

# Determination of ecologically relevant pools for soil organic matter stability in terra firme oxisols

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## ABSTRACT

Increasing the soil organic matter (SOM) contents is an important factor for improving soil fertility. Not only the amount of organic carbon in soil is ecologically important for SOM stability, but also its physical and chemical properties. The appropriate technique for the assessment of ecologically relevant soil pools can vary between soils, and information about this is lacking for oxisols in the Amazon basin. This work should identify soil pools which are sensitive to land-use changes in terra firme oxisols and yield easy to handle techniques for the evaluation of SOM properties. For this purpose, we have studied the influence of 10 different trees and annual crops on SOM properties on an oxisol near Manaus. A combination of aggregate and density fractionation was found to be most suitable for physical SOM characterization. The particulate organic matter (POM, density less than  $1.6 \text{ g cm}^{-3}$ ) varied by one order of magnitude between sites and could be used as a sensitive indicator of land-use changes. The obtained results are extremely important for the evaluation of the sustainability of the investigated land-use systems and are the basis for soil ecological research on terra firme oxisols.

## RESUMO

O aumento do teor de matéria orgânica do solo (SOM) é um fator importante no melhoramento da fertilidade. A quantidade de carbono orgânico no solo é ecologicamente importante tanto para a estabilidade da SOM quanto em relação às propriedades físicas e químicas do solo. A técnica apropriada para acessar os "pools" ecologicamente relevantes do solo pode variar entre os diferentes solos e, esta informação não existe para os oxisolos na bacia Amazônica. Este trabalho tem como objetivo identificar os "pools" no solo que são sensíveis à mudança do uso da terra em oxisolos de terra firme e facilitar as técnicas para avaliação das propriedades da SOM. Para esta finalidade, nós estudamos a influência de 10 diferentes árvores e culturas anuais sobre as propriedades da SOM em oxisolos na região de Manaus. A combinação do fracionamento de agregados por tamanho e por densidade mostrou ser a melhor técnica para a caracterização física da SOM. A matéria orgânica particulada (POM, densidade menor que  $1.6 \text{ g cm}^{-3}$ ) varia em ordem de magnitude entre as diferentes áreas e pode ser usado como um indicador sensível das mudanças do uso da terra. Os resultados obtidos são extremamente importantes para a avaliação da sustentabilidade dos sistemas de uso da terra estudados e são a base para pesquisas ecológicas em oxisolos de terra firme.

## ZUSAMMENFASSUNG

Eine Erhöhung der Gehalte an organischer Bodensubstanz (SOM) ist ein wichtiger Faktor zur Verbesserung der Bodenfruchtbarkeit. Aber nicht nur die Menge an SOM sondern auch ihre physikalischen und chemischen Eigenschaften sind wichtig für eine ökologische Bewertung ihrer Stabilität, weil nur so ein Verständnis für die Prozesse gewonnen werden kann. Meist können Einflüsse unterschiedlicher Landnutzung auf SOM nicht mit einer Untersuchung der Gesamthumusgehalte erfasst werden, selbst wenn sie ökologisch relevant sind. Geeignete Methoden zur Erfassung sensitiver und ökologische relevanter Eigenschaften von SOM unterscheiden sich zwischen verschiedenen Böden und Informationen für Oxisols der Amazonasregion sind nicht vorhanden. In dieser Arbeit wurde der Einfluß 10 verschiedener Bäume und annueller Kulturen auf SOM Eigenschaften untersucht. Den größten Teil der organischen Bodensubstanz wurde in der Grobsandfraktion gefunden, war aber in Aggregaten gebunden. Eine Kombination von Aggregat- und Dichtefraktionierung war am besten zur Charakterisierung von SOM geeignet. Die partikuläre organische Substanz wurde als sensitiver Parameter zur Erfassung des Effektes von Landnutzungsänderungen auf SOM identifiziert. Die gewonnenen Ergebnisse sind äußerst wertvoll für die Beurteilung der Nachhaltigkeit der untersuchten Landnutzungssysteme und stellen eine Grundlage der bodenökologischen Forschung auf den Terra firme Oxisolen dar.

