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Organic matter stabilization in a Xanthic Ferralsol of the central Amazon as affected by single trees: chemical characterization of density, aggregate, and particle size fractions

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Abstract

Not only the amount of organic carbon in soil is important for soil organic matter (SOM) stability, but also its physical and chemical properties. The appropriate technique for the assessment of SOM dynamics can vary between soil types, and information about this is lacking for Ferralsols of the central Amazon basin. First, this work identified SOM pools which are sensitive to land-use changes on the terra firme in the central Amazon. In a second step, the effects of single trees on SOM properties were evaluated in a mixed tree crop plantation in comparison to secondary and primary forest sites. Thus, the processes of organic matter stabilization could be studied in the highly aggregated soils. 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 Mg m^{-3}) varied by one order of magnitude between sites and could be used as a sensitive indicator of land-use changes. Aggregate stability was not related to SOM contents or bulk SOM properties. The incorporation of plant material into stable SOM, however, was enhanced by aggregation. Among aggregate separates, the fraction, 0.25–0.5 mm, showed single-tree effects the most. SOM replenishment was higher under tree species with low quality litter, i.e. high C-to-N and polyphenol-to-N ratios. High quality litter from a leguminous ground cover, however, showed low soil nitrogen and carbon replenishment but increased nitrogen concentrations in light fractions. Litter with a high quality may improve soil nitrogen availability but not amounts of total SOM, which could only be shown for low quality litter. The results indicate the importance of aggregation and POM dynamics for SOM stabiliza-

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tion in the studied Xanthic Ferralsols of the central Amazon basin.

Keywords: aggregate stability; ferralsol; humid tropics; nitrogen; physical fractionation; soil organic matter

1. Introduction

In the humid tropics, high leaching rates can lead to large nutrient losses from applied fertilizer in crop production systems (Seyfried and Rao, 1991). The minimization of these unproductive nutrient losses and a closed nutrient cycling are the precondition of sustainable land-use management. Adding to the problem of nutrient leaching, the Ferralsols of the central Amazon are characterized by severe nutrient limitations (Cravo and Smyth, 1997). Therefore, nutrient conservation and the replenishment of nutrient contents are vital for crop production on these soils. Increasing the soil organic matter (SOM) content is the key factor for improving soil chemical fertility, first as a source of slow release of nutrients and secondly, as a means of enhancing the soil cation exchange capacity in order to reduce nutrient leaching (Coleman et al., 1989).

Integrating trees into farmland and combining different tree species in multi-strata agroforestry systems may increase SOM contents and improve soil nutrient availability as shown for single-tree influences on soil properties in natural forest and savanna ecosystems (Rhoades, 1997). The effectiveness to replenish SOM contents may vary between different tree species. Very little is known about the potential of indigenous fruit trees to replenish SOM contents in agroforestry systems in comparison to secondary vegetation and primary forest in the central Amazon.

Not only the amount of organic carbon in soil is ecologically important for SOM stability, but also its physical (Feller and Beare, 1997) 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 the chemistry of SOM (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 SOM pools can vary between soils. Several studies are available for highly weathered soils from semi-arid northeastern Brazil (Shang and Tiessen, 1997), the Brazilian Cerrado (Neufeldt et al., 1999), and Colombia (Guggenberger et al., 1995), but information on SOM pools is lacking for Ferralsols on the terra firme of the central Amazon basin.

The objectives of this study were (i) to identify SOM pools which are sensitive to land-use changes, (ii) to evaluate the effects of different trees on

SOM properties, and (iii) to characterize processes which are relevant to SOM stabilization in Xanthic Ferralsols on the terra firme of the central Amazon.

2. Materials and methods

This study was conducted on the SHIFT experimental fields at the Embrapa (Empresa Brasileira de Pesquisa Agropecuária) Amazônia Occidental station, near Manaus, Brazil. The average precipitation is 2503 mm year^{-1} (1971–1993) with a maximum between December and May. The natural vegetation is a tropical rainforest. The soils are classified as Xanthic Ferralsols (FAO, 1990) and are clayey with over 80% clay, strongly aggregated, having medium organic carbon and nitrogen contents of 28 and 2.3 mg g^{-1}, respectively, medium to low pH of 4.5–5.0 (H_20), low effective cation exchange capacity of 4.9 mmol$_c$ kg^{-1} and low base saturation of 33%.

The investigated sites were soils under cupuaçu (*Theobroma grandiflorum* Willd. (ex Spreng.) K. Schum.), peachpalm (*Bactris gasipaes* Kunth.) managed for heart of palm production, Brazil nut (*Bertholletia excelsa* Humb.&Bonpl.), annatto (*Bixa orellana* L.) and pueraria (*Pueraria phaseoloides* (Roxb.) Benth.) in an agroforestry system, and under peachpalm in monoculture. In November and April, these sites were fertilized according to local recommendation with 95, 42, 42 and 85 g N/year (ammonium sulfate) and plant for cupuaçu, peachpalm, Brazil nut and annatto, respectively. Additionally, sites with spontaneous gramineous vegetation, in the secondary vegetation of vismia (*Vismia* spp.) and in the primary forest under mata-mata (*Eschweilera* spp.) and bacaba (*Oenocarpus bacaba*) were chosen. Two topsoil samples (0–5 cm) were taken at 50 cm from three individual trees of the same species in September 1997 and combined. From sites of cupuaçu, peachpalm, pueraria, vismia and bacaba soil samples were obtained in three replicates using a completely randomized design, for the other species, samples were obtained only in one replicate. The soil samples were air-dried, separated from litter larger than 2 mm and sieved to pass 2 mm.

