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Soil aggregation, soil organic matter and soil biota interactions : implications for soil fertility recapitalization in the tropics

Interactions agrégation, matière organique, biologie du sol : implication sur la fertilité du sol dans les tropiques

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In tropical developing countries, the degradation of arable soil is not compensated for by the high inputs that, in temperate developed countries, help to sustain high agricultural production. The reduced productivity of degraded tropical soils is often associated with a reduction in the availability of water and nutrients that results from the soil structural degradation. For example, structurally unstable soils are more susceptible to erosion which, in turn, leads to a reduction in water holding capacity and nutrient availability, both of which influences crop productivity. Structurally unstable soils are also more susceptible to soil compaction which impedes root growth and, therefore, lowers above ground production. The structural stability of soil is influenced by its inherent properties (eg. texture, mineralogy), the quality and quantity of soil organic matter inputs and the activities of soil biota (i.e. microflora, roots and fauna).

This paper investigates the potential for soil aggregation to influence soil fertility recapitalization in the tropics, with particular attention to the interactions between SOM, biological activity and soil structural stability. Many of the examples given are based on research from West Africa, Brazil and West Indies, though research from subtropical and temperate soils is also presented for comparison. The findings are consider within the context of the inherent properties of soils (texture and mineralogy) and their climatic constraints.

Keywords : Africa, aggregation, agricultural soil, bacteria, Brazil , earthworms, erodibility fungi, soil biota, soil compaction, soil organic matter, soil fertility, soil restoration, tropical soils, USA, West Indies
Mots clés : Afrique, agrégation, sol agricole, Brésil, lombric, biologie du sol, compaction, matière organique, fertilité, restauration du sol, sol tropical, Etats Unis, Indes occidentales

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Introduction

The need for tropical soil fertility recapitalisation is based on the observation that tropical agriculture management practices are increasingly unsustainable. Furthermore, the exploitation of tropical soil resources seems to increase with increasing population growth. By comparison, the agricultural systems of developed countries, where exogenous inputs (fertilisers etc.) are high and the recycling of organic resources is often greater (e.g. crop residues, manures, etc.) allow for better maintenance and/or restoration of the soil resource (Sanchez et al. 1997). Successful tropical soil fertility recapitalisation depends on adopting measures that: 1) improve the efficiency of soil resource utilisation and, thereby, minimize (slow) soil degradation, 2) provide compensation for the resources removed in plant and animal products or lost to the wider environment (e.g. leaching, gaseous emissions, erosion), and 3) include restorative phases in the landuse rotations.

Most tropical agricultural practices involve few external inputs and, therefore, rely heavily on the mineral and organic properties of soils to sustain plant production. As a result, soil organic matter management (SOM) is an important tool for soil fertility recapitalisation. Furthermore, the dynamics of SOM are indissociable from soil biological activity, as SOM is the primary source of energy and nutrients for soil biota and soil biota are responsible for the transformations that regulate SOM storage. One of the important mechanisms by which soil biota influence SOM storage is through the formation and stabilisation of soil aggregates.

The size, quantity and stability of aggregates recovered from soil reflects an environmental conditioning that includes factors which enhance the aggregation of soil (e.g. wet-dry cycles, organic matter amendments) and those that cause disaggregation (eg. cultivation, bioturbation)(Beare and Bruce, 1993). The measurement of soil aggregates depends on both the forces that bind particles together and the nature and magnitude of the disruptive forces applied. Soil aggregation influences the susceptibility of soil to erosion, organic matter storage, soil aeration, water infiltration and mineral plant supply. Many studies have shown the effects of organic constituents on the amount and stability of soil aggregates. However, understanding the role that soil aggregation plays in fertility recapitalisation also requires a knowledge of how aggregation contributes to organic matter storage in soil. Both processes are mediated by soil biological activity.

Clearly then, to understand the role that soil aggregation plays in tropical soil recapitalisation it is first necessary to understand the relationship between soil aggregation, SOM and biological activity. The aim of this paper is to evaluate: 1) the influence of physical environment and landuse management on soil aggregation, 2) the processes (physical, chemical and biological) that regulate aggregate formation and stabilisation and 3) the role that aggregates play in maintaining the physical and chemical fertility of soil. Understanding these influences is essential to adapting fertility recapitalisation strategies to the specific constraints (e.g. soil type, climate) of different agricultural regions in the tropics.