## INTRODUCTION

The terra firme oxisols near Manaus are characterized by severe nutrient limitation (Schroth et al. 1998). High leaching rates lead to high losses of nutrients from decomposing litter or of applied fertilizer in crop production systems in the humid tropics (Seyfried and Rao 1991; SHIFT ENV-45 1997). A closed nutrient cycling and the minimization of unproductive nutrient losses are the precondition of a sustainable land-use management (Lehmann et al., 1998b). Increasing the soil organic matter (SOM) content is an important factor of improving soil fertility, first as a source of slowly releasing nutrients and secondly as means of enhancing the soil cation exchange capacity in order to reduce nutrient leaching (Coleman et al. 1989). Not only the amount of organic carbon in soil is ecologically important for SOM stability, but also its physical and chemical properties (Zech et al. 1997). Using particle size, aggregate and density fractionation methods (Tiessen and Stewart 1983; Tisdall and Oades 1982) together with the analysis of chemical SOM compounds (Degens 1997), profound statements can be made about SOM stability and dynamics.

These techniques usually indicate land-use changes more sensitively than bulk soil analyses as shown in many studies from tropical and temperate soils (Christensen 1992). The appropriate technique for the assessment of ecologically relevant soil pools can vary between soils, and information about this is lacking for oxisols of the Amazon basin. This work should identify soil pools which are sensitive to land-use changes on terra firme oxisols and yield easy to handle techniques for the evaluation of SOM properties. For this purpose, we have studied the influence of 10 different trees and annual crops on SOM properties of an oxisol near Manaus.

## MATERIALS AND METHODS

This study was conducted on the SHIFT experimental fields at the EMBRAPA Amazônia Ocidental station near Manaus, Brazil. The average precipitation is 2503 mm yr<sup>-1</sup> (1971-1993) with a maximum between December and May. The natural vegetation is a tropical rainforest. The soils are classified as xanthic Ferralsol (FAO 1990) and are clayey, strongly aggregated, with medium organic C and N contents, medium to low pH of 4.0-4.5 and low base saturation (Table 1).

**Table 1:** Chemical and physical characterization of the terra firme oxisols (0-10 cm) near Manaus (fallow plots from Schroth et al., 1998).

Properties		
pH	(H <sub>2</sub> O)	4.5
pH	(KCl)	4.0
Organic C	[mg <sup>-1</sup> g <sup>-1</sup> ]	18.9
N	[mg <sup>-1</sup> g <sup>-1</sup> ]	1.6
P available	[mg <sup>-1</sup> g <sup>-1</sup> ]	6.3
CEC	[cmol <sub>c</sub> kg <sup>-1</sup> ]	0.49
BS	[%]	33

The soil samples were taken from 0-5 cm depth in 50 cm distance from 8 different trees and two understorey vegetation in June 1997. The sites were soils under cupuaçu (*Theobroma grandiflorum* (Willd. (ex Spreng.) K. Schum.), pupunha (*Bactris gasipaes* Kunth.) managed for palmito production, brazil nut (*Bertholletia excelsa* Humb. and Bonpl.), urucum (*Bixa orellana* L.) and pueraria (*Pueraria phaseoloides* (Roxb.) Benth.) in an agroforestry system, and under pupunha in monoculture. These sites were fertilized according to the recommendation of the EMBRAPA. Additionally, sites with spontaneous gramineous vegetation (grama), in secondary regrowth of *Vismia* spp. (vismia) and in the primary forest under mata-mata (*Eschweilera* spp.) and bacaba (*Oenocarpus bacaba*) were chosen. Two samples were taken from three individual trees of the same species and combined. The soils were air-dried and sieved to pass 2 mm.

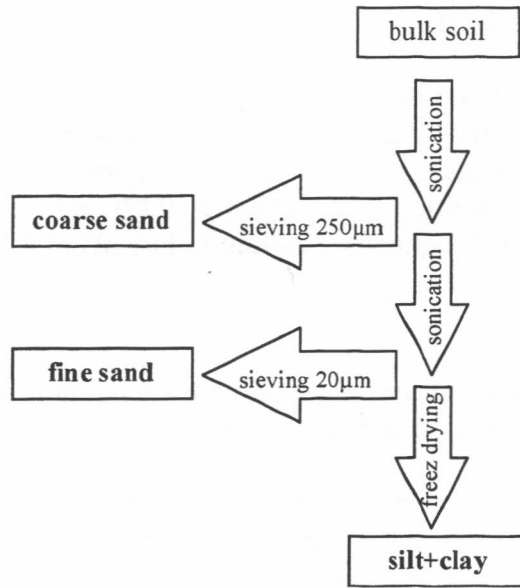


Figure 1: Particle size fractionation procedure.