2.1. Soil fractionation

The soil samples were physically fractionated according to their particle size, aggregate size, and particle density. Aggregate size and density fractionation was performed for all samples, particle size fractionation only for one replicate, for which samples of all sites were available. For the particle size separation, 30 g fine earth were ultrasonically dispersed with an energy of 200 J ml^{-1} using 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^{-1}, 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 h. The silt and clay fractions (<20 μm) were not separated and were freeze dried, because carbon redistribution could not be excluded during further fractionation. The mean recovery amounted to 87%. Two different methods of aggregate fractionation were conducted in triplicate: dry and wet fractionation (modified from Angers and Giroux, 1996), the latter being combined with a density fractionation (Fig. 1). 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 was 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 inside a

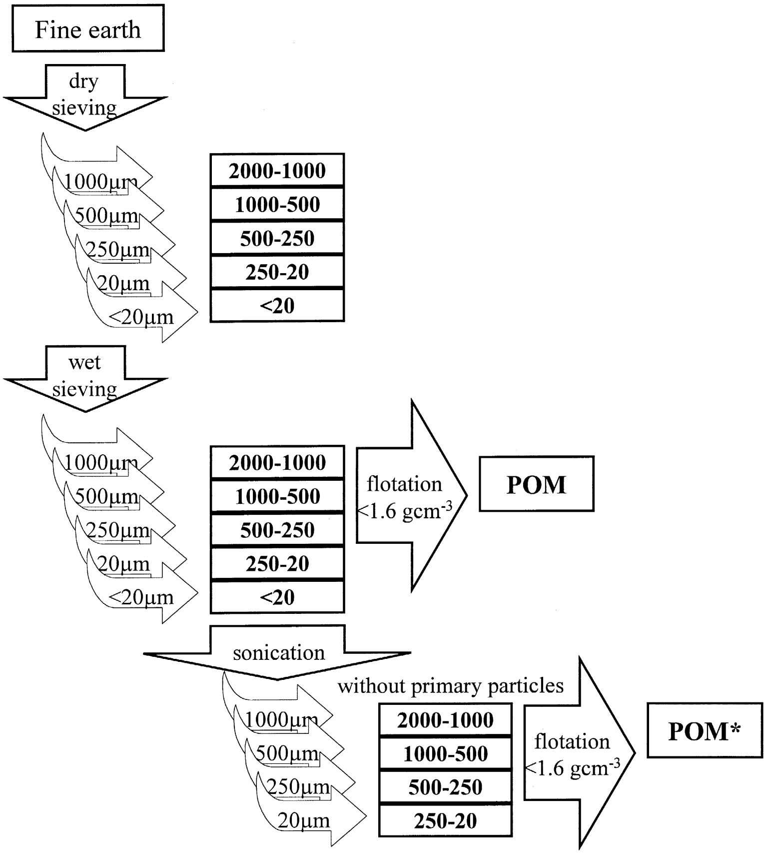

Fig. 1. Sequence of dry and wet aggregate fractionation procedure coupled with a density fractionation yielding five aggregate size classes and the particulate organic matter (POM) of soil and the POM bound inside aggregates.

water bath (Yoder, 1936). The aggregates were slowly wetted from below. This procedure could not completely exclude slaking and corresponded to the method of wet sieving without pre-wetting, of Gijsman (1996). The aggregates were separated using a 30-mm vertical displacement and 31 rpm for 30 min. The sieves were removed from the water bath and transferred into a pan with a sodium polytungstate (SPT) solution of 1.6 Mg m^{-3}. The POM, which was lighter than 1.6 Mg m^{-3}, 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 through the 250-μm sieve of the Yoder apparatus, were poured through a 20-μm sieve. The remaining fraction, < 20 μm, was flocculated with $MgCl_2$ and allowed to settle before discarding the supernatant. All fractions were dried at 40°C for 48 h and weighed (recovery 95%). The aggregate fractions were again fractionated in primary particles, POM and mineral matrix after sonication, using the respective sieve and energy described above. Thus, the “true” amount of aggregates in the respective fractions 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. The POM contained within the aggregates (hereafter referred to as POM^*) was separated from the aggregate fractions with the SPT solution as described above (Fig. 1). 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, 1987):

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

The MWD and the ratio of MWD from wet and dry aggregate fractionation ($\mathrm{MWD}_{\mathrm{wet}}$-to-$\mathrm{MWD}_{\mathrm{dry}}$) were taken as a measure of aggregate stability.

2.2. Soil analyses

Carbon and nitrogen were analyzed by dry combustion with an automatic C/N-Analyzer. All carbon and nitrogen values of aggregate and density fractions were calculated (i) as “contents” related to the fraction and (ii) as “amounts” related to the whole soil, taking into account the different sizes of each fraction. 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). A total of 500 mg of soil or 50 mg of POM was oxidized with CuO and 2 M NaOH for 2 h at 170°C under a N_2 atmosphere. The oxidation products were analyzed as trimethylsilyl derivates by capillary gas chromatography (OV-1 column) with a FID detector. The lignin contents were calculated as the sum of the phenolic compounds (vanillyl, syringyl and cumaryl compounds, V + S + C). The acid to aldehyde ratio (ac-to-al) indicates the extent of side-chain oxidation and 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 and analyses of variance with a completely randomized design (STATISTICA 5.0). If effects were significant, means were compared to the least significant difference method (LSD, $p < 0.05$).

