Geoderma Regional 11 (2017) 37–43

Contents lists available at ScienceDirect

Geoderma Regional

journal homepage: www.elsevier.com/locate/geodrs

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

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ARTICLE INFO

Keywords:
POM status
Arenosols
P availability
N and C concentrations
Acacia
Eucalypt
Savanna

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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http://dx.doi.org/10.1016/j.geodrs.2017.07.009

Received 29 May 2017; Received in revised form 21 July 2017; Accepted 24 July 2017

Available online 13 September 2017

2352-0094/

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).