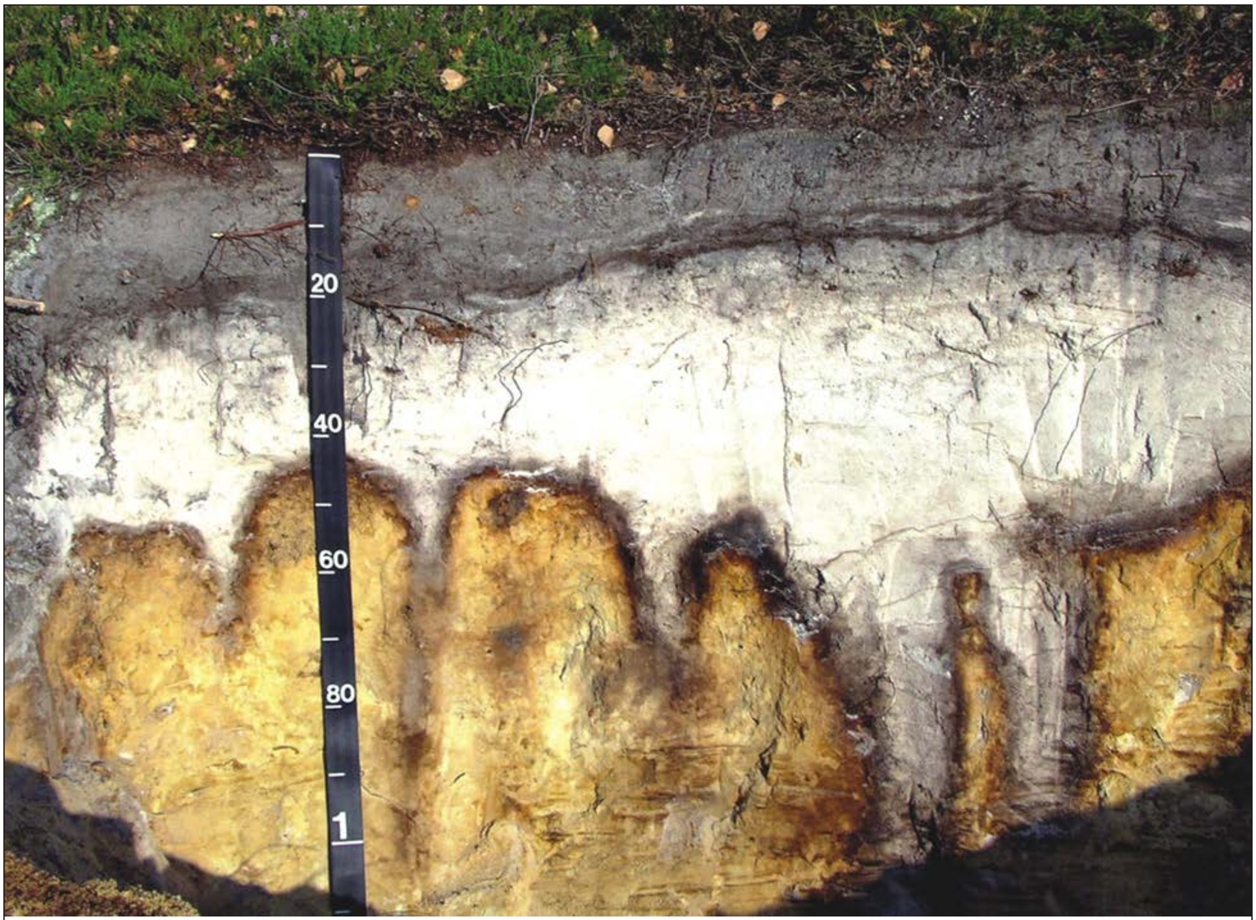

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Carbon and Nitrogen Storage in Soil Aggregates from Different *Terminalia superba* Age Plantations and Natural Forest in Kouilou, Congo