3. Results and discussion

3.1. Weight, carbon and nitrogen distribution in SOM fractions

Most of the particles had clay and silt sizes, whereas only 20% and 10% of the soil constituted of coarse and fine sand, respectively (Fig. 3). However, when the aggregates were not disrupted but dry sieved, more than 80% of the soil was larger than 250 μm (21% in the corresponding coarse sand size fraction with disruption) and 38% in the 1–2 mm class (Fig. 2). Even with wet sieving, the aggregate separates larger than 250 μm amounted to 70% (Fig. 3). The aggregate stability seemed to be very high in these soils compared to, e.g. a

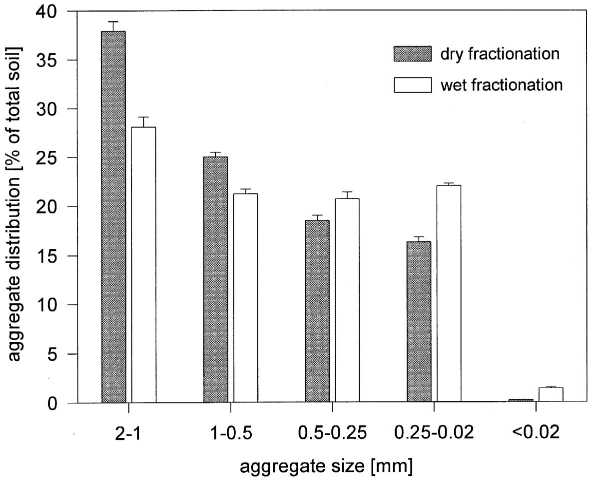

Fig. 2. Aggregate size distribution of dry and wet fractionation without removal of primary particles as percentages of the whole soil from means of all sites in one replicate on the terra firme near Manaus, Brazil ($n = 10$); means and standard errors.

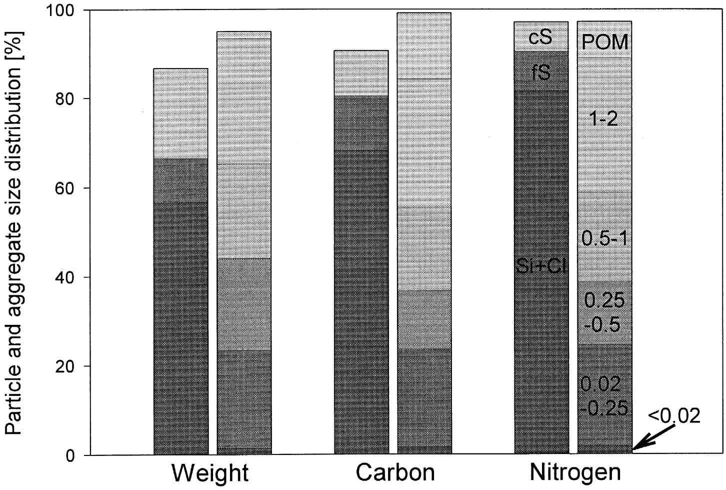

Fig. 3. Average weight, carbon and nitrogen distribution in particle size (left bar), density and aggregate size fractions (right bar; wet fractionation) of Ferralsols under different trees and cover crops in the central Amazon ($n = 10$); cS, coarse sand (0.25–2 mm); fS, fine sand (0.02–0.25 mm); Si + Cl, silt and clay size fractions (< 0.02 mm); aggregate sizes in millimeters; total bar height denotes recovery.

Neufbois silty loam from Canada (Angers and Giroux, 1996). Even higher aggregate stability was described from a Ferralsol from Colombia, which had only 10% of total soil in the aggregate fraction < 250 μm (Gijsman, 1996).

The carbon and nitrogen distribution across particle, density and aggregate fractions shows this pattern even more strongly than the weight distribution (Fig. 3): 68% of the organic C was found in clay and silt size separates, only 10% in the coarse sand size fraction. 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 aggregate fractions from 0.02 to 2 mm. The POM amounted to 15% of the soil organic carbon. The carbon distribution across aggregate separates changed (i) when primary particles and the POM* were separated or (ii) when merely the proportion of primary particles was deducted (Lehmann et al., 1998a). In both the actual separation of primary particles and the calculation, the carbon distribution became more uniform between aggregate separates and increased only in the micro-aggregate fraction (Lehmann et al., 1998a). This differed from the results of other authors (Angers and Giroux, 1996) who found the same carbon distribution regardless of the 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 only slightly decreased from larger to smaller aggregate fractions but increased in the fraction 0.02–0.25 mm (Table 1). This is in contrast to results from a Peruvian Alisol with uniform carbon distribution between aggregate separates after cor-

Table 1

Carbon, nitrogen, lignin and carbohydrate contents in particle size, density, and aggregate size fractions of Ferralsols under different trees and cover crops in the central Amazon ($n = 10$)

