



# Afforesting savannas with *Acacia mangium* and eucalyptus improves P availability in Arenosols of the Congolese coastal plains

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## ABSTRACT

Phosphorus (P) is an essential constituent for all living organisms, scarce with finite reserves. P is deficient in Sub Saharan Africa threatening primary production. That in part is due to the occlusion of P in Fe and Al oxides in the weathered soils. This problem is aggravated by the high cost of P fertilizers, lack of both appropriate technologies for its application and government support to facilitate and strengthen its use in small-scale farming. Evaluation of soil P availability in the mixed-species plantations established on natural savannas in the Congolese coastal plains highlights that high C accretion involves low P availability in the mixed-species (50% acacia and 50% eucalyptus) stands relative to others. P availability in 0–0.05 m in the mixed-species stands ( $6.94 \pm 0.45 \text{ mg kg}^{-1}$ ) was lower than in acacia ( $8.07 \pm 0.63 \text{ mg kg}^{-1}$ ) and eucalyptus ( $8.46 \pm 0.79 \text{ mg kg}^{-1}$ ). C stock in the 0.25 m was higher in the mixed-species ( $17.8 \pm 0.7 \text{ t.ha}^{-1}$ ) relative to acacia ( $16.7 \text{ t.ha}^{-1} \pm 0.4$ ) and eucalyptus ( $15.9 \text{ t.ha}^{-1} \pm 0.4$ ). However, afforesting the inherently nutrient-poor and sandy soils beneath savannas evidenced an improvement in soil P availability to plant, along with soil N status and C sequestration in both soil and biomass, with a potential impact on mitigating climate change.

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## 1. Introduction

Despite being the 11th most abundant element in the earth's crust, phosphorus (P) is a life-essential and finite element necessary to all living organisms, i.e., required for animals, plant growth and fecundity, crop and wood production (Syers et al., 2008; White and Hammond, 2008; Yang et al., 2013; Scholz et al., 2014). P is defined as a trilemma; for being essential constituent for all life forms; critical as it may be considered as a pollutant; and scarce as it is not renewable and finite (Syers et al., 2008; Elser and Bennett, 2011; Scholz et al., 2014). P concentration in soils generally ranged from 100 to 3000 mg P kg<sup>-1</sup> soil, or 200–6000 kg P ha<sup>-1</sup> (Hedley et al., 1995). Asia comprises around 60% of the world population and uses 64% of the over world consumption of P. This leads to overuse or application of inorganic P fertilizers (Pi) in many Asian countries such as India, Bangladesh etc..., while the worse situation is found in China (Lui et al., 2016). In contrast, in large areas of Sub-Saharan Africa, where disregarding very low P availability involved by P occlusion in the Fe and Al oxides common to the weathered soils (Sanchez, 1976; Sanchez and Uehara, 1980; Bunemann et al., 2004; Yerokun, 2008) and P loss from leaching (Sugihara et al., 2012), inorganic P fertilizers are poorly applied due to their high costs, lack of appropriate technologies and government policies to facilitate and

strengthen its use (Badiane and Delgado, 1995; Larson and Frisvold, 1996; Vitousek et al., 2009).

The role of P fertilizers in agriculture and forestry is undeniable (Cleveland et al., 2002; Lan et al., 2012; Yang et al., 2014). However, when considering both P over fertilization in China (Lui et al., 2016), the eutrophication of rivers and lakes in the US (Elser and Bennett, 2011), and the increasing costs of Pi fertilizers, the question arises: should Sub-Saharan African countries still rely on large use of inorganic fertilizers to replenish P availability, increase crop production to ensure food security and sustain forestry for the growing population? The population of Sub-Saharan African countries drastically grows. Three countries (Nigeria, Ethiopia and DR Congo) out of the 54 of the continent are amongst the 20 largest countries by population representing around 5% of the world population (<http://www.worldometers.info/world-population>). Therefore, more than ever, Sub-Saharan Africa needs to intensify and modernize agriculture and forestry to become self-sufficient in both food and fuel energy for the coming decades. However that must be done with noteworthy care of soil resources, since the weathered soils are mostly nutrient-poor and fragile (Swift et al., 1994; Laclau et al., 2010; Sugihara et al., 2012), they often have a strong ability to fix P in Al and Fe oxides (Sanchez, 1976; Bunemann et al., 2004; Yerokun, 2008) with organic P pool being the major source to the available P (Gama-Rodrigues et al., 2014). Nevertheless, other aspects must also be taken into account like the finite aspect of world inorganic P reserves (Syers et al., 2008; Scholz et al., 2014), and the impact of adaptation and resilience in mitigating climate change on soil fertility (P and N

