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Earthworms and soil structure and physical properties in kaolinitic and smectitic tropical soils
Vers de terre et structure et propriétés physiques des sols tropicaux kaolinitiques et smectitiques

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Effects of earthworms on the formation and maintenance of soil structure and associated physical properties has been highly studied. Their intense feeding and burrowing activities generally affect soil structure (aggregation, and porosity) and partly determine associated physical properties : structural stability, erodibility, water retention, water infiltration...
In the tropics, most of studies on earthworms/soil structure relationships were led on kaolinitic soils (ferruginous and ferrallitic soils). In these type of soils, irrespective of the clay content, it was observed that endogeic, geophagous earthworms have strong effects on soil properties. Large-sized earthworms egest large and compact casts. They increase the proportion of large aggergates in soil and the bulk density; they may be called "compacting species". Their effect on soil physical properties may be strongly linked to the presence of organic residues at the soil surface. In contrast, small earthworms feed at least partly on large compact casts and egest smaller and fragile aggregates. They decrease the proportion of large aggregates in soil and the bulk density; they may be called "de-compacting species". At Lamto, in Côte d'Ivoire, the regulation of soil structure was showed to result from the antagonistic activities of both small and large earthworms. The activity of one single type of earthworms may lead to important changes in soil physical properties. In Amazonia, the degradation of soil structure (compaction) observed under some pastures is linked to the intense activity of *Pontoscolex corethrurus*. In kaolinitic soils, whatever the clay content is, endogeic earthworms play a major role in the formation and maintenance of tropical soil structure. A few studies have been led on the earthworms/soil structure relationships in smectitic tropical soils. In the vertisols of Martinique, the effects of earthworms on structure and physical properties (aggregation, aggregate stability, erodibility) restoration is not really clear. The effects of roots and organic matter seem predominant in soil structure development while earthworms play a secondary role.

Keywords : endogeic earthworms, tropical soils, smectitic soils, kaolinitic soils, soil aggregation, structural stability, soil porosity, soil erodibility, soil conservation

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INTRODUCTION

In the tropics, land clearing and development of food crop production generally lead to chemical, physical and biological degradations of soils. The conservation and/or the rehabilitation of soil structure and physical properties seems much more difficult than the control of plant nutrient reserves. In fact, the control of soil erosion and soil porosity is fundamental as erosion imperils the sustainability of systems, and as porosity determines water availability for plant growth. For many years, studies on earthworms have shown that those animals, through their feeding and burrowing activities could significantly influence soil structure and physical properties (aggregate stability, erodibility, water retention, infiltration), as well as decomposition and translocation of organic matter (Lavelle et al., 1994). However their use in order to improve soil properties, and especially the resistance to erosion is rarely quoted by specialists of tropical soil conservation (Pankhurst & Lynch, 1994). This is partly due to the lack of studies on earthworms/soil structure relationships in agrosystems and to the importance of other parameters in soil structure regulation (especially organic matter and agricultural practices) (Fragoso et al., 1997). In this paper, the role of endogeic, geophagous earthworms in the formation and regulation of tropical soil structure (aggregation and porosity) will be presented. We will especially focus on physical properties that influence erosion (erodibility, aggregate stability, infiltration, run-off) and water availability for plants (infiltration, water retention). After a short chapter on the production and the main characteristics of structures created by earthworms in tropical areas, a second chapter will analyse the potential role of earthworms in conservation and rehabilitation of kaolinitic (ultisol, alfisol, oxisol) and smectitic soils (vertisols).

PRODUCTION AND CHARACTERISTICS OF CASTS OF ENDOGEIC, GEOPHAGOUS EARTHWOMS

1. Production

Cast production is often studied although its measurement is difficult for most of casts are egested in the soil; only a small proportion is egested at the soil surface (Lavelle, 1978). Nevertheless high values can be noticed : 850 to 1200 $Mg.ha^{-1}.y^{-1}$ in Lamto's savannas (Lavelle, 1978), 1280 $Mg.ha^{-1}.y^{-1}$ by *P. elongata* in a pasture in Martinique (Blanchart, unpub. data, 1997), 2600 $Mg.ha^{-1}.y^{-1}$ in Thailand (Watanabe & Ruaysoongnern, 1984).