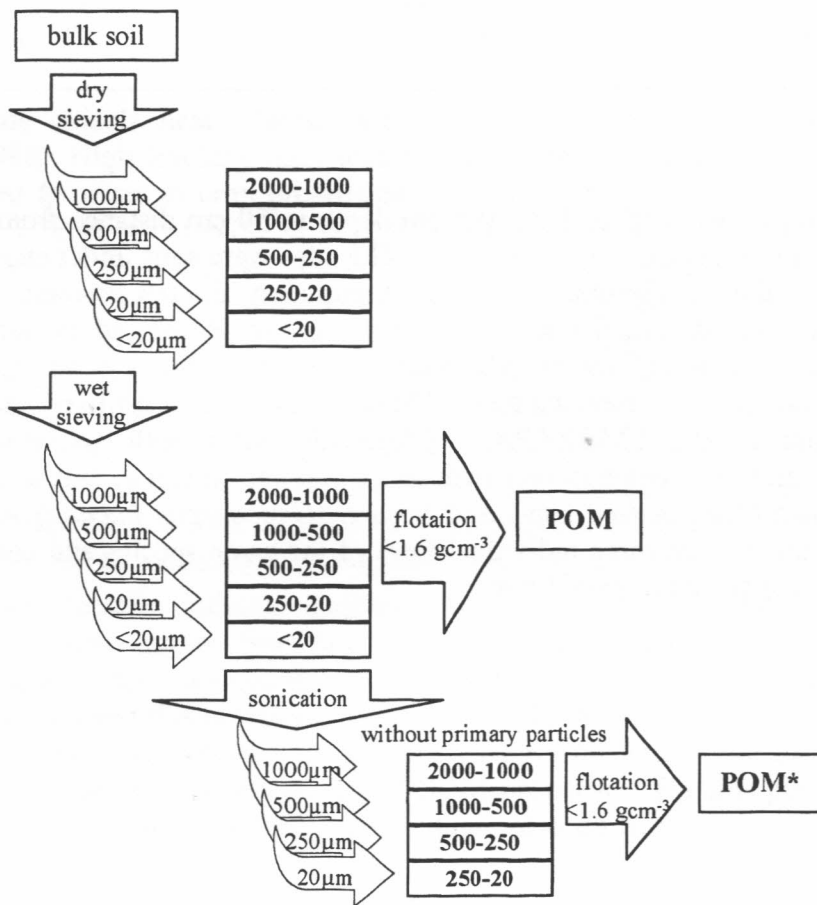


Figure 2: Aggregate and density fractionation procedures.

The soils were physically fractionated according to their particle size, aggregate size and density. For the particle size separation (Figure 1), 30 g fine earth were ultrasonically dispersed with an energy of 200 J ml<sup>-1</sup> with a soil:water mixture of 1:5 and then sieved to yield the coarse sand fraction (2000-250 µm). After a subsequent sonication with 300 J ml<sup>-1</sup>, the fine sand fraction 250-20 µm was separated. The sonication energy was adjusted after preliminary experiments to ensure complete dispersion (after North 1976) without redistribution of organic carbon. Both fractions were dried at 40°C for 48 hours. The silt and clay fractions (<20µm) were not further separated and freeze dried. The mean recovery amounted to 87 %. Two different methods of aggregate fractionation were conducted in three parallels: dry and wet fractionation (changed after Angers and Giroux 1996), the latter being combined with a density fractionation (Figure 2). First, 30 g soil was put on a cascade of sieves with 1000, 500, 250 and 20 µm sieve openings, vertically shaken for 50 times, turned 90° and again shaken. Tests verified that after this procedure only aggregates larger than the respective sieve opening size remained on the sieves, and the recovery laid between 97 and 99 %. The separates were weighed. For the combined aggregate and density fractionation, aggregates from the dry fractionation were combined and again put on the cascade of sieves but with the 20 µm sieve removed. The cascade was installed in a Yoder apparatus in a water bath (Yoder 1936). The aggregates were slowly wetted from below. This procedure could not completely exclude slaking and corresponded to the method wet sieving without prewetting of Gijsman (1996). They were separated using a 3 cm vertical displacement and 31 rpm for 30 min. The sieves were removed from the water bath and transferred into a pan with a sodiumpolytungstate (SPT) solution of 1.6 g cm<sup>-3</sup>. The particulate organic matter (POM) which was lighter than 1.6 g cm<sup>-3</sup> was washed with the SPT solution through a 250 µm sieve to separate POM and SPT. All aggregate fractions and POM were washed several times with deionized water to remove the SPT. The aggregates which passed the 250 µm sieve of the Yoder apparatus were poured through a 20 µm sieve. The remaining fraction <20 µm was flocculated with MgCl<sub>2</sub> and allowed to settle before discarding the supernatant. All fractions were dried at 40°C for 48 hours and weighed (recovery 95 %). The aggregates were again fractionated in primary particles, POM\* and mineral matrix after sonication with the respective sieve and energy described above. Thus, the „true“ amount of aggregates could be determined excluding the mineral particles which would belong to the aggregate class because of their size alone. The primary particles were separated with the sieve of the respective size class, dried, weighed and discarded. POM\* was separated from the aggregates with the SPT solution as described above. POM\* and the remaining soil were thoroughly washed with deionized water, dried and weighed.