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availability linked to C sequestration) and food security (Syers et al., 2008; [www.4per1000.org](http://www.4per1000.org); Yang et al., 2014).

Soil P availability is undeniable linked to soil carbon (C) accretion (Binkley, 1992; Kirkby et al., 2013; Sang et al., 2013). Along with N and S, P is positively linked to C, favouring soil aggregation, increasing their availability, and finally enhancing the conversion of labile C from crop or animal residues into stable soil humus (Lal, 2014). The link between P dynamics and C sequestration occurs mostly and indirectly via microbial and faunal activities (Binkley, 1992; Binkley et al., 2000). P limitation in microbial decomposition may involve profound implications for C cycling in moist tropical forests (Cleveland et al., 2002). Low concentrations of P in the litter may produce a stoichiometric imbalance (N: P) inducing both low microbial biomass and activity, and involving starvation/inhibition of decomposers (Santos et al., 2017). Nitrogen ( $N_2$ ) fixing species from the atmosphere (NFS), such as fast-growing exotic acacia species or legumes, improve soil fertility e.g., reduce N depletion (Khanna, 1998; Binkley et al., 2000; Forrester et al., 2006). They may enhance overall biological activity in soil-plant system enhancing P cycling and availability (Oberson et al., 1999, 2001). A higher nitrification and lower denitrification in  $N_2$  fixing stands in mixed-species plantations with non-fixers, revealed a distinct microbial community for the respective monocultures, which positively effects soil P and nitrate amounts (Rachid et al., 2013). Litter decomposition in monocultures of *Acacia mangium* and eucalyptus plantations depends not only on litter C quality (water soluble compounds and lignin content), but also on the activity of decomposers, which may be limited by energy starvation and low P availability (Bachega et al., 2016). Benefits of introducing acacia in the eucalyptus plantations established in the Congolese coastal plains are obvious i.e., increased: (i) standing wood biomass in the mixed-species (50% acacia and 50% eucalyptus) stands (Epron et al., 2013), (ii) N and C stocks in the pure acacia and mixed-species relative to eucalyptus stands (Koutika et al., 2014; Koutika et al., 2017), and (iii) cumulative net production of mineral N e.g., ( $343 \text{ kg ha}^{-1}$ ) in acacia relative to eucalyptus ( $189 \text{ kg ha}^{-1}$ ) stands (Tchichelle et al., 2017a). Other advantages are (i) providing fuel wood energy since around 94% of Congolese homes use forest products as fuel energy reducing a high pressure on the native forests (Shure et al., 2010); (ii) mitigating climate change by storing C in both soil and biomass (Epron et al., 2013; Koutika et al., 2014), while the risk of the competition for the light and soil water between two species is reduced, showing that both species benefit from growing in a mixed stand (Tchichelle et al., 2017b).