Effect of the soil type: the physical environment

Soil mineralogy (shrink-swell clays, clay-iron and aluminium oxide interactions) defines the principle characteristics of and limitations to soil aggregation (Oades & Waters, 1991). This paper focuses on tropical soils composed of crystallized clays and excludes those with andic characteristics. In this respect, soils may be classified by the quantity and mineralogy of clay; i.e. low activity clay [LAC] soils composed of kaolonites or 1:1 clays and high activity clay soils [HAC] composed of smectites or 2:1 clays). In LAC soils the quantity of oxides is an important factor. The nature of exchangeable cations is an important factor in HAC soils. Modes of aggregation in LAC and HAC soils are different. The modes may be defined by the disaggregation of soil in water (Figure 1, Albrecht & Laurent, unpublished data) and its distribution among three aggregate size classes, macroaggregates (> 200 m), mesoaggregates (5-200 µm) and microaggregates (< 5 µm). For example, clayey LAC soils, with high amounts of oxides (oxisols), are composed of macroaggregates (size> 200 µm) that are very stable in the water (MAE disaggregation mode). These macroaggregates are gradually replaced by mesoaggregates (ME disaggregation mode) as the soil texture becomes increasingly sandy. For clayey HAC soils (e.g. vertisols), the water-stable aggregation is related to the nature of exchangeable cations (Dalal & Bridge, 1996). Calcic vertisols develop water-stable macroaggregates that are primarily composed of microaggregates (MAI disaggregation mode). When the contributions of sodium and exchangeable magnesium to CEC exceed 30%, water-stable macroaggregates are rare and this type of vertisol is particularly susceptible to dispersion (MI disaggregation mode) (Albrecht, 1998).

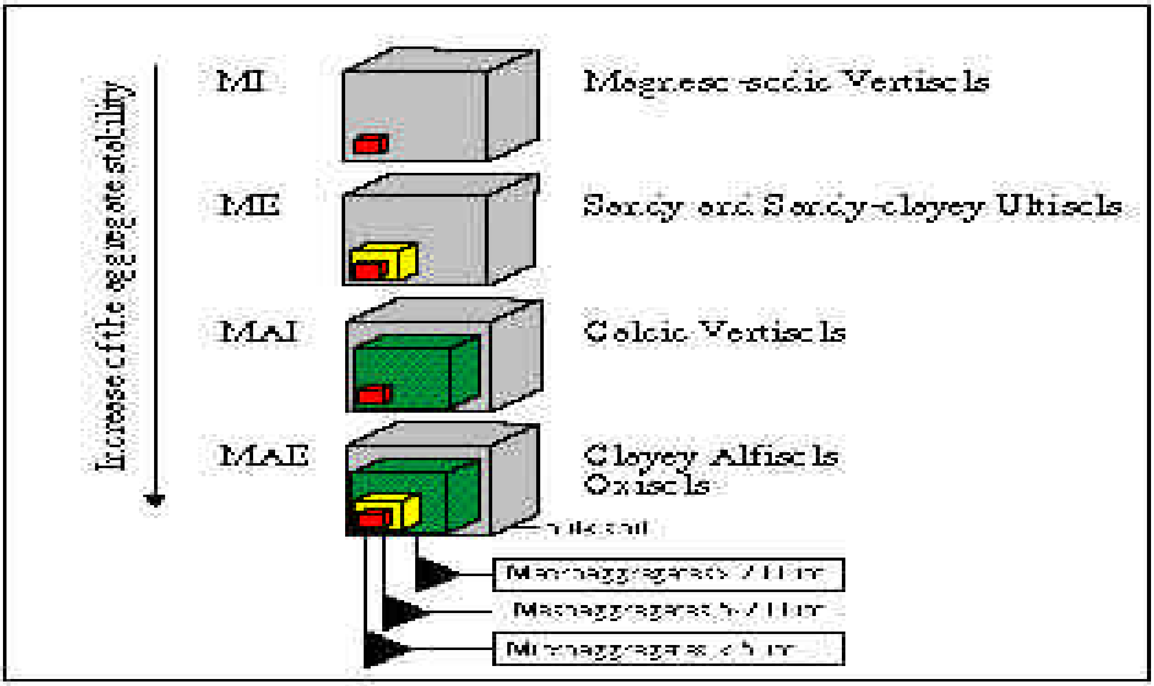

Figure 1: Modes of disaggregation of some tropical soils. MAE : disaggregation Mode in mAcro- and mEsoaggregates , MAI disaggregation Mode in mAcro- and mIcroaggregates, ME disaggregation Mode in mEsoaggregates, MI disaggregation Mode mIcroaggregates definitions

The Influences of soil Organic Matter: Management and Indicators

The organic matter content of a soil is determined by climate, soil type and landuse management (Feller, 1994; Feller & Beare, 1997). The formation of stable soil aggregates is influenced by mineralogy, texture, landuse management and soil biological activity. These factors interact to determine the now well established relationship between SOM content and water-stable aggregation. This relationship is probably best known for temperate agricultural soils where aggregation depends on the quantity and mineralogy of clay (Feller & Beare, 1997). This fact is shown clearly in the studies of Douglas and Goss (1982) where increasingly higher quantities of C were required to achieve the same level of aggregate stability in soils of increasing clay content (16-49% clay).

