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Acacia and eucalypt change P, N and C concentrations in POM of Arenosols in the Congolese coastal plains[☆]

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ABSTRACT

As an active part of soil organic matter (SOM), particulate organic matter (POM; 4000–50 μm) quickly reveals changes occurring in SOM status after land-use change. To evaluate the impact of planting eucalypts and acacias in the tropical savannas of Congolese coastal plains on SOM quality, we determined P, N and C concentrations in POM in the 0–10 cm layer in afforested stands (pure or in combination) and savannas.

Soil available P in the coarse fraction of POM (cPOM; 4000–250 μm) in afforested stands (> 60 mg kg^{-1}) was higher than in savannas (11 mg kg^{-1}), probably due to both high P content and high decomposition rates of organic residues that have accumulated over a 30-year period. However, only in the afforested stands containing acacias was N concentration ($> 1.50\%$) in cPOM higher than in savannas ($< 1\%$), while the whole soil C content of afforested stands ($> 1.25\%$) was significantly higher than in savannas ($< 0.60\%$). Low C:N ratios of whole soil and cPOM in afforested stands containing only acacia confirmed the improvement of N status in these stands compared with afforested stands of pure eucalypt and mixed-species stands. Planting acacias and eucalypts in the savannas of coastal Congolese plains improved SOM quality of inherently infertile soils. This practice may be used for this purpose in other areas of savanna of surrounding countries of the central Africa.

1. Introduction

Soil organic matter (SOM) is an important reserve of nutrients for plant or tree growth and crop production (Paustian et al., 1990; Swift et al., 1994; Sikora et al., 1996). Its status is strongly linked to vegetation type, soil substrate, climate, landscape and land-use change (Six et al., 1998; Macedo et al., 2007; Plaza-Bonilla et al., 2014). This link is even more pronounced in particulate organic matter (POM), an active component of SOM (Cambardella and Elliot, 1992; Wander, 2004). Studies have shown that POM can reflect changes occurring in SOM status following land-use change, after 9 months to annual cropping systems (Koutika et al., 2001) or after longer periods in forest systems (Versini et al., 2014; Epron et al., 2015).

Fast-growing plantations of eucalypts were established in the 1950s on the inherently infertile soils of the native tropical savannas of the Congolese coastal plains of the Republic of the Congo (Makany, 1964). These plantations cover large areas of savanna in central Africa, reaching an extent of 6 million hectares in Gabon, the Democratic Republic of the Congo and the Republic of the Congo (Schwartz and Namri, 2002), providing wood for the pulp industry and for the energy needs of the rural population (Delwaulle et al., 1978, 1981; Shure et al., 2010). However, their productivity declines sharply with successive rotations due to soil nutrient depletion (Corbeels et al., 2005; Laclau et al., 2003, 2005). In these low-input systems, the nutrients exported at harvest are not replenished with fertilizers, and the nutrient demand of the stands mostly depends on the mineralization of organic residues (Laclau et al., 2005). To sustain these plantations and help restore and improve the fertility of the depleted soils of the Congolese coastal plains, nitrogen-fixing tree species (NFS) such as acacias have been introduced since the 1990s (Bernhard-Reversat, 1993; Bouillet et al., 2013).

In addition to their ability to induce accretion of soil C (Forrester et al., 2013; Koutika et al., 2014), increase forest productivity (Bouillet et al., 2013; Epron et al., 2013), and change faunal and microbial activities and communities (Bernhard-Reversat, 1993; Huang et al., 2014), mixed-species plantations containing acacias reduce soil N deficiency through an increase in N stock and mineralization (Binkley, 1992; Macedo et al., 2007; Tchichelle et al., 2017). Acacias as some other trees have also been shown to alleviate P deficiency due to their ability to access P from deep soil layers and to utilize organic forms of P

Abbreviations: P, Phosphorus; N, Nitrogen; C, Carbon; SOM, soil organic matter; POM, particulate organic matter; NFS, Nitrogen-fixing species; OMF, organo-mineral fraction.

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through the secretion of phosphatase enzymes (Sitters et al., 2013). P deficiency can occur due to its occlusion by Al and Fe oxides in highly weathered soils (Sanchez and Uehara, 1980) and high P demand by N fixing species (Inagaki et al., 2011). This limits the potential contribution of NFS to improve soil fertility and ensure tree growth (Binkley, 1992; Crews, 1993; Crème et al., 2016).