Food and wood production in large areas of farmland in sub humid and semiarid Africa is widely constrained by both N and P deficiencies (Ssali et al., 1986; Hartemink, 2003; Vitousek et al., 2009; Gonçalves et al., 2008; Laclau et al., 2010). Soil N deficiency can be compensated by symbiotic fixation of atmospheric  $N_2$  by introduced nitrogen fixing species (Binkley, 1992), while, soil P deficiency can only be alleviated by addition of inorganic or organic fertilizers (Sanchez and Uehara, 1980; Nziguheba et al., 1998; Scott and Melendez, 2001; Ayaga et al., 2006). Soil P deficiency remains crucial in most African agricultural and forestry systems because most farmers cannot afford the use of P fertilizers due to the lack of government policies and high costs (Badiane and Delgado, 1995; Larson and Frisvold, 1996). How to promote and secure food or forest production, and avoid over fertilization without compromising both crop yield and forest sustainability? The Sub-Saharan African area, as the Congolese coastal plains, would gain by adopting the improved agronomic strategies, greater use of alternative P-fertilizers, such as manures, animal wastes (Scholz et al., 2014), and the developed crop genotypes that are more efficient in acquiring P from the soil according to acidity, salinity, drought and/or in utilizing P more economically in their tissues.

The objective of this paper is to evaluate how establishment of mixed-species plantations of *A. mangium* and *Eucalyptus urophylla*  $\times$  *grandis* may impact P availability of nutrient-poor soil in the Congolese coastal plains. Supported by the literature review, this paper is presenting the soil P available status taking into account constraints as (i) the

high P fixation ability by Fe and Al oxides common to most weathered soils; (ii) the difficulty to afford the use of inorganic P fertilizers; and (iii) the lack of both appropriate technologies for P application and government policies to facilitate and strengthen P use. The over application of P inorganic fertilizers in Asia or developed northern countries led to test two main hypotheses: (i) introducing mixed-species plantations of acacia and eucalyptus may have a beneficial impact on P availability of nutrient-poor soils of savannas of the Congolese coastal plains (ii) soil P availability in this area should not be replenished by the large use of inorganic fertilizers to secure fuel energy for rural population and forest productivity and sustainability. As in most parts of Sub-Saharan Africa, the government would not afford the restoration of the polluted lands, rivers or lakes, in the case of the over fertilization and environmental damages.