2. Physical characteristics of earthworm casts

Endogeic, geophagous earthworms ingest soil that they egest as casts. The size of their casts depends on earthworm size and may vary from a few mm to a few cm in diameter. If compared with bulk soil, casts are characterized by : (1) a finer texture (especially when individuals have a small size and when soil is sandy); (2) a higher water content when egested; (3) a higher bulk density, due to a decrease of macroporosity; casts of *M. anomala* cultured on sandy soils of Lamto (Côte d'Ivoire) have peaks of porosity around 20-30 µm (Blanchart et al., 1993); casts of *P. corethrurus* cultured on clayey soils of Central Amazonia (Brazil) have only a few pores larger than 100 nm (Grimaldi et al., in prep); casts of *P. elongata* cultured on vertisols have an air specific volume ranging from 0.026 to 0.045 $cm^3.g^{-1}$ according to soil organic matter content; (4) the presence of a cortex (a thin external layer made up of fine organic and mineral particles) which influences air and water movements between the inner and outer parts of casts (Blanchart et al., 1993); (5) a lower stability of fresh casts and a higher stability of aged casts; the processes of cast stabilization have been often discussed (see for instance Schrader & Zhang, 1997).

In soils with abundant earthworm communities, the high production of casts with particular properties will quite obviously lead to strong effects on soil structure and physical properties.

EFFCTS OF TROPICAL EARTHWORMS ON SOIL PHYSICAL PROPERTIES

1. Kaolinitic soils

Most of studies on relationships between earthworms and physical properties have been realized for kaolinitic soils (in the frame of EEC Project "Macrofauna" coordinated by P. Lavelle). The main study sites were : (i) Lamto (Côte d'Ivoire), ferruginous sandy soils (ultisols, 4,5% clay), (ii) Yurimaguas (Peru), ultisols (20% clay), (iii) Manaus (Central Amazonia, Brazil), yellow latosols (oxisols, 80% clay).

Under natural conditions, studies underlined the important role of earthworms in building and maintaining a soil structure (aggregation and porosity). At Lamto, pot and field experiments showed that large-sized earthworms (like *M. anomala*, 5 g at the adult stage) were responsible for the formation of a macroaggregate structure of these sandy soils. In these soils, the single activity of (grass)roots does not lead to a macroaggregate structure and can not conserve the existing structure. In those soils, the structure is regulated by the simultaneous presence of large-sized and small-sized (a few hundreds of mg at the adult stage) earthworms (Figure 1) (Blanchart et al., 1997). The absence of one earthworm type entailed strong modification of soil structure. The only presence of small-sized earthworm induced an increase of total porosity (due to an increase of structural porosity at the expense of textural porosity) and an increase of 0.5-2 mm diameter aggregates (at the expense of larger aggregates). This structural modification led to a decrease of water retention capacity. The same effects were observed when both earthworm types were excluded from the soil, with an increase of < 0.5 mm diameter at the expense of larger aggregates. Conversely, the only presence of large-sized earthworms resulted in opposite effects, with sometimes, the formation of a sticky and impermeable surface horizon, which impedes water infiltration. This phenomenon was also observed in Central Amazonia where the only presence of *P. corethrurus* (around 1 g at the adult stage) in a pasture led to a strong decrease of infiltration due to the formation of an impermeable horizon in the first 10 cm of soil (Grimaldi et al., in prep.). In pastures with higher soil fauna diversities, this horizon does not appear and infiltration is relatively good. In Peru, experiments and observations brought out the same conclusions : the presence of large-sized earthworms (*P. corethrurus*) involved an increase of the proportion of aggregates > 2 mm and a joined decrease of total porosity. The absence of those earthworms induced an increase of the proportion of aggregates < 0.5 mm and an increase of total porosity (Alegre et al., 1996). Duboisset (1995) showed that the formation of a sticky horizon at the soil surface (0-4 cm) was due to the coalescence of *P. corethrurus* casts, only in the absence of organic residues. The application of crop residues induced a decrease of its thickness (0-1.5 cm). The addition of both crop residues and legume green manure prevents the formation of this horizon.