To better understand the role of acacia and eucalypt stands on SOM quality and nutrient cycling in these nutrient-poor soils of the Congolese coastal plains, we measured N, C and P concentrations in POM after more than 30 years of rotational harvests. There were one hypothesis: the large organic residues (litter, leaves, bark), including those left after harvest, result in an increase in the P, N and C concentrations in POM of afforested stands relative to savannas.

2. Materials and methods

2.1. Site description

The experimental plantations of acacias and eucalypts were established on sites located 35 km outside Pointe-Noire city, on the coastal plains close to Tchissoko village in the Republic of the Congo (4° 44′ 41″S & 12° 01′ 51″ E, 100 m in elevation). The annual precipitation is *ca.* 1,200 mm, with a dry season extending from June to September, and the climate is subequatorial (annual air humidity and air temperature of 85% and 25 °C respectively, with a low seasonal variation of 5 °C). The soils of afforested stands and surrounding selected savannas are deep Ferralic Arenosols overlying sandstone dating from the Plio-Pleistocene, and are characterized by a coarse texture (> 90% sand and < 10% clay) and low cation exchange capacity (CEC < 0.5 cmol kg^{-1}) (Mareschal et al., 2011). The soils are low in both total N content (< 0.07%) and C content (0.4–1.18%) (Koutika et al., 2014). Mean soil total phosphorus (P), aluminium (Al), iron (Fe) and manganese (Mn) are respectively 0.06 ± 0.01%, 1.02 ± 0.03%, 0.99 ± 0.03 % 4.8 ± 0.2% in the 0–5 cm surface layer (Koutika et al., 2016).

The area was first afforested in 1984 with pure eucalypt hybrids replacing the original vegetation of native tropical savannah dominated by the poaceae *Loudetia arundinacea* (Hochst.) Steud. This original vegetation is still found in the three selected surrounding savannas. The plantation was harvested in May 2004; an experimental trial consisting of a randomised complete block (4.375 ha of total area, Fig. 1a) with five replications was established and replanted with *Eucalyptus urophylla* S.T. Blake × *E. grandis* Hill ex Maid (18–52) and *Acacia mangium* Wild, with a starter fertilization of 43 kg ha^{-1} of N as ammonium nitrate. Each block contained three stands of 10 × 10 trees (100 trees) at a density of 800 trees ha^{-1}, made up of either 100% *A. mangium* (100A), 100% *E. urophylla* × *E. grandis* (100E) or a 1:1 mixture of the two species (50A50E) (Epron et al., 2013; Tchichelle et al., 2017).

Each stand (1,250 m^2) consisted of an inner plot of 36 trees (6 × 6), flanked by two buffer rows on all sides. In the mixed-species 50A50E stand, the two species were planted alternately along each row. The spacing between rows was 3.75 m, with 3.33 m between the trees of a row (Fig. 1b). These are densities commonly used in commercial plantations and optimal regarding stem wood production in eucalypt monocultures at this site i.e., 800 trees ha^{-1} (Epron et al., 2013). The rotation ended after 7 years and the trees were harvested in January 2012. The debarked commercial-sized boles were removed at harvest while all remaining residues, i.e. branches, bark and leaves were left behind and evenly distributed on the soil surface in each stand. The site was replanted in March 2012 following the same design, with a closely related *Eucalyptus urophylla* × *grandis* hybrid (18–147) and *Acacia mangium* - but with no addition of N fertilizer. However, potassium (K) was supplied three months after planting (150 kg ha^{-1} as KCl) to avoid the risk of K depletion on these highly weathered tropical soils (Epron et al., 2013).