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Abstract: A comparative study was carried out in Mayombe, between the soil of natural forest and the soil under three *Terminalia superba* plantations of 7, 12 and 48 year-old. In each plantation type and natural forest composite soil samples were taken in 0-10 cm layer. The goal was to investigate the dynamic of total carbon and nitrogen in whole and soil aggregate fraction in order to assess the impact of reforestation on the soil fractions. Organic carbon was analyzed by the modified Walkey and Black method. Total nitrogen was determined using the Kjeldhal procedure. Statistically differences between the sites were tested using the Analysis of Variance (ANOVA). The results showed that in the surface soil the carbon content and total nitrogen were respectively 22.2 and 1.56 μg g^{-1} in the forest. The carbon content was between 14.9 and 23.5 mg g^{-1} while total nitrogen was between 1.31 and 2.24 μg g^{-1} in the plantations. The results also revealed that plantation aging had a marked impact on the total carbon and nitrogen concentration of soil aggregate fractions. The carbon and the nitrogen associated with the sand and the clay exhibited a significant increase. The carbon concentration was between 1.51 and 2.09 mg g^{-1} in the light aggregate fractions and between 0.95 and 1.04 mg g^{-1} in the organomineral aggregate fraction. The accumulation of total carbon in the whole soil and soil aggregate fractions and their increase during plantation aging suggested that the *T. superba* plantations could facilitate significant carbon storage.

Key words: Soil organic fraction, aggregate fraction, *Terminalia superba*, reforestation

INTRODUCTION

Soil organic matter influences soil chemical and biological properties that control nutrient cycling and consequently has a major effect on forest productivity and sustainability. Due to the important role of soil organic matter in nutrient cycling, there has been an interest in understanding how forest and management affects soil organic matter pools (He *et al*., 2008). Soil organic matter is considered to be a major component in the evaluation of soil quality changes after the conversion of natural vegetation into cultivation. Its use most focus on active forms which are thought to be involved in supplying nutrients for plant growth and are the first depleted as result of system perturbations. These active fractions include particle organic matter, microbial biomass and specific respiration (Zagal *et al*., 2009; Sikora *et al*., 1996; Koutika *et al*., 2002). The role of soil physical structure is important as determinant of soil organic matter sequestration (Christensen, 2001; Six *et al*., 2004). Afforestation or reforestation is known to affect the distribution of organic matter in either particulate soil organic matter or organomineral aggregates (Guggenberger and Zech, 1999), microbial biomass and specific respiration (Sikora *et al*., 1996). The investigation of physical location and chemical composition of soil organic matter within the soil environment might be relevant to assess the impact of land use on soil fertility. Analyses of soil physical structure are usually conducted using physical fractionation methods, which are based on the premise that the association of the primary soil particles and their spatial arrangement play a key role in the function of soil organic matter (Gregorich *et al*., 2006; He *et al*., 2008). Physical fractionation techniques can augment the detection limits for soil organic matter dynamics by isolating soil organic matter more sensitive to changes in land use and management and thus has been widely utilized to distinguish specific carbon and nitrogen pools responsive to land use and management (Christensen, 2001; Six *et al*., 2002; He *et al*., 2008). According to He *et al*. (2008) elucidation of the interactive relationships between different soil organic matter functional pools and the corresponding soil chemical and biological processes are warranted for improved research into land use and management issues forests.

In the Mayombe of Kouilou region several hectares of native forest are converted each year into monospecific plantation forests either with native species *Terminalia superba* or with exotic species such as eucalypt, pine and acacia, in order to meet the increasing demand for the timber. Reforestation with these species is one of the most wide spread changes in land use in Kouilou region. The *T. superba* plantations have been recently investigated for soil organic matter concentration (Goma-Tchimbakala and Makosso, 2008). Long term impacts of afforestation and reforestation on soil organic matter into aggregate size fractions have not been reported for the kouilou region. Research regarding the effects of reforestation, on soil organic quality, with *T. superba* plantation aging will help to determine the potential of recovery of these soils for carbon sequestration.

The purpose of this study was to assess changes in soil organic matter quality due to reforestation with *T. superba* in Mayombe in comparison with natural forest soil characteristics.