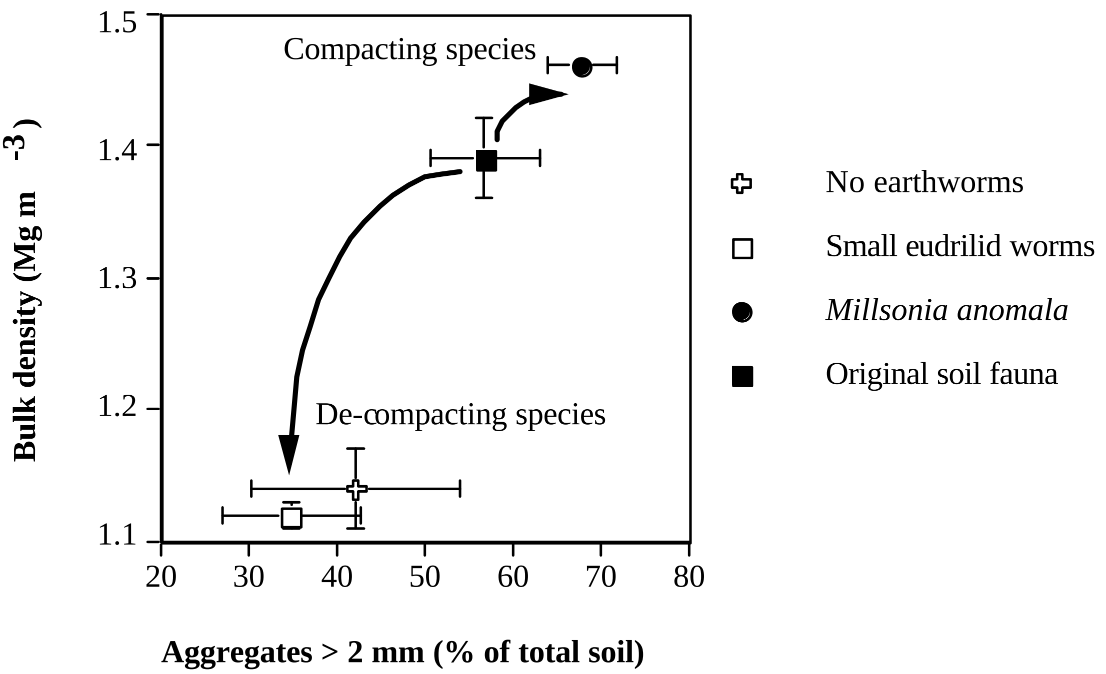

Figure 1 : Evolution of bulk density and macro-aggregates in undisturbed soil (0-10 cm) submitted to different earthworm populations in a field experiment (Lamto, Côte d'Ivoire) (adapted from Blanchart et al., 1997).

All studies realized in the tropics, for kaolinitic soils bring to the same conclusions, irrespective of the clay content :

- endogeic, geophagous earthworms play a major role in the formation and the conservation of soil structure;
- "compacting" earthworms egest large-sized casts (as crumbs). Their activities lead to (i) an increase of the proportion of aggregates larger than a few (2-5) mm, at the expense of smaller aggregates, (ii) an increase of macroporosity (ca. 1 mm) and of microporosity (ca. 10 µm), (iii) a decrease of mesoporosity (ca. 100 µm), (iv) a decrease of total porosity, linked to the compaction in casts, (v) an increase of the water retention capacity, (vi) a higher water-stability and mechanical resistance than aggregates formed by roots, (vii) an increase of surface roughness, (viii) the formation of an impermeable horizon in the absence of organic residues (and especially green manure);
- "decompacting" earthworms egest small-sized casts (granules). Their activity involves (i) an increase of medium-sized aggregates (0.5-2 mm), at the expense of larger aggregates, (ii) a decrease of macro- and microporosity, (iii) an increase of mesoporosity, (iv) an increase of total porosity, (v) a decrease of the water retention capacity, (vi) a lower water-stability than casts of "compacting" species;
- the activity of large-sized earthworms which leads to an increase of macroporosity and an increase of surface roughness may be a means of reducing soil erosion (by facilitating infiltration and reducing run-off).