2.2. Soil sampling and preparation

Soils (0–10 cm) were sampled 3 years into the second rotation, in March 2015, in 3 out of the 5 blocks in the afforested stands and in three selected savannas nearby. Nine soil samples (18 for the mixed-species 50A50E stand, i.e., 9 samples collected near an acacia tree, noted 50A(50e), and 9 others near a eucalypt tree, noted (50a)50E) were collected in each plot (1.250 m^2) in 0–0.10 m layer using 5 × 5 cm sampling cylinders in 3 blocks and surrounding savannas. In each plot, three transects (six for the 50A50E) were setup starting at the base of a tree and ending in the centre of the area delimited by four trees. The three soil samples were separated by 0.7 m from each other on each transect (Fig. 1b). In the three surrounding savannas, soil was collected along three transects selected inside an area of the similar surface than the afforested stands. There was no significant difference in texture, soil moisture or tree growth across the selected plots and sites (Epron et al., 2013; Koutika et al., 2014; Tchichelle et al., 2017). Soil sampling was carried out in the 0–0.10 m because SOM dynamics and soil faunal activities are mainly concentrated in the shallow layer in these nutrient-poor soils (d'Annunzio et al., 2008; Epron et al., 2015). A composite sample of 9 samples for each stand and savanna has been made. The soil samples were air-dried, sieved to 4 mm, and root fragments were removed. The water pH (sample:solution ratio 1:5) was measured after the suspensions were shaken for 30 min and equilibrated for one hour using a S47 SevenMulti TM (Mettler Toledo, Switzerland).

2.3. Particulate organic matter

POM was determined according to the method described in Epron et al. (2015). 20 g of air-dried sieved soil, 50 ml of distilled water and five glass beads were introduced in a 100-ml plastic bottle and shaken for 16 h at 25 °C and at 40 rotations per minute in an end-over-end shaker to ensure physical fractionation of SOM. The suspension was wet-sieved to separate the 4000–250 μm, 250–50 μm and 0–50 μm fractions. In the two larger fractions, the organic components were separated from the mineral fraction by decantation. The following fractions were obtained: coarse POM (cPOM, 4000–250 μm), fine POM (fPOM, 250–50 μm), organo-mineral fraction (OMF, < 50 μm), and the coarse and fine mineral fractions (cMIN 4000–250 μm and fMIN, 250–50 μm). Of these, only cPOM, fPOM and OMF composed of organic material are considered in the study presented in this paper. All fractions were dried at 45 °C and weighed. The POM and OMF were ground and analysed for carbon, nitrogen and phosphorus concentration. Total nitrogen and carbon were determined by combustion with an elemental analyser (NCS 2500, Thermoquest, Italy). For resin-extractable P determination, two anion-exchange resin strips (BDH#551642S) each 20 mm × 60 mm were added to 0.5 g (soil) or 0.2–0.4 g (POM fraction) and suspended in 30 ml distilled water. Phosphate adsorbed by the anion-exchange resin was recovered in 30 ml of 0.5 M HCl after shaking for 16 h (100 revs min^{-1}) according to the method of Tiessen and Moir (1993). Malachite reactive P was determined at 630 nm with a GENESYS 10 UV-Visible spectrophometer (Cambridge, UK).

2.4. Statistical analyses

Mean and standard error of the mean were calculated. One-way analyses of variance followed by Tukey's HSD were used to estimate the effect of the type of land use on each measured variable. Differences were considered significant when $P < 0.05$. Pearson correlation coefficients (r) between these measured variables were calculated and considered significant when $P < 0.05$. All statistical analyses were carried out with the R software, version 3.2.4 (R Core Team, 2016).