SOM pools [fraction (mm)]	C (mg g^{-1})	N (mg g^{-1})	C-to-N ratio	VSC[a] (mg g^{-1} C)	ac-to-al Ratio	VSC-to-N (‰)	CS (mg g^{-1} C)	NCS (mg g^{-1} C)	NCS-to-CS ratio
Bulk soil	28.4	2.3	12.6	9.5	0.53	120	38.4	315	8.3
Particle size fractions:									
2–0.25	14.1	0.7	19.2	20.3	0.28	390	79.3	362	5.0
0.25–0.02	36.4	2.1	17.8	9.4	0.51	167	nd	nd	–
< 0.02	34.1	3.3	10.5	5.2	1.23	55	nd	nd	–
Density fraction:									
POM	299.2	12.4	24.6	15.6	0.31	384	26.4	252	9.6
Aggregate size fractions:									
2–1	26.4	2.3	11.6	13.9	0.48	161	nd	nd	–
1–0.5	24.3	2.1	11.4	11.8	0.47	134	nd	nd	–
0.5–0.25	27.4	2.9	9.4	7.8	0.67	73	nd	nd	–
0.25–0.02	30.7	3.1	9.8	4.9	0.97	48	nd	nd	–
< 0.02	32.6	3.1	10.4	4.8	0.88	50	nd	nd	–

[a] VSC, lignin compounds; CS, cellulosic sugars; NCS, non-cellulosic sugars; ac-to-al ratio of acids to aldehydes of the vanillyl compounds.

recting for the sand content (Elliott et al., 1991). The increase of carbon in small aggregate separates of our soils may indicate a relative carbon enrichment in micro-aggregates as shown for a loamy but not a sandy Ferralsol from southern Brazil (Neufeldt et al., 1999). These were also the same aggregate fractions, which showed the highest amounts of strongly humified, stable SOM (see Section 3.2).

Gijsman (1996) found higher carbon contents and amounts with increasing aggregate size, supporting the concept of SOM being the binding agent in large aggregates (Tisdall and Oades, 1982). Our data do not confirm this hypothesis. If this criterion is applied here, aggregates seemed not to be held together primarily by organic matter in the studied Ferralsols.

3.2. Chemical properties of SOM pools

The lignin distribution (Table 1) revealed that the coarse sand size fraction and POM mainly consisted of labile organic matter, i.e. weakly decomposed and humified organic matter. High VSC contents and low ac-to-al ratios indicate low oxidation of intact lignin (Ertel and Hedges, 1984). Furthermore, the aggregate fraction, 1–2 mm, also showed relatively high VSC contents compared to POM and the sand size separates. Therefore, undecomposed lignin was not only found in POM as suggested by Metherell et al. (1993) but also in large aggregate separates. With decreasing aggregate sizes, the VSC signatures decreased and the ac-to-al ratios increased, indicating higher degrees of lignin decomposition in smaller aggregate fractions. The same was found for the particle sizes (Table 1), which is well documented for particle size fractions of tropical soils (Bonde et al., 1992; Guggenberger et al., 1995; Lehmann et al., 1998b; Koutika et al., 1999). The C-to-N ratios, however, were low in all aggregate classes in contrast to particle size separates. Therefore, the aggregate fractions may have differed less among each other in their amount of microbial biomass than particle size separates, and a large portion of POM was probably contained in the sand size fraction. However, the aggregate separates were not simply differently sized and devoid of POM, but also showed distinctly differing properties between each other. Similar to the VSC contents, the ratios of VSC-to-N decreased towards smaller aggregate sizes. Lehmann et al. (1998b) showed that the polyphenol-to-N ratios of particle size separates changed more between size classes than the C-to-N ratios and sensitively indicated additions of organic material to soil. Therefore, weakly humified organic material similar to POM was bound in larger aggregates in the studied Xanthic Ferralsol. This result was not an artifact by contamination with POM, since even the POM* was removed. However, the average particle size may have been different between aggregate fractions and may invalidate the conclusion that humification progresses from larger to smaller aggregate fractions, because larger particle size fractions usually contain less humified organic matter. The high proportion of clay-associated carbon of

70%, however, suggests that the chemical properties, even of clay-bound carbon, were different between aggregate fractions.

The POM and the coarse sand size fraction had very similar carbon and nitrogen pool sizes (Fig. 3) as well as ac-to-al and VSC-to-N ratios (Table 1). The proportion of VSC lignin and carbohydrates of total carbon, however, was higher in the sand than in POM. This result has to be interpreted with caution, as the extraction of the carbohydrates may be incomplete in pure plant material.

The aggregate fractionation revealed that the formation of water-stable aggregates increased the incorporation of fresh organic matter with high VSC values into more stable organic matter associated with finer particle sizes. Therefore, soil aggregation was shown to be an important process for the stabilization of SOM in the studied Ferralsols. The importance of micro-aggregation for SOM stabilization was also stressed by Shang and Tiessen (1997) for semi-arid Ferralsols in northeastern Brazil, but aggregate protection of SOM was much weaker than in the studied central Amazonian Ferralsols.

3.3. *Sensitive indicators of land-use changes*

The carbon and nitrogen contents of POM and the coarse sand size fraction generally varied more between sites than other soil fractions, nitrogen slightly less than carbon (Table 2). Therefore, POM and the coarse sand size fraction can be used as sensitive indicators of single-tree effects on SOM. These

Table 2
Coefficients of variation [CV (% standard deviation of mean)] of the carbon and nitrogen contents in particle size, density, and aggregate size separates as indicators for the sensitivity of the respective organic matter pools of a Xanthic Ferralsol concerning land-use changes in the central Amazon ($n = 10$)

