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Soil P availability under eucalypt and acacia on Ferralic Arenosols, republic of the Congo

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ABSTRACT

Introducing nitrogen fixing species (NFS) in forest plantations reduces soil N-limitation, but also involves changes in phosphorus (P) availability in the Ferralitic Arenosols of the Congolese coastal plains or Batéké Plateaux in Central Africa. We evaluated soil-available P and total P in above-ground litters, leaves, bark and wood in pure (100A, 100E) and mixed-species (50A50E) stands of acacia (a NFS) and eucalypt plantations in the Congolese coastal plains at year 2 of the second rotation (Y2R2) compared to the end of the first 7-year rotation (EndR1). Soil available P was measured as resin P, bicarbonate-extractable inorganic (P_i-HCO_3) and organic (P_o-HCO_3). Soil resin-P values (15–19 mg P kg^{-1}) in 100E were 80% higher relative to 100A (8–17 mg P kg^{-1}) at Y2R2 against no difference for both 100E and 100A (8–12 mg P kg^{-1}) at EndR1. Total P concentration was higher in acacia wood (0.61 g P kg^{-1} of dry mass (DM)) than in eucalypt wood (0.57 g P kg^{-1} of DM) in 50A50E at Y2R2, while higher stock of P and higher ratio of N:P ratios were found in the foliage of acacia than of eucalypt trees. Our data suggests that the risk of shifting from N-limitation to P-limitation system is minor. However, in the long term, P-limitation may eventually occur in pure acacia plantations, due to mining of soil available P by acacia's higher P uptake relative to eucalypt and additional requirement for symbiotic fixation of atmospheric N_2.

1. Introduction

The productivity of fast-growing tree plantations declines in second and subsequent rotations owing to a reduction in soil fertility when nutrients exported at harvest are not supplied as fertilizers (Corbeels et al., 2005; Laclau et al., 2005; Nambiar and Kallio, 2008; Tiarks and Ranger, 2008). In the Congolese coastal plains, eucalypt plantations deplete soil fertility in the highly-weathered inherently nutrient poor sandy Ferralitic soils, due to the large nutrient exported in harvested biomass, and the subsequent leaching of nutrients after harvest at the end of each rotation (Laclau et al., 2005). These soils are typical of large areas of savannah in central Africa, especially in the Batéké Plateaux spanning over 6 million hectares in Gabon, the republic of the Congo and the DR Congo (Schwartz and Namri, 2002). The retention of harvest residues (Corbeels et al., 2005; Kumaraswamy et al., 2014), the plantation of trees fixing nitrogen from the atmosphere, so called N_2 fixing species (NFS) such as fast-growing exotic acacia species or their introduction in eucalypt plantations may improve soil fertility by reducing N depletion and sustaining forest productivity (Khanna, 1998; Binkley et al., 2000; Forrester et al., 2006; Epron et al., 2013; Koutika et al., 2014). These practices have been implemented in the Congolese coastal plains in the republic of the Congo (Nzila et al., 2002; Bouillet et al., 2013) as well in the Batéké Plateaux in the DR Congo (Kasongo et al., 2009).

In addition to soil N supply, phosphorus (P) is an essential nutrient for forest productivity in most tropical soils due to its major role in biological nutrient cycling (Hinsinger, 2001; Yang et al., 2013). Without regarding P export and potential leaching at harvest, soil P availability to plants is greatly reduced by strong adsorption of P due to the large amounts of Al and Fe oxide surfaces present in weathered soils (Sanchez and Uehara, 1980; Hinsinger, 2001). Soil P availability is especially critical in mixed-species plantations containing NFS owing to the high P requirement for symbiotic fixation of atmospheric N_2 (Binkley, 1992; Hinsinger, 2001; Inagaki et al., 2011). Thus, increasing N availability in mixed-species plantations including NSF trees may shift the system from N-limitation to P-limitation, with a potential negative feedback on N_2 fixation after several rotations, even though the phosphatase activity of NFS may enhance P availability (Blaser et al., 2014).