The mean weighted diameter (MWD) was calculated from dry and wet aggregate separates in order to get a parameter of aggregate size distribution from each sample (Kemper and Rosenau 1986):

$$MWD = \sum_{i=1}^n \bar{x}_i w_i$$

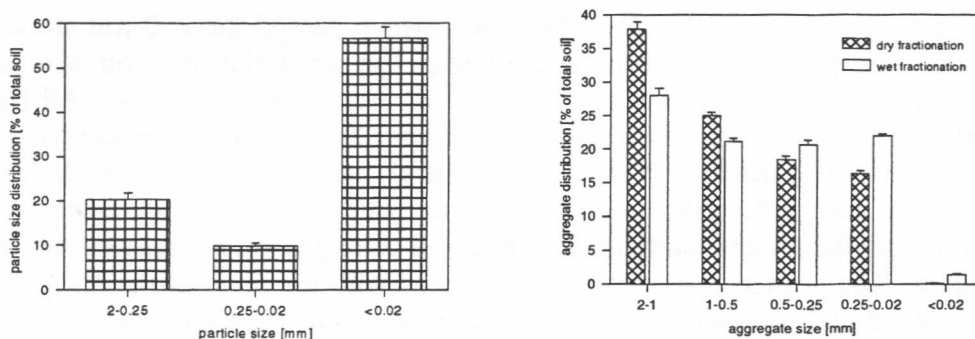
The MWD and the ratio of MWD from wet and dry aggregate fractionation (MWD<sub>wet</sub>/MWD<sub>dry</sub>) was taken as a measure of aggregate stability.

Carbon and nitrogen were analyzed by dry combustion with an automatic C/N-Analyzer. The lignin content and its stage of oxidative degradation was determined in the bulk soil, the particle size fractions and all aggregate and POM fractions with combined parallels using

alkaline CuO oxidation (Ertel and Hedges 1984). 500 mg of soil or 50 mg of POM were oxidized with CuO and 2 M NaOH for 2 hours at 170°C under a N<sub>2</sub> atmosphere. The oxidation products were analyzed as trimethylsilyl derivates by capillary gas chromatography (OV-1 column) with a FID detector. The amounts of lignin were calculated as the sum of the phenolic compounds (vanillyl, syringyl and cumaryl compounds, V+S+C). The acid to aldehyde ratio (ac/al) was taken as an indicator of the degree of microbial degradation of the lignin (Ertel and Hedges 1984). Non-cellulosic (NCS) and cellulosic (CS) sugars were determined with the MBTH method (Beudert 1988) after sequential acid hydrolysis according to Miltner (1997). Statistical analyses were performed using linear regression (STATISTICA 5.0).