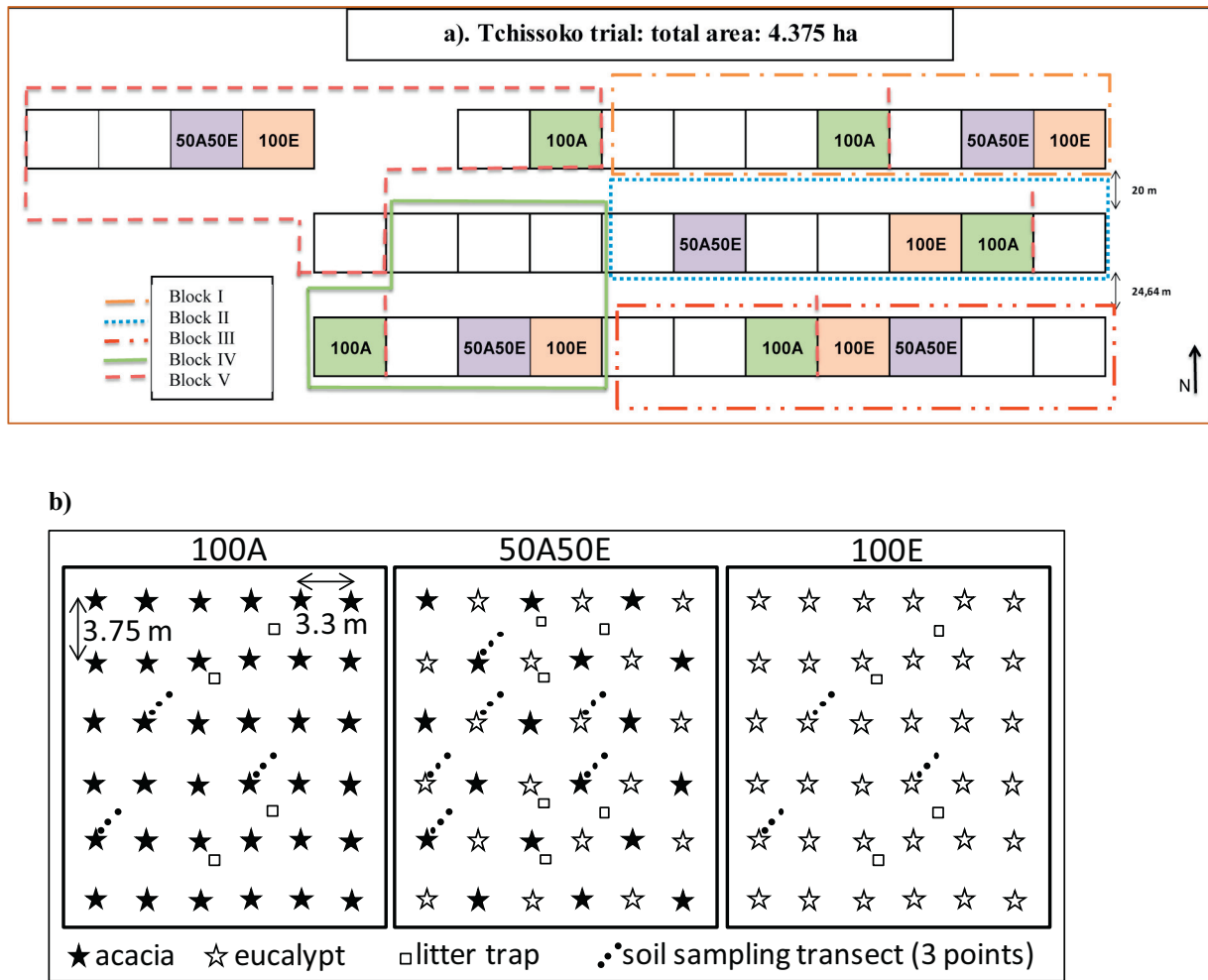
## 2. Material and methods

### 2.1. Description of studied site

The studied site is located on a plateau close to Tchissoko village in Congo ( $4^\circ\text{S}$ ,  $12^\circ\text{E}$ , 100 Alt.), on a deep Ferralic Arenosol laying on a bedrock composed of thick detritic layers of continental origin dated from plio-pleistocene at about 35 km of Pointe-Noire city. The climate in the area is subequatorial with high mean annual air humidity and air temperature ( $85\%$  and  $25^\circ\text{C}$ , respectively) and low seasonal variation (about  $2\%$  and  $5^\circ\text{C}$ , respectively). Annual precipitation averages 1200 mm with a dry season extending from June to September. The original vegetation of the studied site was native tropical savanna which was first afforested in 1984 with eucalyptus hybrids. These savannas cover large areas in Central Africa, and reach an extent of 6 million hectares in Central Africa i.e., Gabon, the Democratic Republic of the Congo and the Republic of the Congo (Schwartz and Namri, 2002). The soils of this area are characterized by a low CEC ( $< 0.5 \text{ cmol kg}^{-1}$ ), a high sand content ( $> 90\%$ ), very low clay and silt content (6 and 2% respectively), low iron oxides content ( $< 1.5\%$ , Mareschal et al., 2011) and low soil organic matter (SOM) content (Koutika et al., 2014). Mixed *Eucalyptus urophylla*  $\times$  *grandis* hybrid (18–52) and *Acacia mangium* stands were established in May 2004 (starter fertilization of  $43 \text{ kg ha}^{-1}$  of N as ammoniumnitrate). Pure acacia (100A), mixed-species with 50% acacia and 50% eucalyptus trees (50A50E, the two species being alternately planted in the row and between adjacent rows) and pure eucalyptus (100E) stands were compared within a randomised block design with five replicates (planting density of  $800 \text{ trees ha}^{-1}$ ). Each stand ( $1250 \text{ m}^2$ ) consisted of an inner plot comprising 36 trees ( $6 \times 6$ ) and two buffer rows (Fig. 1 adapted from Koutika and Mareschal, 2017). The first rotation ended after 7 years which is a full length rotation for eucalyptus plantations established in the area. Trees were harvested in January 2012. Using the same design, the second rotation was planted in March 2012, with a closely related *Eucalyptus urophylla*  $\times$  *grandis* hybrid (18–147) and *Acacia mangium* but without any N fertilizer added, while potassium (K) was supplied three months after planting i.e.,  $50 \text{ kg ha}^{-1}$  as KCl. No P inorganic fertilizers were added because P is not a limiting nutrient for the eucalyptus tree growth in the area (Laclau et al., 2010; Koutika et al., 2014, 2016). The biomass of the wood, bark, leaves and branches of the mixed-species plantations at 12 and 24 months in the second rotation are represented in the Table 1.