MATERIAL AND METHODS

Site Description

The sites were previously described by Goma-Tchimbakala and Bernhard-Reversat (2006). Briefly they are located at Bilala in the Mayombe at 4°31'S, 12°4'E and above mean sea level 300 m altitude. Mean annual rainfall is 1250 mm. Relative humidity is high all over the year close to 85%. The temperature ranges from 28°C in the rainy season to 18°C in the dry season. The soil is desaturated ferralitic and lies on sandy-clayey or clayey-sandy material resulting from the weathering of cretaceous green rock and dolomitic limestone. In this study the clay content has narrow range from 27 to 29% in the surface soil (Table 1). *Terminalia superba* plantations were established by the National Reforestation Service (SNR) after clear cutting the forest and burning all plants residues. Tree spacing was

Table 1: Average particle size distribution of the surface soil under *T. superba* plantations and natural forest

		Terminalia superba		
Soil properties	Natural forest	7 years	12 years	48 years
Sand	53.8±0.3	54.5±0.2	54.3±0.2	52.6±0.2
Silt	18.1±0.3	16.2±0.3	16.6±0.3	18.8±0.2
Clay	27.9±0.2	28.6±0.3	28.7±0.3	28.4±0.2

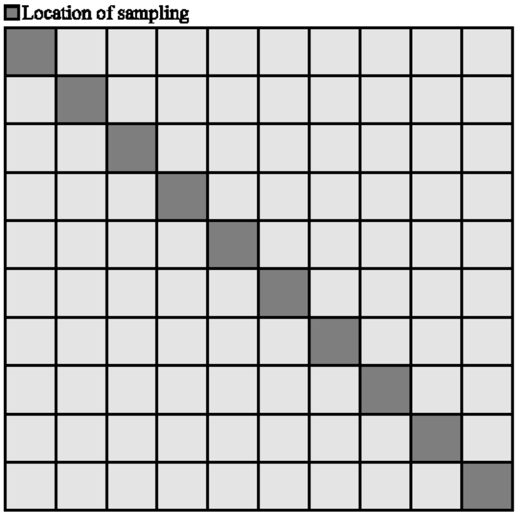

Fig. 1: Map of sampling in *T. superba* plantations and natural forest. Original map sampling site made by the author during the processing of the thesis

10×10 m. During the two first years the undergrowth was clear cut. Three plantations of 7, 12 and 48 years old were chosen for this study. The undergrowth vegetation was well developed in the planted plots and the Fabaceae, Annonaceae, Euphorbiaceae, Moraceae, Marantaceae and Menispermaceae were the most numerous plant families. The nearby natural forest was used for comparison with the planted plots. The most represented tree families in the natural forest are the Cesalpiniaceae, followed by the Rubiaceae and the Euphorbiaceae. All the stems larger than 10 cm Diameter at Breast Height (DBH) were listed together with the plants of the understory (Goma-Tchimbakala and Bernhard-Reversat, 2006).

Soil Sampling, Fractionation and Chemical Analyses

Soil samples were collected from ten systematically located squares (1 m^2 for each square) in each plantation type and natural forest (Fig. 1). In each square two composite soil samples were taken in 0-10 cm layers. Each composite soil sample was combined from four cores from a layer. Samples for chemical analyses were air-dried and then were passed through a 2 mm mesh soil sieve.

Soil aggregate size fractionation was achieved by a wet-sieving method (Balesdent *et al*., 1991). The soil fractionation was performed by sieving under water, to sort three light organic fractions (F_1: 0.5-2 mm; F_2: 0.2-0.5 mm; F_3: 0.05-0.2 mm) and one organomineral fraction (F_4<0.05 mm).

All fractions were dried and then they were analyzed at the same time with the whole soil for C and N. Organic carbon was analyzed by the modified Walkey and Black method. Total nitrogen was determined using the Kjeldhal procedure.

Calculation of Organic Carbon and Nitrogen Storage and Statistical Analysis

Using the measurement mentioned above, plantations and forest organic carbon and organic nitrogen storage were calculated as:

$$\text{C storage} = 10^{-6}\times C\times S\times BD\times d$$

$$\text{N storage} = 10^{-6}\times \text{N}\times \text{S}\times \text{BD}\times \text{d}$$

where, C is the organic carbon concentration of the soil, N is the organic nitrogen concentration of the soil, S is the area of the calculated soil (ha), BD is the bulk density of the measured soil layer (g cm^{-3}), d is the depth (10 cm) of the measured soil layer.

Data were analyzed with Stat View software. A one-way Analysis of Variance (ANOVA) model was used for individual treatment comparisons at $p<0.05$, with separation of mean by the Protected Least Significant Differences (PLSD) Fisher test. The determination of differences in soil organic carbon and soil organic nitrogen between aggregate fractions was performed using a two-way ANOVA with factors being age of plantations and the aggregate-size fractions.