SOM pools [fraction (mm)]	Carbon	Nitrogen
Bulk soil	18	10
Particle size fractions:		
Coarse sand (2–0.25)	67	49
Fine sand (0.25–0.02)	45	46
Silt + clay (< 0.02)	17	16
Density fraction:		
POM	64	59
Aggregate size fractions:		
2–1	12	16
1–0.5	20	14
0.5–0.25	25	18
0.25–0.02	16	9
< 0.02	21	20

fractions were mainly constituted of weakly altered plant material as seen from the high proportion of intact lignin. Although POM amounted to only 15% of the total soil organic carbon, it was significantly ($p < 0.001$; Table 3) related to total soil organic carbon. This did not hold for the sand fraction (Table 3). The performed correlation seemed valid, because the relationship of POM with the remaining soil carbon pool excluding POM was significant ($p < 0.05$), but not coarse sand carbon and the sum of fine sand, silt, and clay carbon. Thus, the POM fraction was a better indicator for SOM changes than the coarse sand size fraction in the Ferralsols at our site. This may not only indicate that the effects of trees on SOM were sensitively reflected by POM carbon contents but also that SOM replenishment was related to POM in a functional sense. Higher amounts of POM carbon resulted in a higher incorporation of organic matter into the more stable SOM pools, which was promoted by the formation of aggregates.

Barrios et al. (1996) found the light fraction with a density of less than 1.13 Mg m^{-3} to be most suitable for detecting effects of land-use on SOM in an Alfisol in Kenya. Guggenberger et al. (1995), however, reported the sand size separates to be a sensitive indicator of land-use change from native savanna to pasture on a Ferralsol. Information on which method is better suited for different types of organic matter input and for different soils, can rarely be drawn from the available literature because comparisons between methods have seldom been done (e.g. Shang and Tiessen, 1997).

Table 3
Correlation coefficients and levels of significance of the relationship between the organic matter composition in the bulk soil, the POM, and the coarse sand size fraction with either (i) the ratio of MWD from MWD_{wet}-to-MWD_{dry} or (ii) the bulk soil organic carbon content for a Xanthic Ferralsol in the central Amazon ($n = 25$)

Fraction	Soil compounds[a]	MWD_{wet}-to-MWD_{dry}	Bulk soil C
Bulk soil	C amount	0.07 ns	np
	CS	0.03 ns	-0.65^{***}
	NCS	-0.36 ns	-0.28 ns
	VSC	0.39 ns	0.58^{**}
POM	C amount	0.06 ns	0.91^{***}
	CS	0.43^{*}	-0.29 ns
	NCS	-0.30 ns	-0.27 ns
	VSC	0.24 ns	-0.28 ns
Coarse sand[b] (2–1 mm)	C amount	0.25 ns	0.58 ns
	VSC	nd	0.09 ns

ns, Not significant; nd, not determined; and np, not performed interaction.

[a] CS, cellulosic sugars; NCS, non-cellulosic sugars; VSC, lignin compounds.

[b] $n = 10$.

$^{*}p < 0.05$.

$^{**}p < 0.01$.

$^{***}p < 0.001$.

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., 1998b). 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) and in Tanzania (Solomon et al., 2000) or deplete them as shown from a Victorian grey clay in Australia (Golchin et al., 1995). In the different cultivation systems with an age of 4–5 years in our study, significant effects of the trees on stable SOM were not expected. For the studied single-tree effects on SOM of the Ferralsols, the determination of the POM seemed to be sufficient for an estimation of SOM replenishment. An advantage of POM determinations are also their easier analytical procedure than particle size fractionations in strongly aggregated Ferralsols. The dispersion of aggregates for a particle size fractionation without redistributing SOM may pose considerable difficulties and needs to be verified for each analysis.

3.4. SOM and aggregate stability

The relationship of the organic compounds in physical SOM pools with aggregate stability was investigated to elucidate the driving forces of aggregation and possible effects of trees. No positive relations could be found between organic carbon contents in physical SOM pools and aggregate stability expressed as the reduction of MWD by wet sieving (Table 3; only bulk soil, POM, and coarse sand size fraction shown). A weak correlation was determined for the CS sugar content of POM carbon and aggregate stability (Table 3). Polysaccharides may indeed act as a binding agent for clay minerals (Chenu and Guerif, 1991). The differences of aggregate stability in the studied soils, however, were small and did not change due to the effect of single trees, not even in comparison to the primary forest sites. The aggregation seemed not to be increased by an input of organic matter, which leads us to the conclusion that aggregation and organic matter were not related in the studied Ferralsols as already assumed above. Golchin et al. (1995), however, could demonstrate that the occluded POM* correlated with aggregate stability; this was not able to explain the effects of trees on aggregation in our soils (data not shown). Our results are also in contrast to reports from a Cerrado Ferralsol which showed significant and close relationships between SOM, POM, sugar contents and aggregate stability (Neufeldt et al., 1999). Castro Filho et al. (1998) also found a close relationship of soil organic carbon and aggregate stability in a Ferralsol of the Parana state. Over a wide range of soils, however, no consistent conclusion on the effects of SOM properties on aggregation could be gathered, as shown by Feller and Beare (1997).

Apart from organic matter, Fe and Al complexation may also play an important role in SOM stabilization within aggregates of Ferralsols in contrast to temperate soils (Gijsman, 1996). Oades and Waters (1991) even stated that micro-aggregation of Ferralsols are generally controlled by oxides. Complexation by oxides was not the main reason for the aggregation of Cerrado Ferralsols (Neufeldt et al., 1999) but the soils in the central Amazon possess completely different mineralogy and chemical properties than those of the Cerrado. They contain more kaolinite, have lower pH and higher Al saturation than Cerrado Ferralsols (Demattê and Demattê, 1993). Aggregating effects of SOM may be limited under low pH conditions and high Al saturation in the Amazon, whereas the high contents of Fe and Al oxides in the Cerrado soils form strong complexes with the SOM as described by Boudot et al. (1989).

