10 cm layer of F is very close to that of M (respectively 0.032 and 0.030 $cm^3.g^{-1}$); in the 20/30 and 30/40 cm they are slightly higher in F (Fig. 1). The relative low value measured at 10/20 cm (0.024 $cm^3.g^{-1}$) is difficult to explain whereas the relative high value at 50/60 cm may be due to a more sandy texture at the bottom of the profile. The thin sections show a much more heterogeneous groundmass for F than for M at both studied depths. There are still peds with striated clay. Numerous peds containing organic matter and being non-birefringent can also be observed. The packing of the different peds seems as close as in M. There is an increase in the number of small root galleries (diameter < 1 mm) at both depths (0/10 and 30/40 cm) and most of them are filled with roots.
As for M, the $\nu a(500)$ values of the upper layers (0/20 cm) are higher than the deeper layers because of the shrinking/swelling processes. If compared to M, there is an non significant increase of $\nu a(500)$ in the 0/10 cm layer (respectively 0.072 and 0.058 $cm^3.g^-$

[1]). That increase can be attributed to the numerous and heterogeneous large roots galleries.

It appears finally that, despite the long time under fallow, rehabilitation is very low for the structural pore volume and concerns much more the fabric of solid constituents. Bakker & Davis (1995) already showed that solid phase reorganisation can occur after compaction with low consequences on the pore volume; this is consistent with our results.

Rehabilitation under pasture

If compared to F and M, the values obtained in P are significantly higher up to the depth of 20 cm and 30 cm respectively (Fig.1). The groundmass fabric observed on the thin sections is only slightly different from F. There are still non-birefringent peds containing organic matter (OM) separated by striated zones (sometimes infilling voids); the differences consist of the abundance of earthworm casts with various OM content. In the void phase there is an increase of root galleries (0/10 and 30/40 cm) and an important increase (especially in the 0/10 cm) of irregularly shaped voids which break the continuity of the groundmass. Those pores mainly contribute to the structural porosity observed on the thin sections.

As the huge earthworm increase is related to a significant increase of νa (5), earthworms could be the main factor of porosity rejuvenation as suggested by Friend & Chan (1995). When observed *in situ*, earthworms burrows are often filled with casts; on thin sections, the casts are differentiated from the adjacent material by a different fabric or OM content. There are no voids between casts and adjacent solid material. Thus, at that scale, *P. elongata* burrowing activity does not significantly contribute to the structural porosity rejuvenation.

Pasture installation also induces an increase of carbon contents (Table 1). We tested the hypothesis of a relation between carbon content (C) and νa (5) and found a significant positive relation (νa (5) = 0.001C + 0.022 ; R^2= 0.71, P<0.001). (Fig. 2).

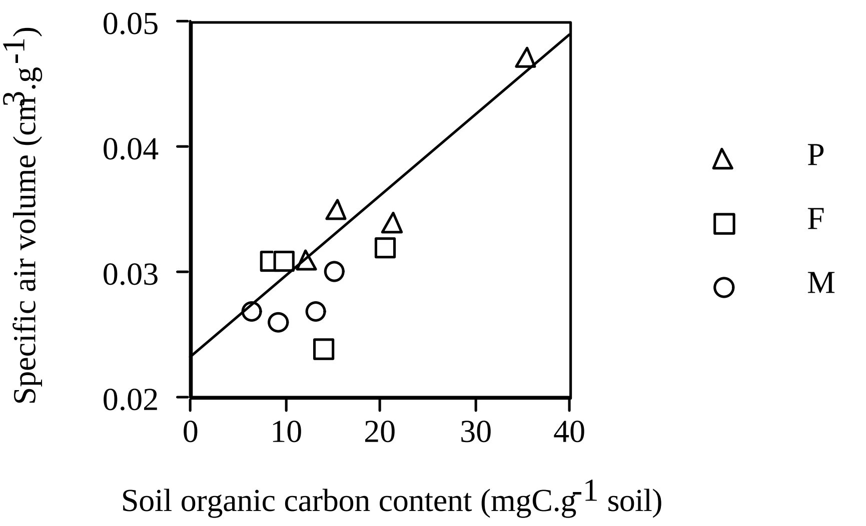

Fig. 2. Relation between mean soil carbon content and mean specific air volume of 5 cm^3 clods, νa(5), in the 0/10, 10/20, 20/30 et 30/40 horizons of the M, F and P plots.

It must be noticed that if, compared to M, the carbon content increased slightly in the grassland under natural climate (F) but increased significantly and deeply in the irrigated grassland (P) (Table 1). Thus the relation between water management techniques and soil structural changes must also be examined. The pasture is irrigated when plant water stresses appear, i.e. when structural voids are empty and matric water is consummed (Ozier-Lafontaine & Cabidoche, 1995). Irrigation is thus conducted on shrinking soil and induces a new swelling. Therefore, during the dry season, irrigation in P allows a high root biomass production and induces repeated shrinking/swelling cycles ; other plots have a lower root biomass and are mainly shrinking during the same period. Hussein & Addey (1995) demonstrated the consequence of such climate induced cycles on the surface layer aggregate developement. The dense root development in P induces a water pumping in the whole explored volume. As the repeated shrinking and swelling phenomena will concern a similar soil volume, this could induce an aggregate reorganisation and structural pore rejuvenation deeper than only the soil surface.
If compared to F and M, the specific air volume $\nu a(500)$ obtained in P for the 0/20 cm layer are significantly higher but the 30/60 cm are not significantly different. The process of large scale structural porosity improvement concerns the upper layer, whereas rehabilitation at small scale occurs up to 30 cm.

Conclusion

The aim of this paper was to analyse the respective role of physical and biological processes in rejuvenation of a 'weakly cracking' compacted Vertisol under two grasslands. It was seen that rehabilitation is mainly due to the clay reorganisation and the increase of structural porosity at small organisation levels. This rehabilitation is in relation with an improved biological activity and also with changes in soil water regime. Compared to a natural fallow, the irrigation and plant water pumping under pasture increase the water transfers (depth and number of annual wet/dry cycles) and consequent shrink/swell phenomena.
Earthworms do not have an important role in the rehabilitation at the measured scales; on the other hand, in that study, it was not possible to specify the influence of organic matter on the structural rehabilitation. Thus, in those 'weakly cracking' Vertisols, structural rehabilitation is induced by plant development associated to a well-suited water management. As a conclusion, installation of irrigation on pastures seems an appropriate technique to rapidly rehabilitate compacted vertisols.

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