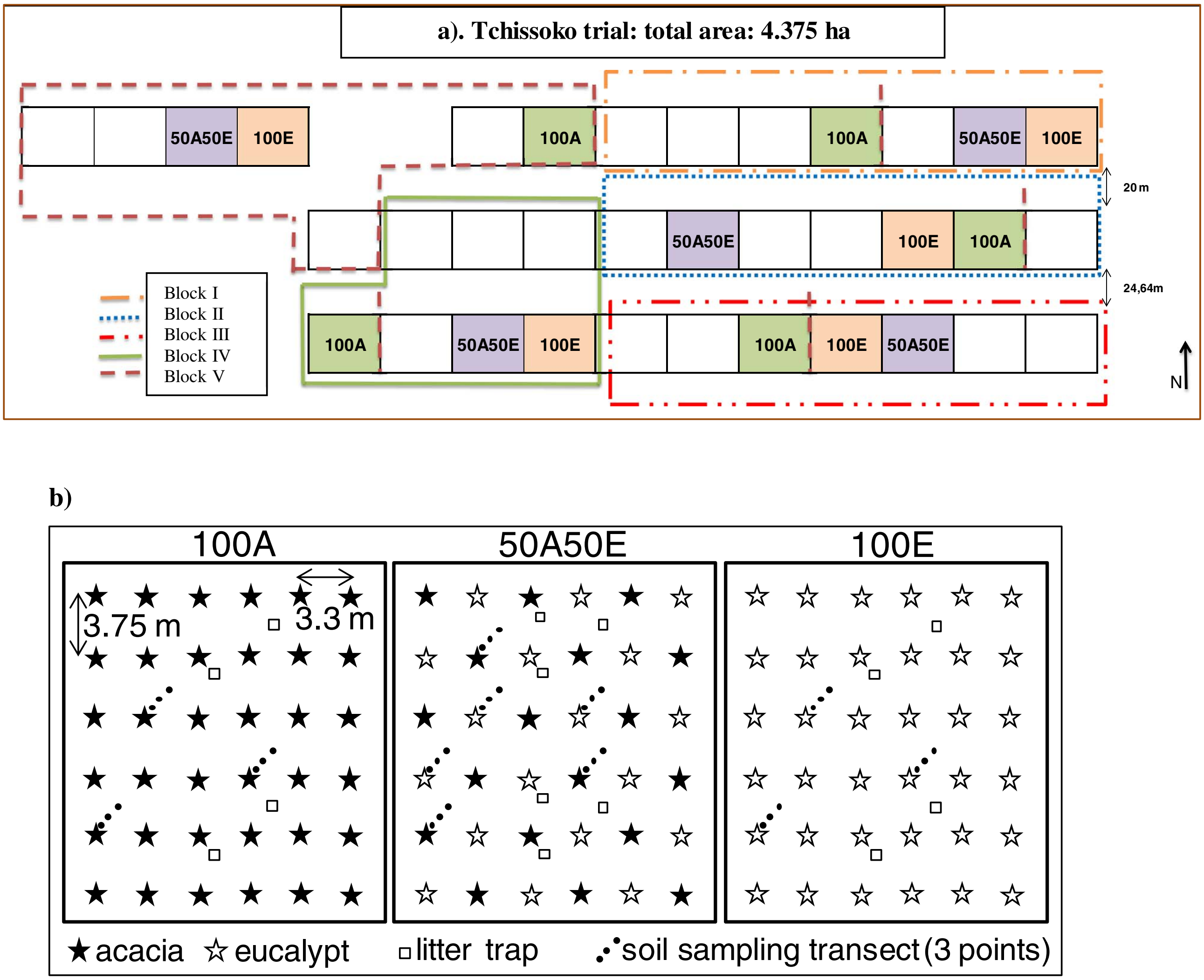

Fig. 1. Schematic representation of the trial (a) and the planting and sampling designs showing the inner plot comprising 36 trees (6 × 6) of pure acacia (100A), mixed-species with 50% acacia and 50% eucalypt trees (50A50E) and pure eucalypt (100E) replicated in five blocks.

3. Results

3.1. Resin P, nitrogen and carbon in whole soils, cPOM, fPOM and OMF

Soil pH varied between 4.3 and 4.6 in the afforested stands, while that of surrounding savannas was 5.1 (Table 1). Resin P in all whole soil samples was below 10 mg P kg^{-1}, with no difference between the afforested stands - i.e., pure acacia (100A), mixed-species near an acacia tree (50A(50e)), mixed-species near an eucalypt tree ((50a)50E), pure eucalypt (100E) - and the savannas (Fig. 2a). Resin P in cPOM (4000–250 μm) was, however, significantly lower in savanna (11 mg kg^{-1}) than in the afforested stands (> 60 mg kg^{-1}). No significant difference was found between afforested stands and savanna concerning resin P in fPOM (250–50 μm) and OMF (< 50 μm) (Fig. 2).

Table 1
Soil pH 3 years into the second rotation in the 0–10 cm layer of the mixed-species acacia and eucalypt plantations of pure acacia (100A), mixed-species with 50% acacia and 50% eucalypt trees (50A(50e) or (50a)50E), pure eucalypt (100E) stands and savanna established in the Congolese coastal plains.

Year and stands	Year 3 of second rotation
Depth	0–10 cm
100A	4.5 ± 0.17a
50A50E	4.3 ± 0.10a
100E	4.6 ± 0.22a
Savannas	5.1 ± 0.38

No significant difference was found between N concentrations (< 0.09%) of whole soil samples, fPOM (< 1.50%) and OMF (0.08%) from afforested stands and savannas (Fig. 3). However, the N content of cPOM of afforested stands containing acacias (> 1.50%) was significantly higher than that of savannas (< 1%) (Fig. 3). Fig. 4 shows that whole soil C content of afforested stands (> 1.25%) was significantly higher than in savannas (< 0.60). However, no significant difference was found regarding the C content in cPOM, fPOM and OMF of afforested stands and savannas, even though lower values were consistently observed in the savannas (Fig. 4).