## RESULTS AND DISCUSSION

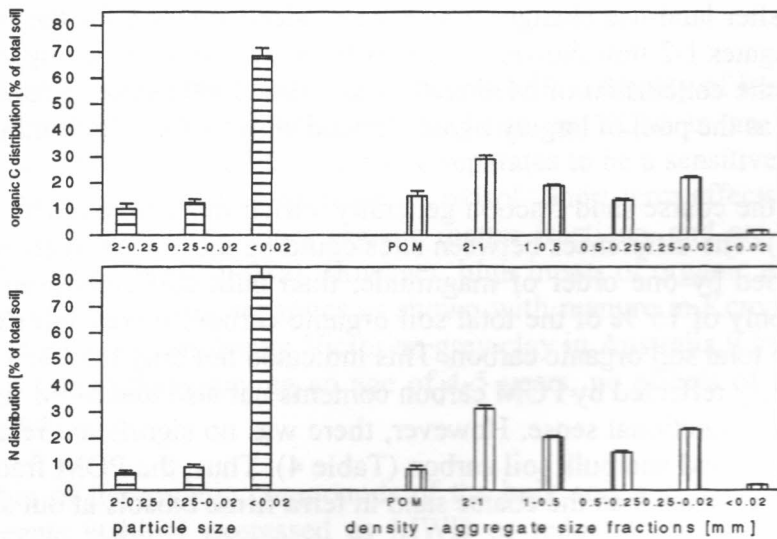
Most of the particles had clay and silt sizes, whereas only 21 and 11 % of the soil constituted of coarse and fine sand, respectively (Figure 3). When the aggregates were not disrupted but dry sieved, however, more than 80 % of the soil was larger than 250 µm (21 % in the coarse sand fraction) and 38 % in the 1-2 mm class (Figure 3). Even with wet sieving, the aggregates larger than 250 µm amounted to 70 %. The aggregate stability seemed to be very high in these soils compared to e.g. a Neuboiss silty loam from Canada (Angers and Giroux 1996). Higher aggregate stability was described from an oxisol from Colombia, which had only 10 % of total soil in the fraction <250 µm (Gijssman 1996).



**Figure 3:** Particle (left) and aggregate size distribution of dry and wet fractionation without removal of primary particles (right) as percentages of the whole soil from means of all sites (n=10); means and standard errors.

The carbon and nitrogen distribution across particle, density and aggregate fractions accentuates this pattern (Figure 4): 70 % of the organic C was found in clay and silt size separates, only 10 % in the coarse sand. When an aggregate fractionation was performed, however, less than 2 % of the total soil carbon was found in the fraction <20 µm, but more than 80 % in aggregates from 0.02-2 mm. In the particulate organic matter (POM), 15 % of the soil organic carbon was found. A separation of the primary particles and the particulate organic matter within the aggregates (POM\*) did not result in a different pattern of carbon stocks among aggregate classes (Table 2). The decrease of the carbon contents (stocks and concentrations) in the aggregates after the separation of primary particles were higher than the

extracted POM\* (data not shown). The difference can be attributed to losses of soluble carbon which was extracted during fractionation; another explanation is that organic carbon was bound to the separated primary particles especially in small aggregate classes. The latter process is probably of minor importance in the large aggregates (> 500  $\mu\text{m}$ ). When the correction for the primary particles was made by calculating the carbon concentrations from the wet fractionation without separation of primary particles and the separated primary particles, the carbon concentrations were higher than with the other two methods and carbon distribution differed from that obtained without separation (Table 2). This is in contrast to results from other authors (e.g. Angers and Giroux, 1996) who found the same carbon distribution regardless of separation of primary particles. With our procedure of separating the primary particles with the sieve size of the lower boundary of the respective aggregate class, the carbon contents were equal between the larger aggregates but increased in the fraction 20-250  $\mu\text{m}$ . This procedure together with the separation of POM proved to be a good procedure to obtain ecologically important aggregate carbon distributions in contrast to several results from related procedures described by Angers and Giroux (1996) who reported inconsistent patterns. Gijsman (1996) found higher carbon concentrations and contents (=stocks) with increasing aggregate size, supporting the concept of SOM being the binding agent in large aggregates (Tisdall and Oades, 1982). Our data do not support this hypothesis. An important difference between our experiment and the cited work was the method of separating primary particles.



**Figure 4:** Organic carbon (above) and nitrogen (below) distribution in particle size, aggregate and density fractions as percentages of the whole soil from means of all sites (n=10); means and standard errors.

**Table 2:** Carbon concentrations ( $\text{mg g}^{-1}$  fraction) and carbon stocks ( $\text{mg g}^{-1}$  soil) and the relationship between organic carbon of aggregate fractions with and without a separation of primary particles.