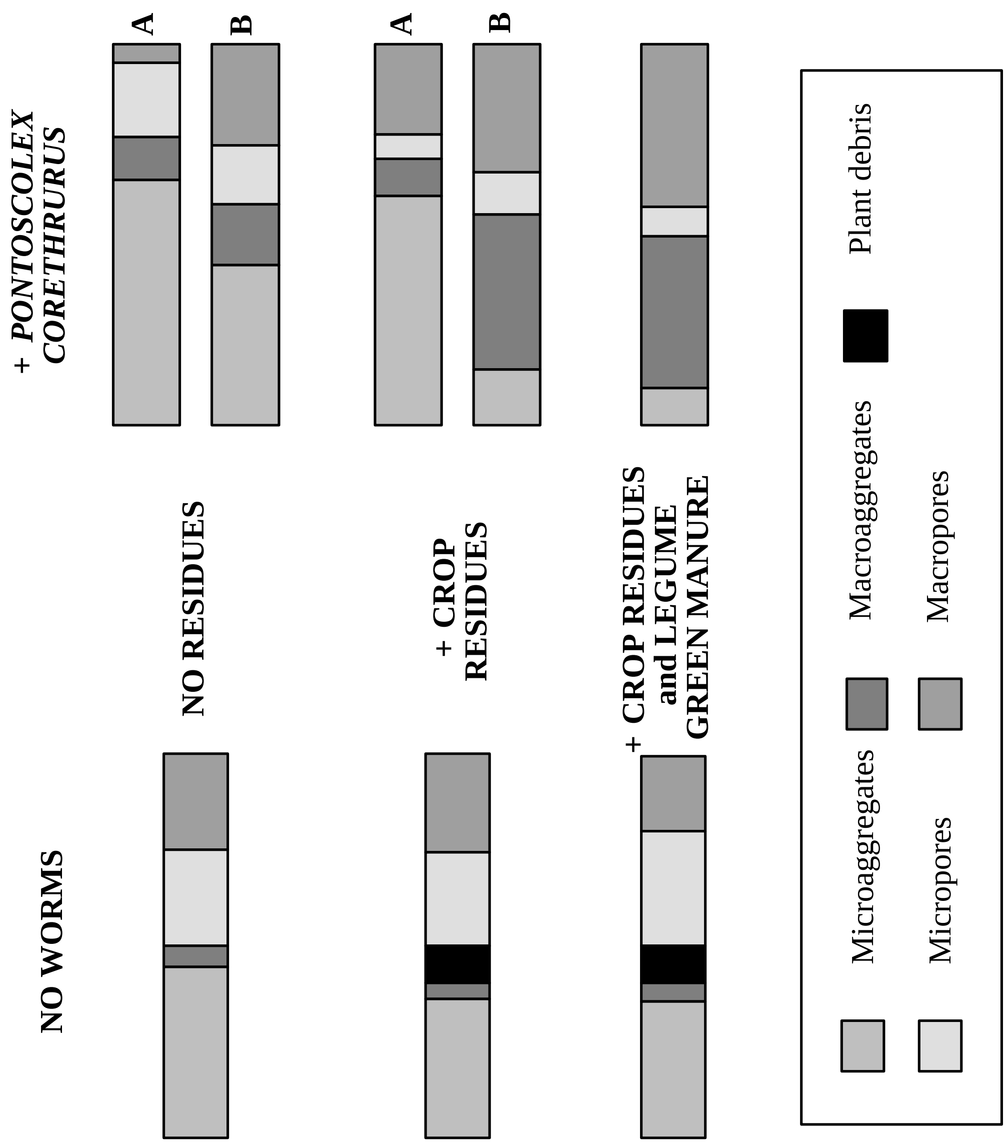

Figure 2 : Effects of earthworm introduction and crop residue application on aggregation, porosity and plant debris in the soil (0-4 cm) of Yurimaguas (Peru) as proportions of surface of thin sections. A= surface strata (0-1.5 cm), B= deeper strata (1.5-4 cm) (adapted from Duboisset, 1995).