RESULTS

Soil Organic Carbon and Soil Organic Nitrogen Concentration

The results showed that soil organic carbon and organic nitrogen were significantly influenced by the *T. superba* plantations and natural forest ($p<0.001$; Table 2, 3). The soil surface in the 7-year-old plantation had the lowest soil organic carbon content whereas the highest content was recorded under the mature plantation (48-year-old). Soil organic carbon content increased with the aging of plantations. Comparison of mean differences among sites revealed that the 48-year-old plantation had similar soil organic carbon with the natural forest (Table 2). Organic nitrogen showed the same trend as soil organic carbon content in the plantations. The 7-year-old plantation had significantly low organic nitrogen content while the 48-year-old plantation had the highest content. However, comparison between the sites showed that the soil of natural forest had low nitrogen content than plantation 48-year-old. However, total nitrogen in natural forest was not different with the 12-year-old plantation.

Soil Organic Carbon and Soil Organic Nitrogen Storage

Soil bulk density (Table 2) was used for calculation of total soil organic carbon and soil organic nitrogen on a per-hectare. The soil organic carbon and soil organic nitrogen were significantly influenced by *T. superba* plantations and the forest (Fig. 2a, b). The soil organic carbon under plantations was highest for *T. superba* 48 years and under *T. superba* 7 years was lowest. Comparison between plantations and forest showed that soil organic carbon was

Table 2: Soil density, organic carbon and total nitrogen concentrations and standard deviation under *T. superba* plantations and natural forest at 0-10 cm depth

		Age of *T. superba* (years)		
Factors	Natural forest	7	12	48
Density (g cm^{-3})	1.40±0.20	1.50±0.20	1.46±0.20	1.45±0.20
Organic carbon (mg g^{-1})	22.20±0.36	14.90±0.18	15.90±0.28	23.50±0.13
Total nitrogen (μg g^{-1})	1.56±0.14	1.31±0.05	1.46±0.07	2.24±0.07

Table 3: ANOVA of soil organic and total nitrogen

	Organic carbon		Total nitrogen	
Parameters	F-value	p-value	F-value	p-value
Horizon 0-10 cm	9705.90	***	567.01	***
Aggregate size fractions	3729.32	***	937.26	***
Plantations	216.58	***	18.78	***
Aggregate size fractions *plantations	64.18	***	20.96	***

***$p<0.0001$; **$p<0.001$; *$p<0.05$

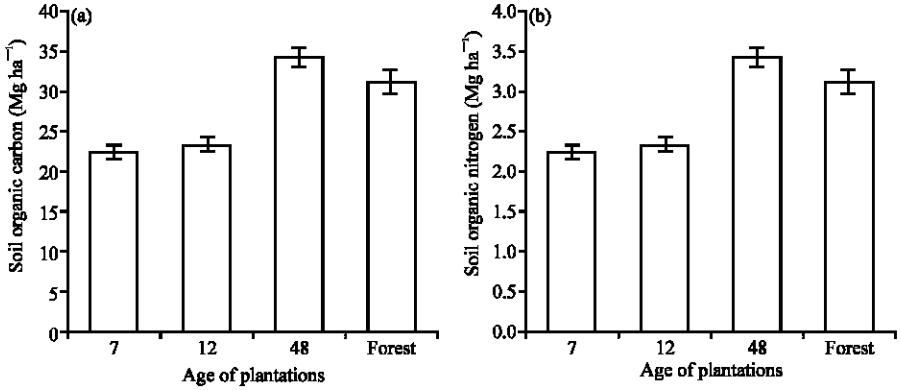

Fig. 2: Soil organic (a) carbon and (b) nitrogen storage under *T. superba* plantations and natural forest. Error bars represents the error standard of the mean

higher for *T. superba* 48 years (3407 kg ha^{-1}) than under forest (3108 kg ha^{-1}) and the other plantations (2235 kg ha^{-1} for *T. superba* 7 years and 2321 kg ha^{-1} for *T. superba* 12 years, respectively). Soil organic nitrogen exhibited similar responses to plantations and forest as soil organic carbon. *T. superba* 48 years had the highest soil organic nitrogen (32.5 kg ha^{-1}) and the lowest soil organic nitrogen was under *T. superba* 7 years (19.6 kg ha^{-1}). Soil nitrogen storage under the forest was low (21.8 kg ha^{-1}) than *T. superba* 48 years (32.5 kg ha^{-1}). However, the storage under forest was higher than under *T. superba* 7 and 12 years.