C/N ratios of whole soil samples ranged between 21.6 (100E) and 17.9 (savanna). C/N ratio of savanna was significantly lower than those of pure eucalypt (100E), mixed-species near an acacia (50A(50e)) and eucalypt ((50a)50E) (Fig. 5a). The C/N ratio of cPOM in 100A was significantly lower than that of both 100E and savanna (Fig. 5b). No significant difference was found between the C/N ratios of fPOM and OMF (Fig. 5c & d).

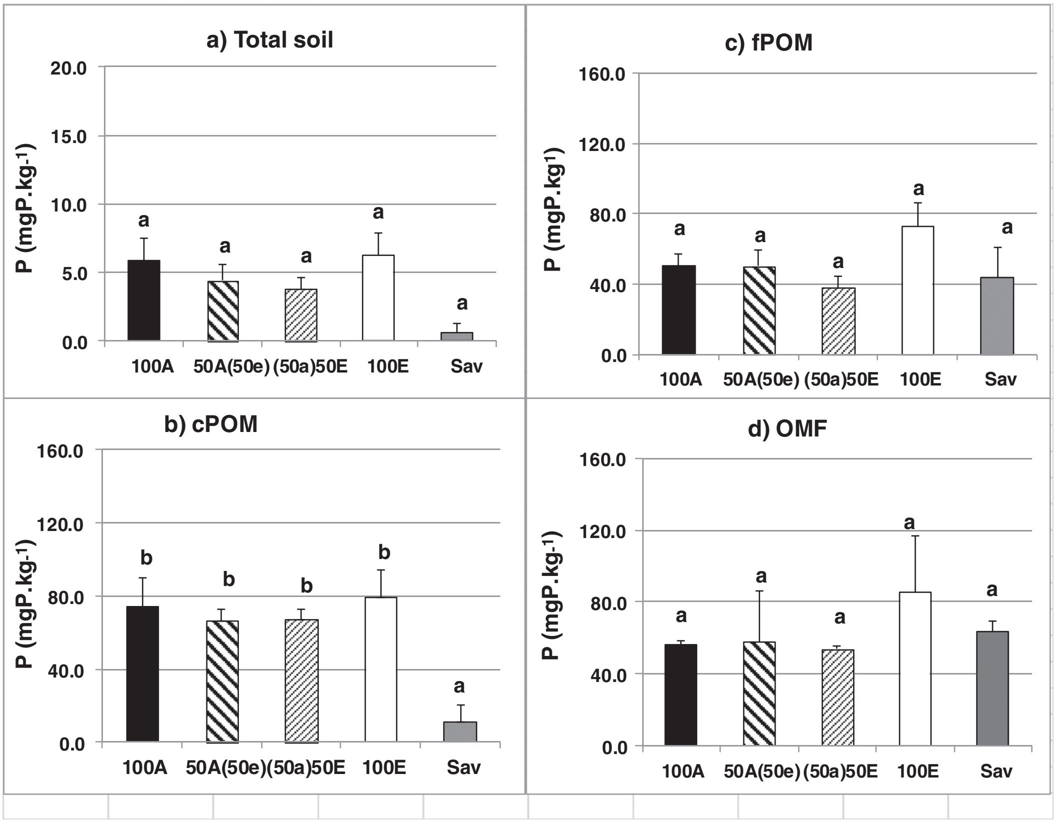

Fig. 2. Phosphorus (P) in (a) whole soil, (b) coarse fraction of particulate organic matter cPOM (4000–250 μm), (c) fine fraction of particulate organic matter fPOM (250–50 μm) and (d) organo-mineral fraction OMF (< 50 μm), in the 0–10 cm soil layer in year 3 of the second rotation of the mixed-species plantation trial of acacias and eucalypts. The letters a, b and c indicate significant differences between pure acacia (100A), mixed-species with 50% acacia and 50% eucalypt trees (50A(50e) or (50a)50E), pure eucalypt (100E) stands and savanna ($p < 0.05$).