The influence of SOM on the aggregation of clayey LAC soils (Kouakoua, 1998) and clayey HAC soils (Albrecht, 1996) is appreciably different (Figure 2a). In particular, the nature of SOM (defined here by the size) involved in soil aggregation appears to differ for LAC and HAC soils (figure 2bc). Indeed, plant debris (size> 200 μm) appear to play an important role in the stability of aggregates from 1:1 and 2:1 clay soils, while soil organic matter associated with clay particles plays a dominant role in vertisols on andesite. Nevertheless, the positive relationship between total SOM and aggregation is not always apparent. For example, in a temperate soil, Angers (1992) demonstrated relatively short-term changes in aggregate stability in response to management that were not related to any measurable changes in total soil organic matter. Despite these observations, many studies have shown stronger relationships between total SOM and Aggregate stability as compared to individual SOM constituents.

A wide range of organic compounds have been shown to influence soil aggregation. These include humic (humin and humic and fulvic acids) compounds, compounds extractable by polar or non-polar organic solvents and, most commonly, polysaccharides (Feller and Beare, 1997). Besides their size, the location and biochemical nature of organic particles influences the formation and stabilisation of soil aggregates. For instance, Golchin et al. (1994) showed that the molecular structure and location of SOM, especially particulate organic matter, strongly influence aggregate stability.

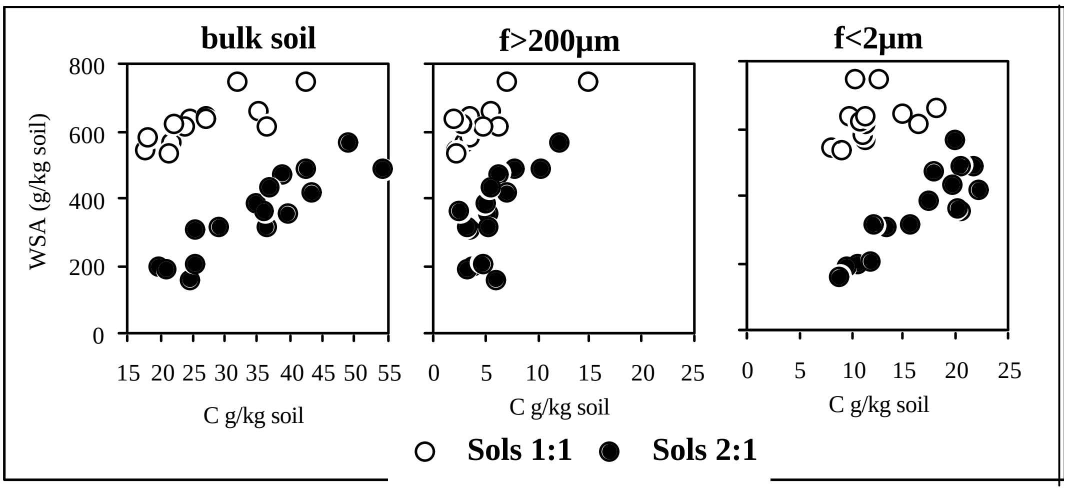

Figure 2: Relationships between the carbon content (in mg C.g soil) of surface soil horizons and the stability of aggregates (WSA) for 1:1 (Kouakoua, 1998) and 2:1 soils (Albrecht, 1996)**;** a: the total carbon content vs water-stable macroaggregates (>200 µm) according to clay type; b: the carbon content of the coarse fraction (>200 µm) vs water-stable macroaggregates ; c: the carbon of the fine fraction (<2 µm) vs water-stable macroaggregates.