Fraction [ $\mu\text{m}$ ]	Carbon concentration				Carbon stocks		
	without separation	with separation	correlation <sup>1</sup>	calculated <sup>2</sup>	without separation	with separation	correlation <sup>1</sup>
2000-1000	29.0	26.4	0.89***	29.5	8.05	6.9	0.90***
1000-500	25.1	24.3	0.69***	29.8	5.34	4.2	0.74***
500-250	18.0	27.4	0.72***	29.2	3.72	3.6	0.75***
250-20	28.2	30.7	0.66**	36.2	6.18	5.1	0.72***

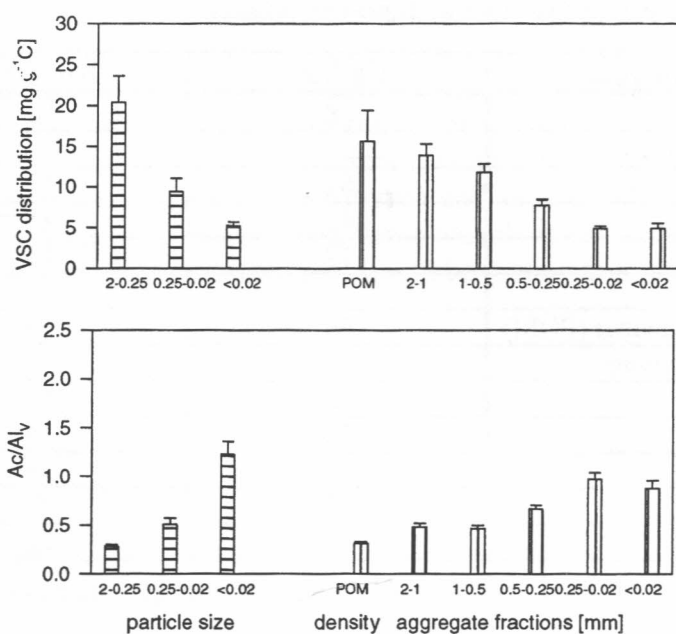
<sup>1</sup> \*  $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

<sup>2</sup> calculated from carbon concentrations without separation deducting the proportion of primary particles assuming that primary particles do not contain carbon

The lignin distribution (Figure 5) revealed that the coarse sand and POM mainly consisted of labile organic matter i.e. weakly decomposed and humified organic matter. High VSC contents indicate low degradation and low Ac-to-Al ratios indicate low oxidation of intact lignin (Ertel and Hedges, 1984). The coarse sand and POM were expected to be the fractions which react first after land-use changes which was indeed verified for the investigated soils. But also the aggregates 1-2 mm showed relatively high VSC contents compared to POM. This result contradicts the conclusion of Metherell et al. (1993) who stated that determinations of POM can be used as the pool of largely lignin-derived slow SOM, which may not hold for our investigated soil.

The POM and the coarse sand fraction generally varied more between sites than other soil fractions (Table 3). The differences between sites could be more sensitively assessed by POM stocks, which varied by one order of magnitude, than bulk soil carbon analyses. Although POM constituted only of 15 % of the total soil organic carbon, it was significantly ( $p < 0.001$ ; Table 5) related to total soil organic carbon. This indicated not only that the effects of trees on SOM was sensitively reflected by POM carbon contents but also that SOM replenishment was related to POM in a functional sense. However, there was no significant relation between the carbon in the coarse sand and bulk soil carbon (Table 4). Thus, the POM fraction was a better indicator for SOM changes than the coarse sand in terra firme oxisols at our site.





**Figure 5:** VSC-lignin (above) and Ac-to-Al ratios (below) in particle size, aggregate and density fractions (n=10); means and standard errors.

Barrios et al. (1996) found the Ludox light fraction with a density of less than 1.13 g cm<sup>-3</sup> to be most suitable for detecting effects of land-use on SOM in an alfisol in Kenya. Guggenberger et al. (1995) reported the sand size separates to be a sensitive indicator of land-use change from native savanna to pasture on an oxisol. Short-term effects of organic inputs are most likely to be found in the light organic matter fractions, and are minimal in stable SOM fractions (Lehmann et al., 1998a). However, high inputs of organic matter can increase carbon contents even in clay size separates as shown with manure in Kenya (Lehmann et al., 1997) or deplete them as shown from a Victorian grey clay in Australia (Golchin et al., 1995). With the different tree systems having an age of 4-5 years, no effects of the trees on stable SOM were expected.