3.5. Single-tree effects on aggregation and sensitive SOM pools

The aggregate stability was significantly higher in soils under cupuaçu than under pueraria, the other sites being in between (Table 4). As it was expected from the results described above, high aggregate stability could not be explained with any investigated physical (Table 4) or chemical SOM pool (Table 5). Castro Filho et al. (1998) concluded from long-term experiments in eastern Brazil that litter input with high C-to-N ratios increased aggregate stability. This would explain the higher aggregate stability of soils under cupuaçu in comparison to the other agroforestry species, but not in comparison to the fallow and primary forest sites.

Bulk soil SOM was significantly higher in the primary forest under bacaba than at all other sites (Table 4). Differences in POM amounts were a lot clearer than those in the bulk soil. Soils from bacaba sites had 4.5 times more POM than soils under pueraria. Cupuaçu was also more efficient in replenishing POM pools than pueraria ($p < 0.05$) and peachpalm (non-significant). The carbon contents of the aggregate fractions did not show the differences between sites as clearly as the carbon contents of POM, but with the same trends (Table 6). Among the aggregate separates, the fraction, 0.25–0.5 mm, showed the single-tree effects the most, being also the fraction where carbon contents increased the most by separating POM* and the primary particles (Lehmann et al., 1998a).

The bulk soil nitrogen contents were not significantly different between sites, but single trees showed significant effects on POM nitrogen contents and amounts (Table 4). Soils under pueraria had high POM nitrogen contents, which could be explained by its high foliar and root nitrogen contents (Table 7). Due to the low amount of POM, however, the nitrogen amounts of pueraria soils were low. On the other hand, the nitrogen contents in the fraction, 0.25–0.5 mm, were significantly higher under pueraria than at the other sites apart from bacaba (Table 6). The high quality of the pueraria litter with low C-to-N and polyphenol-to-N ratios (Table 7) probably led to a high carbon and nitrogen mineralization, which was the reason for the rapid incorporation of nitrogen into aggregates and the low total amount of POM under pueraria. The high nitrogen content in the POM of the pueraria soils may explain the high nitrogen

Table 4
Ratio of MWD_{wet}-to-MWD_{dry}, carbon and nitrogen contents and amounts (mg g^{-1}) and C-to-N ratios in bulk soil and POM of Xanthic Ferralsols under cupuaçu, peachpalm, pueraria, vismia and bacaba on the terra firme near Manaus, Brazil; values in one column followed by the same letter are not significantly different at $p < 0.05$ ($n = 3$)

Sites	MWD_{wet} to-MWD_{dry} ratio	C			N			C-to-N	
		Bulk soil	POM content	POM amount	Bulk soil	POM content.	POM amount	Bulk soil	POM
Cupuaçu	0.89 a	31.0 b	289 b	6.31 b	2.5	13.7 ab	0.29 b	12 c	21 ab
Peachpalm	0.84 ab	25.3 b	238 c	3.59 bc	2.4	11.1 c	0.18 b	11 c	22 ab
Pueraria	0.82 b	27.9 b	258 bc	2.78 c	2.4	14.6 a	0.17 b	11 c	18 b
Vismia	0.84 ab	29.7 b	340 a	6.74 b	2.2	13.1 ab	0.28 b	14 b	27 a
Bacaba	0.83 ab	47.4 a	277 b	12.60 a	2.9	11.7 bc	0.54 a	16 a	24 ab
Effect	(*)	**	**	*	ns	*	*	**	(*)

(*) $p < 0.1$.
* $p < 0.05$.
** $p < 0.01$.

Table 5

Lignin, ac-to-al ratio, CS and NCS sugars in bulk soil and POM of Xanthic Ferralsols under cupuaçu, peachpalm, pueraria, vismia and bacaba on the terra firme near Manaus, Brazil; values in one column followed by the same letter are not significantly different at $p < 0.05$ ($n = 3$)

Sites	VSC[a] (mg g^{-1}C)		ac-to-al ratio[a]		VSC-to-N (‰)		CS[a] (mg g^{-1}C)		NCS[a] (mg g^{-1}C)		NCS-to-CS ratio	
	Bulk	POM	Bulk	POM	Bulk	POM	Bulk	POM	Bulk	POM	Bulk	POM
Cupuaçu	16.8 ab	30.9 ab	0.36	0.22	209 b	650 bc	45.6 a	29.1 a	263	181 c	5.9 c	6.2 b
Peachpalm	18.2 ab	42.8 a	0.57	0.24	196 b	895 b	39.6 a	30.8 a	352	320 a	9.1 bc	11.0 a
Pueraria	14.8 b	29.2 ab	0.48	0.24	170 b	497 bc	38.4 a	25.5 ab	313	258 ab	8.7 bc	10.2 a
Vismia	16.1 ab	17.7 b	0.34	0.24	220 b	458 c	27.8 b	22.1 b	412	184 c	15.0 ab	8.3 ab
Bacaba	25.2 a	43.4 a	0.37	0.25	407 a	1014 a	15.0 c	20.9 b	289	213 b	19.7 a	10.2 a
Effect	(*)	*	ns	ns	**	(*)	***	*	ns	**	*	(*)

ns, Not significant.

[a] VSC, lignin compounds; CS, cellulosic sugars; NCS, non-cellulosic sugars; ac-to-al ratio of acids to aldehydes of the vanillyl compounds.