### 2.2. Soil sampling

Soil sampling was done in December 2011 (end of the 7 year-first rotation, EndR1) and in March 2014 (year 2 of the second rotation, Y2R2) in 3 selected out of the 5 blocks (Koutika et al., 2014, Koutika et al., 2016). A third soil sampling was performed in the mixed-species plantation and savannas at 3 years into the second rotation (Y3R2) in March 2015. Soils were collected in the 0–10 cm layer depth, in 3 out of the 5 blocks in the afforested stands and in three selected savannas



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

nearby (Koutika and Mareschal, 2017). Nine soil samples (18 for the 50A50E stand) were collected in each plot and separated in three layers (0–0.05 m, 0.05–0.10 m and 0.10–0.15 m) using 5 × 5 cm sampling cylinders (for EndR1 and Y2R2), and only in the layer (0.10 cm for Y2R2). In each plot (1.250 m<sup>2</sup>), 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 (Fig. 1). The three

samples were separated by 0.7 m from each other on each transect. The total number of sampling points was 27 (9 × 3 selected blocks) in both single-species stand and 54 (9 × 2 species × 3 selected blocks i.e., samples collected near an acacia tree, noted 50A(50e), and 9 others near a eucalyptus tree, noted 50a(50E)) in the mixed-species stand. In the three surrounding savannas, soil was collected along three transects selected inside an area of the similar surface in contrast to the afforested stands. Air-dried soil samples were sieved at 4 mm and root fragments were removed.

**Table 1**

Biomass of wood, bark, leaves and branch at 12 and 24 months in the pure acacia (100A), eucalyptus (100E) and mixed-species (50A50E) stands. There are means (± standard error) in five blocks. For each year and tree part, different letters indicate significant differences between stands (HSD-test of Turkey) and Anova at 5% (\*), 1% (\*\*), or 0.1 (\*\*\*), (ns); adapted from Koutika et al., 2018.

		Aboveground biomass (kg m <sup>-2</sup> )			
		100A	50A50E	100E	Significance
12 months	Wood	0.15 ± 0.01a	0.12 ± 0.02ab	0.08 ± 0.01b	**
	Bark	0.06 ± 0.00a	0.04 ± 0.01b	0.02 ± 0.00c	***
	Leaves	0.30 ± 0.01a	0.18 ± 0.02b	0.08 ± 0.00c	***
	Branch	0.20 ± 0.01a	0.14 ± 0.02b	0.08 ± 0.01c	***
	All	0.70 ± 0.04a	0.48 ± 0.05b	0.25 ± 0.02c	***
24 months	Wood	0.82 ± 0.08	0.99 ± 0.06	0.87 ± 0.09	ns
	Bark	0.23 ± 0.02	0.23 ± 0.01	0.18 ± 0.02	ns
	Leaves	0.67 ± 0.06a	0.54 ± 0.03a	0.19 ± 0.01b	***
	Branch	0.91 ± 0.08a	0.77 ± 0.05a	0.36 ± 0.07b	***
	All	2.63 ± 0.25a	2.54 ± 0.15a	1.60 ± 0.19b	**