There is little doubt of the importance of polysaccharides to aggregates stabilisation. Because total C or carbohydrate content often do not explain much of the variation in aggregate stability on a short time scales (Baldock *et al*., 1987) recent studies have focused on the nature and origin of polysaccharide fractions as they related to aggregate stability. For example, research from both temperate and tropical soils has shown that aggregate stability is often more closely correlated with the content of hot water-extractable carbohydrates than with total organic carbon (TOC), hydrolysable (HCl) carbohydrates or NaOH-extractable carbohydrates (Haynes *et al*., 1991; Gisman and Thomas, 1995). These studies concluded that hot water-extractable carbohydrates represent an important fraction for the stabilization of aggregates in temperate soils. In contrast, other studies report no significant correlations between aggregate stability and hot water-extractable carbohydrates (Degens *et al*., 1994) . The origin of polysaccharides may also be important. Cheshire *et al*. (1983, 1984), for example, found that polysaccharides of microbial origin were more important than plant-derived polysaccharides for determining aggregate stability. Other studies have stressed the importance of plant derived polysaccharides (e.g. Benzing-Purdie and Nikiforuk, 1989). Differences concerning the role that plant derived polysaccharides play in aggregate stability may be related to the source of plant-derived organic matter, i.e. plant root exudates are likely to have different influences on soil aggregation as compared to plant litter.

Improvements in soil aggregation can have implications for a number of soil physical and chemical properties including water infiltration rates, oxygen supply, and organic matter mineralization rates. In the later case, stable aggregates may enhance the physical protection of SOM against losses due either to mineralization or erosion. The role of aggregates in the storage and protection of SOM will be discussed below.

Land use and cultural practices influence SOM storage and loss in variety of ways. They may alter the quality and quantity of organic matter (OM) inputs to soils, the soil biological activity, the bioavailability of organic substrates and soil erodibility. In generally, the SOC content of tropical LAC soils (Feller, 1993) depends on the intensity of land use management, the importance of which tends to increase with increases in clay + silt content. On average, the SOC content under annual crops (in non-eroded plots) is about 60% of that under natural vegetation.

The nature of aggregate-associated SOM

Efforts to describe the quality and quantity of aggregate-associated organic matter stem from two particular interests: 1) understanding the importance of organic matter constituents for determining the structural stability of aggregates and 2) identifying the mechanisms by which the aggregation of particles contributes to the physical protection and storage of SOM. As discussed above, both interests are of importance to soil fertility recapitilisation. In each case there is a need to carefully define the size and stability of aggregates using methods that are both quantitative and reproducible (Beare and Bruce, 1993). In contrast to the relatively well-described relationship between bulk soil organic matter and aggregate stability, there are conflicting results regarding the relationship between aggregate size-classes and SOM constituents. Considering differences in the mineral and organic components of aggregate size-classes may be critical to interpreting the results obtained. Elliott *et al*. (1991) corrected for both the sand and light-fraction material in aggregate size-classes collected from a chronosequence of tropical Peruvian Ultisols under cultivation. With this approach the authors demonstrated that the OC concentration of the "heavy" fraction did not differ among size classes or treatments. Similarly, Albrecht *et al.* (1992b) reported fairly uniform concentrations of C (20 mg C/g aggregate) in the heavy fraction (light-fraction free) of a wide range of aggregates (5 to 2000 µm in diameter) collected from a Vertisol and a clayey LAC soil in Martinique. By contrast, Beare *et al*. (1994a) showed that concentrations of total C differed substantially among aggregate size-classes of a sub-tropical Ultisol (Georgia, USA) when normalized to a sand-free basis. In general, the highest concentrations were found in the largest microaggregate (106-250 µm) from undistrubed no-tillage (NT) soils, decreasing in both larger and smaller aggregate size-classes. Their findings provide support for an alternative view of aggregate organization in which microaggregates are formed at the centre of macroaggregates (Beare *et al.*, 1994a, Oades, 1984). In this view, fragmented organic debris (e.g. roots, fungal hyphae, faecal matter) may become incorporated into macroaggregates by, for example, the feeding and casting activities of soil fauna or the shrinking and swelling of soil with drying and rewetting.

Bioavailability of aggregate-associated organic matter

The bioavailability and storage of aggregate-associated organic matter has important implications for soil fertility recapitalisation. The influence of aggregation on the protection of organic matter from microbial attack has been studied by comparing results obtained before and after disaggregation of soil. A number of studies have demonstrated the importance that physical protection mechanisms for organic matter storage in soils (Ladd *et al*., 1993; Elliott 1986; Feller *et al*., 1996). Several studies (e.g. Elliott, 1986, Gupta and Germida, 1988) have shown that from 15 to 45% of the N that is mineralisable from macroaggregates of native sods is protected from microbial attack within the intact structure of macroaggregates. Other research has focussed on separating and characterising of «free» and «occluded» (aggregate associated) particulate organic matter in soils (Golchin *et al.*, 1994b; Puget *et al.*, 1997).