(*) $p < 0.1$.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

Table 6

Carbon and nitrogen contents of aggregate fractions with 2–1, 1–0.5, 0.5–0.25, 0.25–0.02 and < 0.02 mm diameter of Xanthic Ferralsols under cupuaçu, peachpalm, pueraria, vismia and bacaba on the terra firme near Manaus, Brazil; means and level of significance ($n = 3$); values in one row followed by the same letter are not significantly different at $p < 0.05$

	Fraction (mm)	Cupuaçu	Peachpalm	Pueraria	Vismia	Bacaba	Effect
Carbon	2–1	25.9	25.8	28.6	28.8	31.6	ns
	1–0.5	26.6	21.0	22.8	22.9	29.8	ns
	0.5–0.25	18.2 bc	16.0 bc	20.9 b	13.8 c	27.6 a	* *
	0.25–0.02	34.2 b	27.7 b	29.7 b	35.5 b	53.8 a	*
	< 0.02	37.7	29.4	33.6	38.2	38.9	ns
Nitrogen	2–1	2.43	2.44	2.77	2.56	2.62	ns
	1–0.5	2.46	2.03	2.18	2.05	2.40	ns
	0.5–0.25	1.76 ab	1.60 b	2.16 a	1.30 b	2.22 a	*
	0.25–0.02	2.98	2.59	2.73	2.92	3.72	ns
	< 0.02	3.55	3.05	3.62	3.39	3.48	ns
C-to-N ratio	2–1	10.7	10.6	10.3	11.2	12.0	ns
	1–0.5	10.8 b	10.3 b	10.5 b	11.1 b	12.4 a	*
	0.5–0.25	10.4 b	10.0 b	9.7 b	10.6 b	12.5 a	*
	0.25–0.02	11.2	10.5	10.6	11.7	13.9	* *
	< 0.02	10.6	9.6	9.3	11.3	11.2	ns

ns, Not significant.

* Significant at $p < 0.05$.

* * Significant at $p < 0.01$.

mineralization rates under pueraria compared to soils under cupuaçu and peachpalm measured at the same site (E. Salazar, unpublished data). With ^{15}N-labeled leaves, Vanlauwe et al. (1998) could show that litter N of *Leucaena leucocephala* was mainly found in the light fraction of the sand size separates 53 days after application (60%), but consecutively decreased and was mainly recovered in the silt and clay fractions at 858 days after application (80%).

Table 7

Nitrogen, polyphenol contents, C-to-N and polyphenol-to-N ratios of cupuaçu, peachpalm, pueraria and vismia leaves and roots (diameter < 2 mm from 0–0.1-m depth)

Sites		N (mg g^{-1})	Polyphenol (mg g^{-1})	C-to-N ratio	Polyphenol-to-N ratio
Cupuaçu	Leaves	17.7	10.0	28.3	0.57
	Roots	7.8	10.4	59.2	1.33
Peachpalm	Leaves	39.2	11.3	11.8	0.29
	Roots	7.4	2.6	60.5	0.35
Pueraria	Leaves	46.2	16.6	8.9	0.36
	Roots	13.4	3.0	33.4	0.22
Vismia	Leaves	13.8	29.7	33.2	2.15
	Roots	9.7	19.6	46.3	2.02

The opposite was observed for bacaba at our site, where POM nitrogen contents were low but the amounts were high. The long-term organic matter and nitrogen input into the soils under primary forest increased carbon and nitrogen contents in bulk soil and POM amounts. Low litter quality may have promoted the SOM accumulation in POM and the whole soil. Thus, soils under bacaba possessed high contents of unoxidized lignin together with high VSC-to-N and C-to-N ratios but low carbohydrate contents in POM and total SOM (Tables 4 and 5). This may serve as a way of nutrient preservation in order to release only as many nutrients as needed for plant growth. That high amounts of mineral nitrogen were found in the subsoil of the primary forest sites compared to the secondary forest (Schroth et al., 1999) emphasizes the need for a temporary nutrient sink in SOM.

Unexpectedly, the high foliar nitrogen contents of peachpalm (39.2 mg g^{-1}; Table 7) did not result in a high POM nitrogen content and amount. The low nitrogen contents in POM fractions from smaller aggregates confirmed this result (Table 8). The organic matter derived from peachpalm leaves did not seem to enter POM and may not contribute to stable SOM as indicated by the low soil carbon contents under peachpalm. The VSC signatures and the carbohydrate contents under peachpalm were very high compared to the other soils. The foliar and root polyphenol contents could not explain this accumulation of lignin (Table 7). The low effects of peachpalm on SOM and even on nitrogen

Table 8
Amount, carbon and nitrogen contents, and amounts of POM from 2–1, 1–0.5 and 0.5–0.25 mm fractions of Xanthic Ferralsols under cupuaçu, peachpalm, pueraria, vismia and bacaba on the terra firme near Manaus, Brazil ($n = 2$)