Distribution of Organic Carbon and Organic Nitrogen among Aggregate-Size Fractions

The soil organic carbon concentrations were significantly impacted by *T. superba* plantations and natural forest (Fig. 3a-d). Soil organic carbon in F1 fraction was highest under *T. superba* 48 years whereas the lowest and similar concentrations were recorded under the 7-12-year-old *T. superba.* Natural forest had high soil organic carbon than *T. superba* 7-12 years. However, soil organic concentration in natural forest was low than in *T. superba* 48 years. In F2 fraction organic carbon concentration under *T. superba* 7-12 years was similar and low than under *T. superba* 48 years and natural forest. Comparison of mean showed that the highest organic carbon was under natural forest ($p<0.0001$). Soil organic carbon in F3 fraction was significantly different between the sites ($p<0.0001$). The concentration was lower under natural forest while highest concentration was under *T. superba* 48 years. The PLSD Fisher test showed that among plantations the lowest soil organic carbon was under *T. superba* 7 years ($p<0.0001$). In F4 fraction soil organic carbon under *T. superba* 7 years was low while fraction under *T. superba* 12-48 years had high and similar concentrations. Apart between the soil organic carbon in the F3 and F4 fraction under *T. superba* 48 years, there were significant differences between the soil organic concentrations of the fraction in all sites ($p<0.0001$). ANOVA showed that soil organic carbon was significantly influenced by the interaction between site and the fraction ($p<0.0001$).

The soil organic nitrogen in F1 fraction was similar under *T. superba* 7 years and natural forest (Fig. 4a-d). The highest concentration was in fraction under *T. superba* 48 years whereas the lowest concentration was under *T. superba* 12 years ($p<0.0001$). In F2 fraction, similar concentrations were recorded under *T. superba* 7 years and *T. superba* 48 years. The concentration in these two sites was higher than in *T. superba* 12 years. Soil organic nitrogen

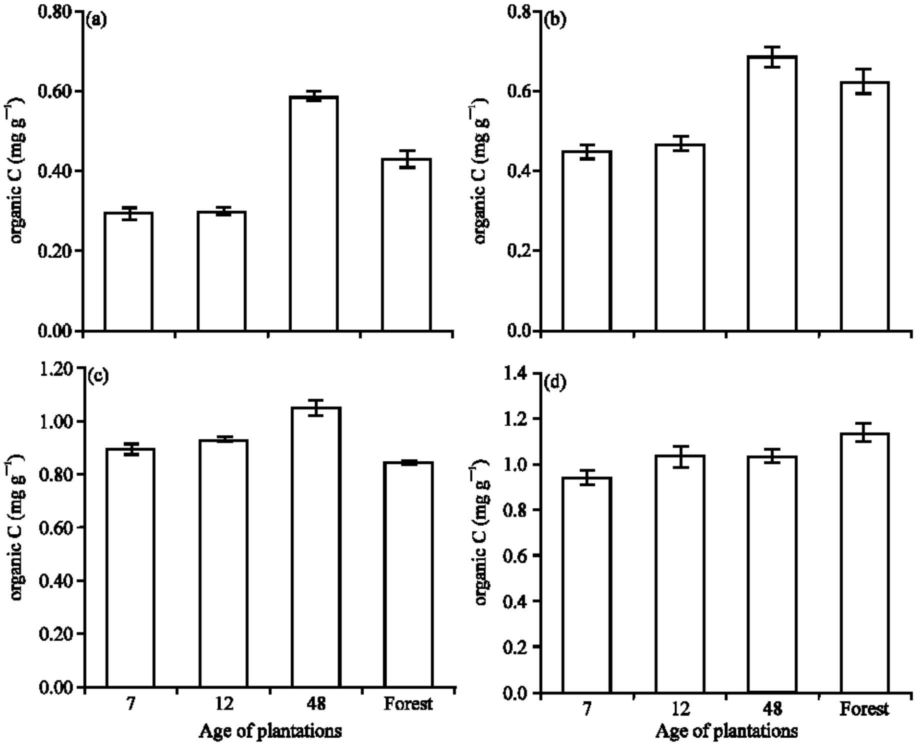

Fig. 3: Distribution of organic carbon among aggregate size fractions under *T. superba* plantations and natural forest. Error bars represent the error standard of the mean. (a) F1: 0.5-2 mm, (b) F2: 0.2-0.5 mm, (c) F3: 0.05-0.2 mm and (d) F4: <0.05 mm