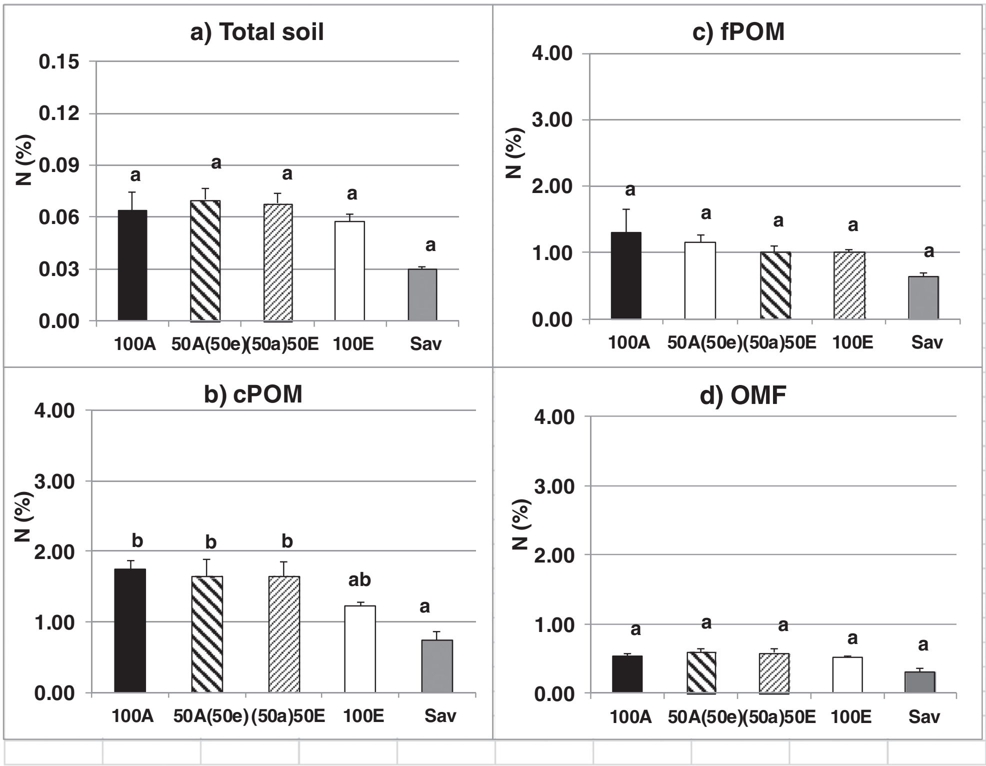

Fig. 3. Nitrogen (N) in (a) whole soil, (b) coarse particulate organic matter cPOM (4000–250 μm), (c) fine particulate organic matter fPOM (250–50 μm) and (d) organo-mineral fraction OMF (< 50 μm), in the 0–10 cm soil layer in year 3 of the second rotation of the mixed-species plantation trial of acacias and eucalypts. The letters a, b and c indicate significant differences between pure acacia (100A), mixed-species with 50% acacia and 50% eucalypt trees (50A(50e) or (50a)50E), pure eucalypt (100E) stands and savanna ($p < 0.05$).