Due to the low input of fertilizers in commercial forest plantations established on the Congolese coastal plains, soil fertility, tree nutrition and early growth mainly rely on the decomposition of organic residues (Laclau et al., 2005; Versini et al., 2013). During the juvenile stage of a

Abbreviations: NFS, nitrogen fixing species; P, phosphorus; EndR1, end of the first 7-year rotation; Y2R2, year 2 of the second rotation; Pi-HCO_3, bicarbonate inorganic phosphorus; Po-HCO_3, bicarbonate organic phosphorus; N, nitrogen.

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eucalypt plantation up to canopy closure, the uptake of nutrients from the soil reserves supplied most of tree growth requirements (Laclau et al., 2003). At a site located on the coastal plains of the Congo, previous results of the first rotation (2004–2011) of a mixed plantation of acacia and eucalypt have shown that eucalypt growth benefits from the N_2 fixed by acacia (Bouillet et al., 2013; Epron et al., 2013). However, a decrease in soil resin P in the topsoil of the mixed-species stands relative to the pure eucalypt stands was observed at the end of the first 7-year rotation (EndR1) (Koutika et al., 2014).

These results obtained at the end of the first rotation raise concerns about the relationship between soil fertility e.g., P availability and the sustainability of mixed-species plantations of acacia and eucalypt. Two questions have emerged: (1) would the decrease in resin P values observed in the mixed-species stands (half eucalypt and half acacia) at the end of the first 7-year rotation amplify at year 2 of the second rotation? (2) Will a low available soil P decrease P uptake by NFS trees during the first 2 years of the second rotation? In this study, soil P availability at two key stages of eucalypt–acacia plantation rotations (EndR1 and Y2R2) was compared. Soil P availability was characterized by quantifying the resin-extractable P, Pi-HCO_3 and Po-HCO_3 fractions from the Hedley soil P sequential extraction procedure that are considered readily available to plants (Tiessen et al., 1984; Tiessen and Moir, 2008). The amount of P in the tree biomass and in litterfall was also estimated at year 2 of the second rotation, a juvenile stage when the nutrients uptake from the soil reserves supplied most of tree growth requirements, especially in low-input systems.

2. Materials and methods

2.1. Site description

The study site is located about 35 km outside Pointe-Noire city on the coastal plains close to Tchissoko village in the Republic of Congo (4° 44′ 41″S & 12° 01′ 51″ E, 100 Alt.). The climate of the area is subequatorial with high mean annual air humidity and air temperature (85% and 25 °C, respectively) and low seasonal variation (about 2% and 5 °C, respectively). Annual precipitation averages 1200 mm with a dry season extending from June to September. The soils in this area are deep Ferralic Arenosols overlying geological bedrock composed of thick detritic layers of continental origin (sandstone) dating from the Plio–Pleistocene. They are characterized by a low cation exchange capacity (CEC < 0.5 cmol kg^{-1}), a high sand content (>90% of the mineral soil) and a very low clay and silt content 6 and 2%, respectively (Mareschal et al., 2011). The soil at the site has a low total N content (<0.07%) and C content (0.4–1.18%). The mean total phosphorus (P), aluminium (Al), iron (Fe) and manganese (Mn) analysed by inductively coupled plasma atomic emission spectroscopy (ICP-AES, soil analyses laboratory, INRA, Arras, France) are respectively 0.06 ± 0.01%, 1.02 ± 0.03%, 0.99 ± 0.03% 4.8 ± 0.2% in the 0–5 cm.