under natural forest was higher than obtained under all plantations. Soil organic nitrogen in F3 fraction was significantly different between the sites ($p<0.0001$). Comparison of mean showed among the plantations, *T. superba* 12 and *T. superba* 48 years had comparable and high organic nitrogen concentration while *T. superba* 7 years had low concentration. Soil organic nitrogen was similar natural forest and *T. superba* 7 years. On the other hand, this concentration was low than of *T. superba* 12 and 48 years. The highest soil organic nitrogen content in F4 fraction was under natural forest and the lowest was under *T. superba* 48 years ($p = 0.0033$). The PLSD Fisher test showed that there was no difference in soil organic nitrogen concentration on one hand between *T. superba* 7 years and *T. superba* 48 years and on the other hand between *T. superba* 12 years and natural forest. In each site, apart the similar content between F1 and F2 fractions in *T. superba* 7 years and *T. superba* 12 years, soil organic concentrations were significantly different between the fractions (Table 3). On the other hand, the interaction site-fraction had significant task on the distribution of soil organic nitrogen (Table 3).

DISCUSSION

The findings indicated that organic carbon and total nitrogen in surface soil increased with aging of plantation due to accumulation of organic matter resulting of high litterfall and low decomposition (Goma-Tchimbakala and Bernhard-Reversat, 2006). Apart in the soil under the 48-year-old plantation, the amount of organic matter under plantations was lower than

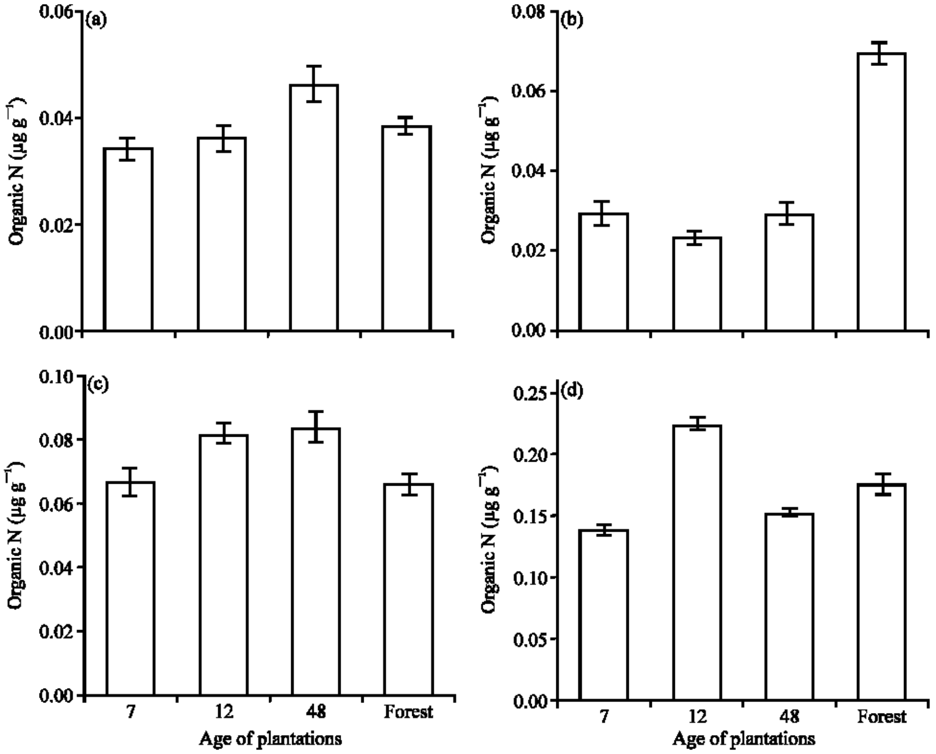

Fig. 4: Distribution of organic nitrogen among aggregate size fractions under *T. superba* plantations and natural forest. Error bars represent the error standard of the mean. (a) F1: 0.5-2 mm, (b) F2: 0.2-0.5 mm, (c) F3: 0.05-0.2 mm and (d) F4 <0.05 mm

in the natural forest due to the lack of litter return in the young plantations, high mineralization of organic matter, losses of organic matter by water erosion (Paul *et al*., 2002; Jaiyeoba, 2003; Yimer *et al*., 2007).