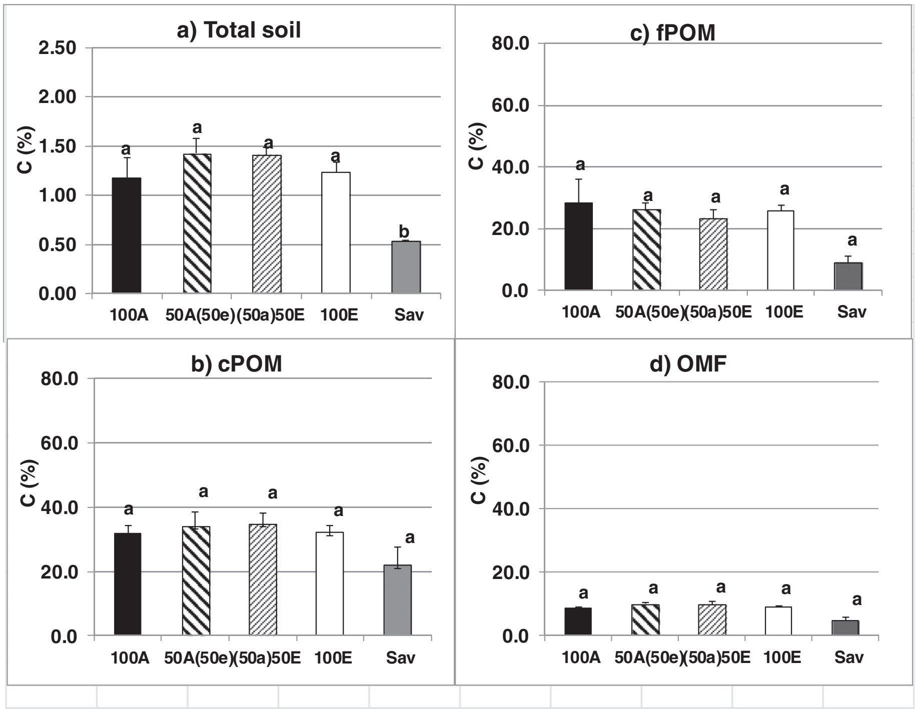

Fig. 4. Carbon (C) in (a) whole soil, (b) coarse particulate organic matter cPOM (4000–250 μm), (c) fine particulate organic matter fPOM (250–50 μm) and (d) organo-mineral fraction OMF (< 50 μm), in the 0–10 cm soil layer in year 3 of the second rotation of the mixed-species plantation trial of acacias and eucalypts. The letters a, b and c indicate significant differences between pure acacia (100A), mixed-species with 50% acacia and 50% eucalypt trees (50A(50e) or (50a)50E), pure eucalypt (100E) stands and savanna ($p < 0.05$).

4. Discussion

4.1. P and N concentrations in coarse POM of afforested stands and savannas

Previous work has showed that differences amongst plantation stands were observed at the end of the 7-year rotation in mixed acacia and eucalypt plantations e.g. (i) the eucalypt tree production benefits from the N_2 fixed by acacias (Bouillet et al., 2013; Epron et al., 2013). Soil N stock in whole (down to 0.25 m depth) also increases, while soil resin available P decreases in mixed-species stands (Koutika et al., 2014), probably due to a higher demand for soil P, to supply the photosynthetic demand of leaves and N_2 fixation (Koutika et al., 2016). Our study highlights an improved P and N status in cPOM of afforested soils relative to savanna soils *via*: (i) higher available P in cPOM of all afforested stands relative to savanna, and (ii) higher N concentrations in cPOM, but only in afforested stands containing acacias, i.e. 100A and 50A50E, relative to both 100E and savanna. This may be due to differences in the relative P and N content of the leaf-litter produced by eucalypts and acacias (eucalypt leaves being P-rich and N-poor while the reverse is true for acacia leaves, see Santos et al., 2017). This may also probably result from the change in faunal activity after afforestation i.e., higher activity of macroarthropods, particularly cockroaches in acacia litter as opposed to ants in eucalypt litter (Bernhard-Reversat, 1993), and in microbial activity, i.e., an increase in soil microbial community diversity and abundance (Huang et al., 2014).

Coarse POM (cPOM, 4000–250 μm) is a POM fraction sensitive to changes in the SOM status following land-use changes. Thus, cPOM of the three afforested stands displays higher amounts of available P than in savannas (Fig. 2b). Given that the studied soils had a similar texture and cover vegetation before afforestation, higher available P concentrations in cPOM of afforested stands are probably due to both high P concentrations in the organic residues (litter, leaves and bark) left after harvest and their high decomposition rates in this subequatorial climate (d'Annunzio et al., 2008; Epron et al., 2015). This result is in agreement with Deng et al. (2017), who reported an increase in soil available P over time in 220 afforested sites relative to native vegetation whilst total P was not sensitive enough to detect the change.