### 2.3. POM fractionation

Twenty grams of air-dried and sieved soil, five glass beads and 50 ml of distilled water were put in 100 ml plastic bottle and shaken for 16 h at 20 °C in an end-over-end shaker at 40 rotations per minute to ensure physical fractionation of soil organic matter (Koutika et al., 2017). Soil was wet-sieved to separate the suspension in 3 fractions: 4000–250 μm, 250–50 μm and 0–50 μm. Separation of the organic components from the mineral fraction of the two largest fractions were separated by decantation. The following fractions were collected: coarse (cPOM, 4000–250 μm) and fine POM fractions (fPOM, 250–50 μm) fractions, coarse and fine mineral fractions (cMin and fMin), and the organo-mineral fraction (OMF, < 50 μm). All fractions were dried at 65 °C and weighed. N and C concentrations in cPOM, fPOM and OMF were analyzed using an elemental analyzer (Carlo- Erba, Milan, Italy).

## 2.4. Above-ground litterfall, forest floor and harvest residues

Above-ground litterfall was sampled every two weeks in litter traps (75 × 75 cm) from October 2010 to September 2011 (R1Y7) and from June 2013 to May 2014 (R2Y2), pooled separated by species and components, oven-dried at 65 °C and weighed. Four traps were installed in 100A and 100E in each block, and 6–8 traps in 50A50E. Annual litterfall N flux ( $\text{kg m}^{-2} \text{ year}^{-1}$  of N) was obtained by summing biweekly mass of litterfall, multiplied by the N concentrations of the different litter components. The forest floor was collected in October 2011 (R1Y7) with a square metallic frame (50 × 50 cm), oven-dried and weighed on 4–6 locations within each plot. The forest floor N ( $\text{kg m}^{-2}$  of N) was computed from the dry mass and N concentration (see Epron et al., 2013; for details). Nitrogen content in the harvested residues (foliage and bark) was estimated by multiplying N concentration of bark and leaves collected on 10 trees per species and stand types at harvest by their respective mass in each plot, estimated using allometric relationships between tree height and diameter at breast height and the mass of either leaves or bark (Epron et al., 2013).

## 2.5. Determination of resin P in bulk soil and POM fractions

Soil resin P was determined using two anion exchange resin strips (BDH#551642S, 20 mm × 60 mm) added to 0.5 g of dried and sieved soil suspended in 30 ml distilled water. Phosphate adsorbed by the anion exchange resin was recovered in 30 ml of 0.5M HCl after shaking for 16 h (100 revs  $\text{min}^{-1}$ ) according to the method of Hedley et al. (1982) as described by Tiessen and Moir (2008) i.e. 16 h of contact between the soil suspension and the resin strips. Malachite green reactive P was determined at 630 nm with an UVmc® Safas Monaco spectrophotometer (Monaco, Principality of Monaco). Soil resin P in each soil layer were converted to  $\text{g P m}^{-2}$ , knowing the thickness and the bulk density of each soil layer, and summed to 0.15 m to estimate the stock of available P.

## 2.6. Statistical analyses

Statistical analyses were performed with R software versions 2.13.0 and 3.2. (R Development Core Team, 2011, 2012 and Core Team R, 2016). Mixed-effect models with blocks and sampling place within blocks as random effects were used to estimate the effects of stand treatment (100A, 100E and 50A50E), soil depth and time in rotation (EndR1 and Y2R2) as fixed effects on soil pH and soil resin P. (Koutika et al., 2014, 2016). 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 (Koutika and Mareschal, 2017). Differences were considered significant when  $P < .05$ . Pearson correlation coefficients ( $r$ ) between these measured variables were calculated and considered significant when  $P < .05$ .