The relationship of the organic compounds of the bulk soil, the large aggregates and the POM with aggregate stability expressed as MWD or reduction of MWD (Table 5) were investigated to elucidate the driving forces of aggregation and possible effects of trees. No positive relations could be found. The aggregate stability was inversely related to the VSC contents in the bulk soil. This would indicate that aggregate stability increased with a higher degree of lignin degradation. Fe and Al complexation may also play an important part for SOM stabilization in aggregates in oxisols opposed to temperate soils (Gijsman, 1996). Further investigations using the amount of O-alkyl carbon and the occluded POM\* should yield valuable data of the effects of trees on aggregation as shown by Golchin et al. (1995).

**Table 3:** Coefficients of variation (CV [% standard deviation of mean]) of the carbon and nitrogen contents in particle size, density and aggregate size separates as indicators of the sensitivity of the respective soil pools towards land-use changes (n=10).

Soil pools (fraction [ $\mu\text{m}$ ])	Carbon	Nitrogen
bulk soil	18	10
<i>particle size fractions:</i>		
coarse sand (2000-250)	67	49
fine sand (250-20)	45	46
silt+clay (<20)	17	16
<i>density fraction:</i>		
particulate organic matter (POM)	64	59
<i>aggregate size fractions:</i>		
2000-1000	12	16
1000-500	20	14
500-250	25	18
250-20	16	9
<20	21	20

**Table 4:** Correlation coefficients and level of significance of the relation between particle size chemical properties and bulk soil organic carbon content.

Soil compounds <sup>1</sup>	Bulk soil C for			
	bulk soil	2000-250 $\mu\text{m}$	250-20 $\mu\text{m}$	<20 $\mu\text{m}$
organic C	-	0.57ns	0.37ns	-
CS	nd	nd	nd	nd
NCS	-0.55ns	nd	nd	nd
VSC	0.38ns	0.09ns	0.49ns	0.28ns

<sup>1</sup> CS cellulosic sugars, NCS noncellulosic sugars, VSC lignin compounds

**Table 5:** Relationship between the organic matter composition in the bulk soil, particulate organic matter (POM), 2000-1000  $\mu\text{m}$  fraction and (i) the mean weight diameter (MWD) of the wet fractionated aggregates, (ii) the ratio of MWD from wet and dry aggregate fractionation ( $\text{MWD}_{\text{wet}}/\text{MWD}_{\text{dry}}$ ) and (iii) the bulk soil organic carbon content.

Fraction	Soil compounds <sup>1</sup>	MWD	$\text{MWD}_{\text{wet}}/\text{MWD}_{\text{dr}}$ y	bulk soil C
Bulk soil	C amount	0.17ns <sup>2</sup>	0.01ns	-
	NCS	0.38ns	0.08ns	-0.61(*)
	VSC	-0.78**	0.08ns	0.38ns
POM	C amount	-0.49ns	0.00ns	0.91***
	VSC	-0.28	0.57(*)	-0.39ns
2000-1000 $\mu\text{m}$	C amount	0.07ns	0.10ns	-
	VSC	-0.49ns	0.39ns	-0.17ns

<sup>1</sup> CS cellulosic sugars, NCS noncellulosic sugars, VSC lignin compounds

<sup>2</sup> (\*)  $p < 0.1$ ; \*  $p < 0.05$ ; \*\*  $p < 0.01$ ; \*\*\*  $p < 0.001$

## CONCLUSIONS

The POM fraction is an important indicator of the effects of different organic inputs on SOM properties. It could be used for assessing the effects of land-use or single-tree effects on SOM. The investigation of different stages of humification and the chemical properties of POM should be intensified. The relationship between aggregation and SOM is only poorly understood and should be continued in future research, as it may give important information about SOM stabilization. The relation between soil organic matter and nutrient availability and the effects of single-trees on the terra firme oxisols is not understood up to now. The soil nutrient availability in different soil pools should be looked at in the future.