The original vegetation was native tropical savannah dominated by the poaceae *Loudetia arundinacea* (Hochst.) Steud. The area was first afforested in 1984 with pure eucalyptus hybrids. In May 2004, mixed *Eucalyptus urophylla x grandis* hybrid (18–52) and *Acacia mangium* stands were established with a starter fertilization of 43 kg ha^{-1} of N as ammonium nitrate. Pure acacia (100A), mixed-species with 50% acacia and 50% eucalypt trees (50A50E, the two species being alternately planted in the row and between adjacent rows) and pure eucalypt (100E) stands were compared within a randomised block design with five replicates and a stocking density of 800 trees ha^{-1}. Each stand (1250 m^2) consisted of an inner plot comprising 36 trees (6 × 6, Fig. 1) and two buffer rows. The first rotation ended after seven years which is a full length rotation for eucalypt plantations established in this area (Laclau et al., 2000). 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 and equally distributed on the soil surface in each stand. The stock of available P (g P m^{-2}) in the soil (0–15 cm) at the end of the first rotation together with the amounts of P in the slash left after harvest calculated from the amount stored in the biomass at the end of the first rotation (Koutika et al., 2014) are given in Table 1. The second rotation was planted in March 2012 using the same design, with a closely related *Eucalyptus urophylla x grandis* hybrid (18–147) and *Acacia mangium* but without any N fertilizer added. Potassium (K) was supplied three months after planting (150 kg ha^{-1} as KCl) owing to the risk of K depletion on highly weathered tropical soils (Epron et al., 2012).

2.2. Soil sampling

Soil was sampled in December 2011 (end of the first rotation after seven years, EndR1) and in March 2014 (after two years of the second rotation, Y2R2) in three out of the five blocks. On each occasion, nine soil samples (18 in 50A50E) were collected in each stand from three soil depths (0–5 cm, 5–10 cm and 10–15 cm) using 5 × 5 cm sampling cylinders. In each stand, three transects (six for the 50A50E) were set up starting at the base of a tree and ending in the centre of the area delimited by four trees (Fig. 1). The three sampling points were separated by 0.7 m from each other on each transect. The total number of sampling points was 27 (9 × 3 blocks) for 100A and 100E and 54 (9 × 2 species × 3 blocks) in 50A50E. The soil samples were air-dried, sieved at 4 mm and root fragments were removed.

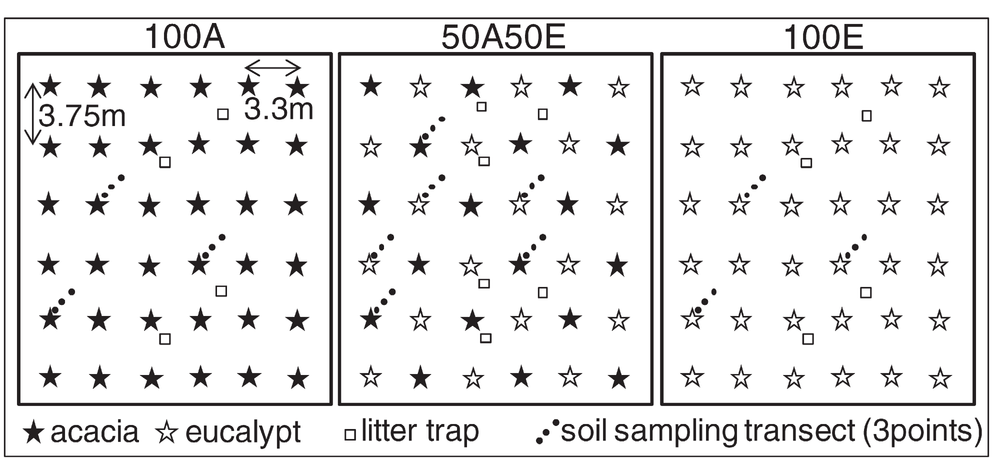

Fig. 1. Schematic representation of the planting and sampling designs showing the inner plot comprising 36 trees (6 × 6) of pure acacia (100A), mixed-species with 50% acacia and 50% eucalypt trees (50A50E) and pure eucalypt (100E) replicated in five blocks.