	Fraction (mm)	Cupuaçu	Peachpalm	Pueraria	Vismia	Bacaba
Weight (%)	2–1	0.89	0.90	0.68	1.31	2.54
	1–0.5	0.57	0.71	0.37	0.68	1.62
	0.5–0.25	0.60	0.38	0.32	0.46	0.77
C contents (mg g^{-1})	2–1	306	260	251	328	284
	1–0.5	238	201	208	227	255
	0.5–0.25	228	177	256	289	309
C amounts (mg g^{-1})	2–1	2.72	2.31	1.64	4.12	7.14
	1–0.5	1.25	1.43	0.79	2.24	4.13
	0.5–0.25	1.36	0.59	0.78	1.30	2.42
N contents (mg g^{-1})	2–1	14.8	12.0	14.1	14.2	11.9
	1–0.5	13.2	10.9	13.4	15.5	11.7
	0.5–0.25	13.5	10.6	16.8	15.1	14.0
N amounts (mg g^{-1})	2–1	0.13	0.11	0.10	0.18	0.31
	1–0.5	0.07	0.08	0.05	0.11	0.19
	0.5–0.25	0.08	0.04	0.03	0.07	0.11
C-to-N ratio	2–1	21.1	21.6	17.9	23.1	24.0
	1–0.5	18.1	18.5	15.5	21.2	21.8
	0.5–0.25	17.0	16.6	15.2	19.3	22.1

contents in POM may be explained by the low total amounts of leaf litter compared to pueraria, low nitrogen contents in roots and low root abundance at the soil surface (0–5 cm) producing small amounts of litter with low polyphenol-to-N ratios (Table 7).

The soil carbon replenishment under cupuaçu was characterized by an enrichment of low degradable litter with low nitrogen contents and high C-to-N and polyphenol-to-N ratios compared to the other agroforestry tree species (Tables 5 and 7). The POM lignin and plant-derived sugars also made up a large proportion of the carbon, whereas the contents of microbially derived sugars were lowest among all sites. In POM, as well as in the bulk soil, the ratio of NCS-to-CS was lowest under cupuaçu, indicating a low microbial degradation of plant litter. Accordingly, McGrath (1998) found more than 60% of cupuaçu but less than 30% of peachpalm litter undecomposed in a litterbag study after 1 year.

High NCS-to-CS ratios were found in the bulk soils of the primary and secondary forest sites indicating a high proportion of microbially derived sugars, which hints at high microbial activity (Table 5). On the other hand, the C-to-N ratios were significantly higher than below the trees in the agroforestry systems (Table 4), which would hint at low decomposition rates and an accumulation of plant material. The low C-to-N ratios of soils in the agroforestry system (cupuaçu, peachpalm, and pueraria) were mainly caused by fertilization and biological nitrogen fixation of the pueraria. The added fertilizer nitrogen did not lower the C-to-N ratios of the POM, whereas the fixed nitrogen of the pueraria actually decreased the POM C-to-N ratios. However, despite these nitrogen additions to soil, more weakly decomposed plant material accumulated in the agroforestry system than in the primary and secondary forest sites, as seen from the NCS-to-CS ratios. One reason may be a lower soil fauna abundance (Römbke et al., 1999) in the agroforestry system than in the primary forest.

3.6. Processes of SOM replenishment in Ferralsols of the central Amazon

Partially decomposed leaves and roots become the POM. POM decomposition and humification progressed from POM associated with large aggregates to those associated with small aggregate fractions with decreasing C-to-N ratios (Table 8). The carbon and nitrogen POM amounts generally decreased with decreasing aggregate size. The POM associated with small aggregate separates (0.25–0.5 mm) was largely humified plant material, whereas POM from large aggregates (1–2 mm) mainly consisted of leaf and root debris. In aggregate separates smaller than 0.25 mm, no POM could be isolated.

Carbon or nitrogen distribution in different POM size fractions showed the same differences between sites as whole POM contents. Differences in smaller POM fractions (0.25–0.5 mm) between sites should indicate different effects of trees on stable SOM replenishment, whereas differences in larger POM fractions rather indicate different tree effects on soil nutrient availability. For most purposes, a separation of whole POM will be sufficient to evaluate single-tree effects on SOM.

During decomposition and humification, the added organic material was incorporated into larger aggregates and successively into smaller aggregates, which was shown by soil chemical analyses. This result supports the hierarchical model of aggregation of Tisdall and Oades (1982), which could not be verified by using only the carbon distribution in aggregate separates. The strongly humified POM is incorporated into the fraction 0.25–0.5 mm, since (i) it contained the highest proportion of POM*, (ii) no significant amounts of visible POM smaller than 0.25 mm were found, and (iii) the smaller fraction, 0.02–0.25 mm, showed the highest carbon contents of all aggregate fractions. This was also confirmed by the shift of the VSC values, ac-to-al, VSC-to-N and C-to-N ratios from the aggregates 0.5–1 to 0.25–0.5 mm (Table 1).

4. Conclusions

Using aggregate fractionation, together with the chemical characterization of SOM, the processes of incorporation of plant litter into stable SOM could be successfully studied in the strongly aggregated Ferralsols of the terra firme near Manaus. Thus, it could be shown that aggregation promoted the stabilization of SOM, but differences in SOM amounts were not related to aggregate stability. The POM was an important and valid indicator of the effects of different organic inputs on SOM properties. It could be used for assessing the effects of single trees on SOM of the studied Ferralsols. In the fraction 0.25–0.5 mm, strongly humified POM was incorporated into aggregates. This was the aggregate fraction most sensitive to land-use changes.

Cupuaçu increased SOM contents in comparison to peachpalm or pueraria, which could be related to the low quality organic matter of cupuaçu litter. Despite the similarly low foliar C-to-N ratios of peachpalm and pueraria, peachpalm did not replenish nitrogen contents of the labile SOM.

The investigation of factors controlling humification should be intensified. The relationship between aggregation and SOM is still poorly understood but could yield relevant information about SOM stabilization in these strongly aggregated soils.

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