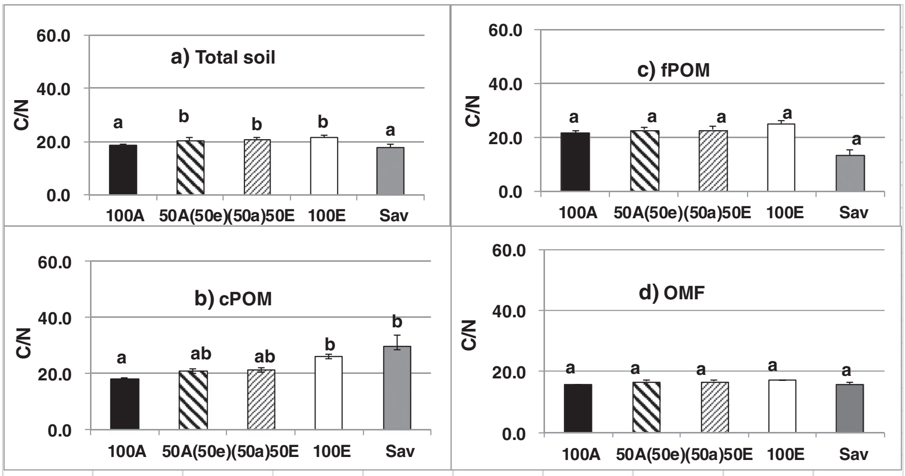

Fig. 5. C/N ratios in (a) whole soil, (b) coarse particulate organic matter cPOM (4000–250 μm), (c) fine particulate organic matter fPOM (250–50 μm) and (d) organo–mineral fraction OMF (< 50 μm), in the 0–10 cm soil layer in year 3 of the second rotation of the mixed-species plantation trial of acacias and eucalypts in the Congolese coastal plains. Mean values (with standard errors) of 3 replicates (composite sample). The letters a, b and c indicate significant differences between pure acacia (100A), mixed-species with 50% acacia and 50% eucalypt trees (50A(50e) or (50a)50E), pure eucalypt (100E) stands and Sav, i.e., savanna ($p < 0.05$).

A greater cPOM N concentration in afforested stands than in savannas also reveals an improvement in the N status of SOM, but only in stands containing acacias, i.e. in 100A, 50A(50e) and (50a)50E (Fig. 3b). This is likely due to high rates of decomposition and return to the soil of the organic residues (litterfall and slash residues) derived from the acacias since the introduction of mixed-species planting (Tchichelle et al., 2017). In a meta-analysis of 292 sites, Li et al. (2012) reported an increase in soil total N stock after 50 years of afforestation. In the Congolese case study, an increase in total N stock was previously noted (Koutika et al., 2014), which is confirmed by the improvement in the N status of cPOM < 35 years after afforestation (1984–2015, this study).

The pure acacia (100A) stands display the greatest improvement in soil N status, as shown by the lower C/N ratio in whole soil and cPOM relative to other afforested stands, as previously noted through higher N mineralisation rates in the study conducted in the same trial 2 years earlier (Tchichelle et al., 2017). In contrast, the yet lower C/N ratio of whole savanna soil may be due to lower inputs, and to the nature and dynamics of organic residues under savanna compared with the afforested stands (Trouvé, 1992; Lata et al., 1999). Unsurprisingly, and as it has been observed in previous studies, mixed-species plantations result in soil C accretion (Forrester et al., 2013; Macedo et al., 2007; Koutika et al., 2014), highlighted in this study by an increase in the C concentration of afforested soils relative to savannas (Fig. 4a). Our results confirm our hypothesis, i.e. that the large organic residues (litter, leaves, bark) left behind at harvest (e.g. N that returned to the soil through in situ mineralization was 3.8 times higher in pure acacia 100 A than in pure eucalypt 100E (7.4 kg ha^{-1} month^{-1} vs 2.0 kg ha^{-1} month^{-1} (Tchichelle et al., 2017) do have an impact on the SOM status of the afforested stands relative to savannas through: (i) an increase of available P in the cPOM in all afforested stands, (ii) an increase in N concentration in cPOM of afforested stands containing acacias, and (iii) an increase in C concentration in whole soil of afforested stands.

5. Conclusions

P and N concentrations in POM and C concentration in whole soils are greater in afforested stands than in the inherently nutrient-poor savanna soils of the Congolese coastal plains. Besides from the C accretion leading to C sequestration in the soil and biota, which is often observed in afforested savannas worldwide, the mixing of acacias and eucalypts in plantations increases soil available P in the coarse POM (4000–250 μm) relatively to the savanna soils. However, the positive effect of NFS on SOM quality was noted only in the afforested stands containing acacias, with a higher N concentration in the coarse POM fraction, the fraction of POM most likely to quickly reflect alterations in the SOM status after land-use change. In the nutrient-poor savanna soils of the Congolese coastal plains, and perhaps of the large savanna areas of central Africa, ascertaining the benefit of planting mixed stands of acacias and eucalypts to sustain forest plantations and improve soil fertility calls for an estimation of POM status of afforested stands relative to savannas in the longer term, after several rotations.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:http://dx.doi.org/10.1016/j.geodrs.2017.07.009. These data include the Google map of the most important areas described in this article.

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