2. Smectitic soils (vertisols)

Only a few studies deal with the relationships between earthworms and physical properties in smectitic soils (Robertson et al., 1994, in Australia). It may be due to the small area covered by vertisols in the tropics and to their chemical richness. Nevertheless, the development of crop production generally leads to important modifications of soil physical properties what involves a dramatic risk of soil erosion and a decrease of water availability for plants (Ozier-Lafontaine & Cabidoche, 1995). In Martinique (West Indies), vertisols under forests and pastures are characterized by (i) a strong biological activity (earthworms *P. elongata*, roots, microorganisms), (ii) high organic carbon contents, (iii) a high aggregate water-stability (linked to C content), (iv) a moderate erodibility, (v) a high air specific volume, and (vi) a high usefull available water (Albrecht et al., 1992). Conversely, vertisols under market gardening crops are characterized by (i) a low biological activity, (ii) low organic C contents, (iii) a low water-stability of aggregates, (iv) a high erodibility, (v) a reduced air specific volume, and (vi) a low usefull available water.

An experiment was realized (from 1993 to 1997), in order to assess the respective roles of grass roots and earthworms in the rehabilitation of physical properties (water-stability, erodibility, porosity) after installation of a pasture (*Digitaria decumbens*) on a soil degraded by many years of market gradening crops. Three treatments were experimented : (i) introduction of a population of *P. elongata* equal to that of a long-term pasture (90 adults.m^{-2}) (P+V+), (ii) eradication (by insecticide) of earthworms only (P+V-), and (iii) eradication of earthworms and plants (by herbicide) (P-V-). The measurements of various soil parameters showed a similar evolution with time of treatments P+V+ and P+V-, and a significant different evolution of the treatment P-V- (Blanchart et al., in prep.). By instance, after 2 years of experiment, the organic C contents (0-10 cm) in P+V+ and P+V- were not significantly different (respectively 22.3 et 20.7 mgC.g^{-1}); the C content in P-V- was significantly lower than the other treatments : 15.9 mgC.g^{-1}, and decreased with time. Aggregates (1-2 mm diameter) of treatments P+V+ and P+V- displayed the same water-stability, they were much more stable than aggregates of the P-V- treatment. In those vertisols, the stability of aggregates is linked to erodibility : the turbidity of run-off water (under rainfall simulation) for the treatment P-V- is close to that measured under food crops (between 18 and 20 g.l^{-1}) (Figure 3).

Under the same rainfall intensity (150 mm.h^{-1}) and the same soil (ploughed) surface, the turbidities of run-off water for the two other treatments P+V+ and P+V- were lower, and close to 10 g.l^{-1}; after 2 years of experiment, the values did not reach those of a long-term pasture.

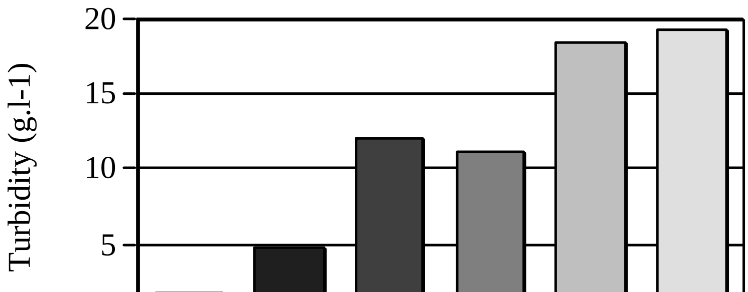

Figure 3 : Turbidities of run-off water (g.l^{-1}) measured by rainfall simulation (rainfall intensity 150 mm.h^{-1}, ploughed surface) (average over 30 mn), in 6 treatments on a vertisol : a forest (For), a long-term pasture (Pas), 3 experimental treatments and a long-term market gardening cultivation (conventional tillage) (Mar) (Blanchart et al., in prep.).