Soil biota and soil aggregation

It is important to note that physical controls on the storage and loss of organic matter can not be viewed in isolation from biological influences. Soil biota are clearly important in mediating physical changes in soil structure that may alter the storage and transformations of SOM. Biological constituents ranging from roots and fungi to microarthropods and earthworms can influence the formation and stabilization of soil aggregates. For example, several studies (e.g. Martin, 1992; Lavelle and Martin, 1992) have shown that earthworm casts store and protect on the order of 20% more organic C than non-ingested soils. This was attributed to the higher C content and stability of the earthworm casts as compared to mineral soil (Blanchart, 1992; Blanchart *et al*., 1993). Other organism may also contribute to the physical protection of organic matter through their influence on soil aggregation. For example, Beare *et al*. (1997) indicated that fungal hyphae were responsible for about 40% of the macroaggregation (>2000 um) and and significantly greater retention of soil organic matter in soils under no-tillage management but a much lesser role in conventionally tilled soils. Some examples of biological influences (positives or otherwise) on soil aggregation and the mechanisms involved are given in Table 1. Soil microbial biomass appears to be a relatively poor indicator of aggregation. Indeed, soil microorganisms may have a spatially heterogeneous influence on soil aggregation through the localized production and deposition of organic matter binding agents. For example, plants with a ramified and fine root structure (Degens, 1997) and a high production of exudates, produce aggregates in the rhizosphere, with consequences for structural stability in the root that may influence the rooting zone of subsequent crops.

Table 1: Some examples of biological influences on soil aggregation (Aus: Australia; Can: Cananda; CI: Ivory Coast; Mart: Martinique; USA: United States)

Biological activities	Location	Soil type	Effect on soil aggregation	SOM forms	References
Bacteria producing exopolysaccharides	Mart	Vertisol	Microaggregation building	Polysaccharides	Achouak et al. (in prep)
Bacteria and fungi	Can		Increase of macroaggregates size	Fungi polysaccharides	Chantigny et al. (1997)
Fungi	USA		Increase of macroaggregates size	Fungi polysaccharides	Beare et al. (1997)
Fungi (fungi length)	Aus	Sandy loam	No effect	-	Degens et al (1994)
Roots	Mart	Vertisol	Macroaggregation building	Organic colloids and plant debris	Albrecht (1996)
Earthworms	CI	Ultisol	Macroaggregation building	-	Blanchart et al (1996)

Conclusion: implications in terms of tropical soil fertility recapitalisation

Soils of low aggregate stability are more susceptible to erosion and, therefore, losses SOM and mineralisable, plant available nutrients (Feller, 1994). Improvement in soil structure can also improve water infiltration and holding capacity, increase the availability of exchangeable cations, and decrease of soil compaction, all of which may enhance soil fertility recapitalisation.

Strategies of aggregate management for soil fertility recapitalisation

According to the SOM-aggregation-biological activities relationships and processes presented in the paper, the following strategies could be proposed:

- in the short term, make more efficient use of inherent fertility by synchronizing SOM mineralisation (N, P and K) to meet crop demand and minimize losses; this approach will be dependent on improved understanding and management of soil structure and SOM dynamics.

- in the mid term, increase of SOM storage capacity (sequestration of carbon) of soil by controlling soil losses and enhancing the build up of aggregate associated organic matter.

These two strategies should be applied according to the level of soil degradation and the soil type. For well-degraded soils, soil fertility replenishment methods must occur. The erosion processes have to be stopped by soil cover with mulch or permanent cover by fast growing legumes grasses as Mucuna used during the cropping season (Azontonde, 199Z). High organic inputs, through improved fallows, in rotations, using plants with a ramified and fine root structure (Degens, 1997; ICRAF, 1997) or biomass transfer (ICRAF, 1997), would increase SOM storage and aggregate stabilization. The quality of these inputs (Palm et al., 1998) could improve the biological activities as microbial (Achouak et al., unpublished data) and earthworms activities (Blanchart et al., 1996) to enhance the formation of stable aggregates. For other less-degraded situations, SOM levels should be sustained by minimum or no tillage practices, against SOM dilution and losses (Ndandou & Albrecht, 1998; Angers et al., 199S); these cultural practices could be associated with temporal soil cover during the fallow season to attempt to preserve threshold levels of SOM (for example for vertisols and alfisols see Albrecht at al., 1992a). Of course, SOM levels would be maintained according to the soil type and disaggregation processes by appropriated and targeted SOM management.

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Mots clés : Afrique, agrégation, sol agricole, Brésil, lombric, biologie du sol, compaction, matière organique, fertilité, restauration du sol, sol tropical, Etats Unis, Indes occidentales