Taking account of the measured bulk densities greater C and N sequestration for *T. superba* 48-year-old plantation than other plantations or forest may be due to differences in aggregation, high organic matter input through the litter return and decomposition (Goma-Tchimbakala and Makosso, 2008), N contents of residues or differences in biochemical aspects of residues. Residue quality often plays an important role in regulating long-term soil organic matter storage (Wright and Hons, 2005). Residues with low C/N ratios stimulated decomposition of native soil organic matter to a greater extent than residues with higher C/N ratios. Average N contents of residues varied, with *T. superba* of 7 and 12 years residues having lower N concentrations than *T. superba* 48 years and forest (Goma-Tchimbakala and Bernhard-Reversat, 2006). In this study soil organic matter storage increased with plantation age. Plantation of 48 years had high soil organic matter in surface soil than in surface soil of forest due to their differences in aggregate, litter return and decomposition. The higher nitrogen content of forest residue likely resulted in rapid decomposition contributing to lower soil organic matter for forest than plantations (Goma-Tchimbakala and Makosso, 2008).

The carbon storage influenced greatly the distribution of soil organic carbon in the aggregate size fractions. The finding demonstrated that the structural depletion of soil organic matter in aggregate size fraction observed under the young plantation disappeared progressively due to high level of storage in the mature plantation. Aging of plantations had an apparent impact on the C and N concentrations of soil aggregate fractions and significantly increased the C and N storage in the 0-10 cm layer. The changes in the carbon and nitrogen stocks of the surface soils with plantation aging might reflect the differences in quantity and quality of above- and belowground litter inputs, litter carbon and nitrogen decay and root biomass carbon (Wu *et al*., 2008; He *et al*., 2009). In this study the concentrations of C and N in soil fractions tended to increase with decreasing aggregate size. According to several authors (Zinn *et al*., 2005, 2007; He *et al*., 2009) this is due to the effect of the dilution of SOM through the aggregate. Indeed the results are consistent with a higher humification degree founded in the small aggregate size fractions by others (Tiessen and Stewart, 1983; Diekow *et al*., 2005). The distribution of soil C and N in the aggregates change significantly as the age of plantation increase. Liao *et al*. (2006) demonstrated that the invasion of grasslands by woody plants results in a linear increase in the C concentration of the soil fractions with time. In agreement with several authors (Wright and Hons, 2004; He *et al*., 2009) the ability to sequester more or less C is closely related to N input during the process of plantation aging. Several authors (Saviozzi *et al*., 2001; Plante *et al*., 2006) claimed that the partitioning of C in soil fractions is an important and better indicator of the quality of C because the C in coarse fractions is usually less decomposed and has a high C:N ratio; moreover, an important component of the C absorbed by clay is highly altered and has a low C:N ratio. In this study effect of land use on soil organic carbon is consistent with results from other studies which also have found great influence of land use on organic carbon stores (Davidson and Ackerman, 1993). Generally, conversion to more intensively cultivated agricultural land induces greater changes in soil C pools, due to lasting physical soil disturbance effects of tillage on the distribution and availability of SOM and its turnover (Christensen, 2001). The proportion of SOM recovered vary widely (Christensen, 2001), but generally, soils under permanent vegetation with large return of litter (forests and grassland) show the highest proportions (Guggenberger and Zech, 1999), consistent with the greater recovery of SOM found under plantation in the current study. The proportion of soil organic C and N in the particulate fraction indicate that the clay and silt-sized material had a higher concentration of C and N on a per unit mass basis. This was in agreement with most other studies dealing with SOM fractionation (Hassink, 1996; Feller and Beare, 1997; Christensen, 2001). However, the particulate fraction contained the majority of the total C and N in these soils, with significantly more C and N under plantation than under forest. This difference was probably mainly due to the physical and chemical nature of the litter inputs, with the woody roots and above-ground litter of *T. superba* being coarser materials than residues from the tree species in forest.

In summary, the storage of C and N in bulk soil and soil fractions increase significantly during the plantation aging. The increase of soil C storage mainly results from the increase of C concentration in aggregate size fractions. Considering that the accumulation of C in the whole soil and soil fractions showed an increase with plantation aging, *T. superba* plantations could considered having a high potential to accumulate C and N from litter and dead roots. The ability of these soils to sequester C would be closely related to N input.

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