Concerning porosity, measurements of air specific volume on large clods (ca. 500 cm^3) showed differences between P+V+ and P+V- (due to the presence of earthworm burrows in P+V+) while measurements on aggregates (ca. 5 cm^3) did not show significant differences (Figure 4). On the other hand, P-V- treatment was characterised by a smaller air specific volume. In vertisols, burrows which are filled in by casts may not have an important role in water infiltration (although it remains to be measured). As those burrows have a large diameter, they do not play any role in the water storage and the availability of water for plants unlike tubular pores measuring a few µm in diameter (Ozier-Lafontaine & Cabidoche, 1995).

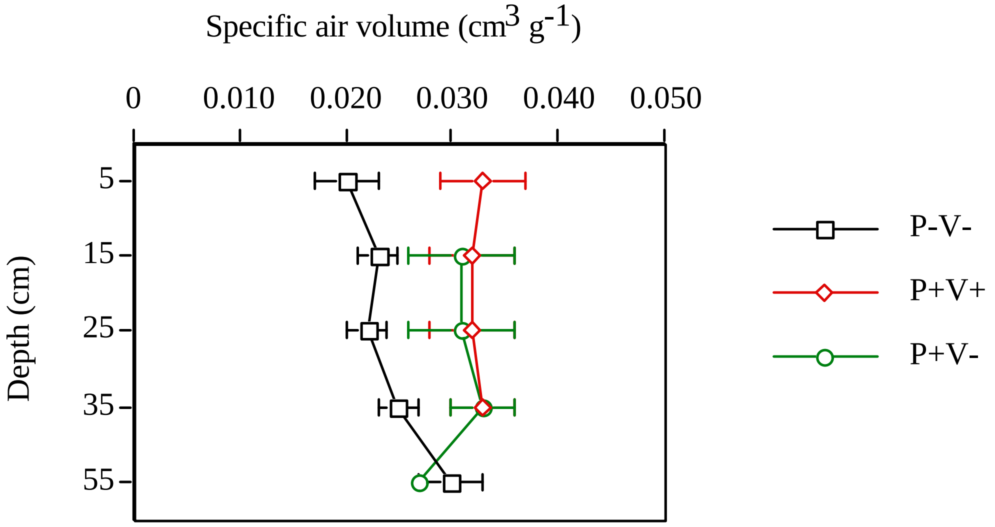

Figure 4 : Evolution with depth of specific air volume in a vertisol for three treatments, after one year of experimentation (Hartmann et al., in prep.).

This study led on a smectitic soil brings to the following conclusions :

- earthworms do not have a major role neither in the formation nor in the conservation of the structure of smectitic soils; the swelling-shrinking behaviour of those soils hides the structurating effect of these animals whose casts are rapidly mixed up with bulk soil;

- in those smectitic soils, grassroots seem to play a major role in the formation of soil structure and the rehabilitation of degraded soils. They act through (i) inputs of organic C to soil (without roots, the organic C content does not stabilize or increase), (ii) water uptake which is responsible for water movements in soil and shrinking phenomenon, (iii) stimulation of bacteria which could play a role in the aggregation of clay tactoids (Achouak & Heulin, pers. comm.).

CONCLUSION

The conservation and the rehabilitation of the physical properties of kaolinitic soils may be based upon the use of endogeic earthworms, if "compacting" species adapted to soil type, climate and agricultural practices are found. Their utilization should be associated with organic residues (especially green manures) and/or with "decompating" species. The ways to manage earthworm populations may be diverse (Lee, 1996). In smectitic soils, however, an intense earthworm activity is not fundamental in the regulation of soil physical properties, unlike grassroots or organic matter. Nevertheless, more research is needed to estimate their importance in determining other components of soil fertility and plant growth (regulation of decomposers or pests, nutrient release...). In this context, agricultural practices which enhance earthworm activity should be chosen. In vertisols, earthworms should rather be considered as soil health and sustainability indicators.

Keywords : endogeic earthworms, tropical soils, smectitic soils, kaolinitic soils, soil aggregation, structural stability, soil porosity, soil erodibility, soil conservation
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