## REFERENCES

- Angers, DA, and Giroux, M, 1996: Recently deposited organic matter in soil water-stable aggregates. *Soil Sci. Soc. Am. J.* 60, 1547-1551.
- Barrios, E, Buresh, RJ, and Sprent, JI, 1996: Organic matter in soil particle size and density fractions from maize and legume cropping systems. *Soil Biol. Biochem.* 28, 185-193.
- Beudert, G, 1988: Mikromorphologische, naßchemische und  $^{13}\text{C}$ -NMR-spektroskopische Kennzeichnung der organischen Substanz von Waldhumusprofilen nach Dichtefraktionierung. *Bayreuther Bodenkundliche Berichte* 8, Bayreuth, Germany. 133p.
- Christensen B.T. (1992): Physical fractionation of soil and organic matter in primary particle size and density separates. *Adv. Soil Sc.* 20, 1-90.
- Coleman, J, Oades, JM, and Uehara, G 1989: *Dynamics of Soil Organic Matter in Tropical Ecosystems*. University of Hawaii Press, Hawaii. 249pp.
- Degens, BP, 1997: Macro-aggregation of soils by biological bonding and binding mechanisms and the factors affecting these: a review. *Aust. J. Soil Res.* 35, 431-459.
- Ertel, JR, and Hedges, JI, 1984: The lignin component of humic substances: distribution among soil sedimentary humic, fulvic and base-insoluble fractions. *Geochim. Cosmochim. Acta* 48, 2065-2074.
- FAO, 1990: *Soil map of the world, revised legend*. FAO, Rome, Italy. 119pp.
- Gijsman, AJ, 1996: Soil aggregate stability and soil organic matter fractions under agropastoral systems established in native savanna. *Aust. J. Soil res.* 34, 891-907.
- Golchin, A, Clark, P, Oades, JM, and Skjemstad, JO, 1995: The effects of cultivation on the composition of organic matter and structural stability of soils. *Aust. J. Soil Res.* 33, 975-993.
- Kemper, WD, and Rosenau, RC, 1987: Aggregate stability and size distribution. In: Klute, A (ed), *Methods of Soil Analysis, Part 1, Agronomy Monograph no. 9*, 425-442. Madison, USA
- Lehmann, J, Küper, U, and Zech, W, 1997: Organic matter properties of soils with varying land use in a semiarid tropical environment. In: Weber, J (ed), *Conference of the International Humic Substance Society 1996*, Poland. in press.

- Lehmann, J, Poidy, N, Schroth, G, and Zech, W, 1998a: Short-term effects of soil amendment with legume tree biomass on carbon and nitrogen in particle size separates in central Togo. *Soil Biol. Biochem.*, in press.
- Lehmann, J, Weigl, D, and Zech, W, 1998b: Nutrient cycling in a runoff agroforestry system in Northern Kenya. *Agrofor. Syst.*, in review.
- Metherell, AK, Harding, LA, Cole, CV, and Parton, WJ, 1993: CENTURY soil organic matter model environment. Technical Documentation Agroecosystems Version 4.0. Great Plains System Research Unit, Technical Report No. 4. Fort Collins, Colorado, USA
- Miltner, A, 1997: Umsetzung organischer Bodensubstanz unter dem Einfluß von Mineralphasen. *Bayreuther Bodenkundliche Berichte* 52, Bayreuth, Germany. 110p.
- North, PF, 1976: An absolute measurement of soil structural stability using ultrasound. *J. Soil Sci.* 27: 451-459.
- Schroth, G, da Silva, LF, Seixas R, and Teixeira, WG, 1998: Significant subsoil accumulation of mineral nitrogen under perennial crops in a ferralitic Amazonian upland soil: effects of land-use systems and single tree patterns. *Agric. Ecosys. Environm.* (in preparation).
- Seyfried, MS, and Rao, PSC, 1991: Nutrient leaching loss from two contrasting cropping systems in the humid tropics. *Trop. Agric.* 68, 9-18.
- SHIFT ENV-45, 1997: Water and nutrient fluxes as indicators of the stability of different land-use systems on the terra firme near Manaus. Annual report 1996 of SHIFT project ENV-45, 73p.
- Tiessen, H, and Stewart, JWB, 1983: Particle-size fractions and their use in studies of soil organic matter. II) Cultivation effects on organic matter composition in size fractions. *Soil Sci. Soc. Am. J.* 47, 509-513
- Tisdall, OM, and Oades, JM, 1982: Organic matter and water-stable aggregates in soils. *J. Soil Sci.* 33, 141-163.
- Yoder, RE, 1936: A direct method of aggregate analysis of soils and a study of the physical nature of soil erosion losses. *J. Am. Soc. Agron.* 28, 337-351.
- Zech, W, Senesi, N, Guggenberger, G, Kaiser, K, Lehmann, J, Miano, TM, Miltner, A. and Schroth, G, 1997: Factors controlling humification and mineralization of soil organic matter in the tropics. *Geoderma* 79, 117-161.