## 3. Results

### 3.1. Comparison of available P at the end of 7 year first rotation and year 2 of the second rotation in the mixed-species plantations of acacia and eucalyptus

Soil resin P down to 15 cm in 50A50E and 100E was significantly lower at the EndR1 relative to Y2R2, while those of 100A did not significantly change with stand age (Fig. 2). At Y2R2, soil resin P down to 15 cm in 100A was significantly lower than those in 50A50E, while the latter was also significantly lower than those in 100E (Fig. 2). Except for 50A50E at Y2R2, values of resin P in the 5–10 and 10–15 cm layers were higher than in the 0–5 cm layer in all stands and at both times of soil sampling. The ratio of nitrogen to phosphorus concentrations (N:P) in the foliage of acacia and eucalyptus trees in pure stands were

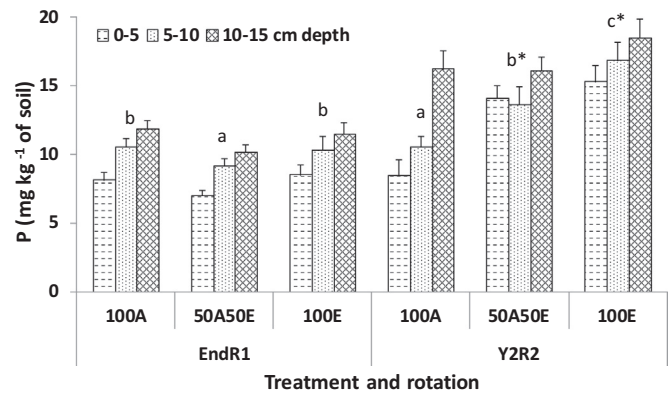


Fig. 2. Soil available P to plants (resin P) down to 15 cm in 100A (pure acacia), 100E (pure eucalyptus) and 50A50E (mixed-species) stands at the end of the first rotation (at age 7 years, EndR1) and at age 2 years of the second rotation (Y2R2). Mean values of 27 ( $9 \times 3$  blocks) replicates for the pure stands and 54 replicates ( $18 \times 3$  blocks) for the mixed species stand. Vertical bars represent standard errors. The different letters indicate that means are significantly different between stands at one age, and the stars indicate significant differences between the two ages ( $p < .05$ ). The increase in P with depth was significant with no significant interaction with stands and ages (not shown for clarity) (adapted from Koutika et al., 2016).

higher at the year 2 of the second rotation (Y2R2) than at the end of the first rotation (EndR1) (Table 2).

### 3.2. Comparison of P availability in the bulk soil and fractions of mixed-species plantation at year 3 of the second rotation and natural savannas

The values of resin P in all bulk soil samples were lower than  $10 \text{ mg P kg}^{-1}$ . No difference was found between the afforested stands i.e., pure acacia (100A), mixed-species near an acacia tree (50A(50E)), mixed-species near a eucalyptus tree ((50a)50E), pure eucalyptus (100E) and the savanna (Fig. 3a). Resin P in cPOM (4000–250  $\mu\text{m}$ ) was, however, significantly higher in the afforested stands ( $> 60 \text{ mg kg}^{-1}$ ) than in savanna ( $11 \text{ mg kg}^{-1}$ ). However, no significant difference was found between afforested stands and savanna concerning resin P in fPOM (250–50  $\mu\text{m}$ ) and OMF ( $< 50 \mu\text{m}$ ) (Fig. 3).

### 3.3. Comparison of P availability in mixed-species forest plantations of the Congolese coastal plains to other studies

P availability of soils in the mixed-species plantations of acacia and eucalyptus established in the Congolese coastal plains varied between  $8.07 \text{ mg P kg}^{-1}$  (100A, EndR1) and  $15.23 \text{ mg P kg}^{-1}$  (100E, Y2R2) (Koutika et al., 2014, 2016, Table 3). The value of available P in the pure eucalyptus plantations located at around 35 km of the mixed-species plantations is the higher  $19.7 \text{ mg P kg}^{-1}$  (Laclau et al., 2010). The lower P availability values in the 0–0.05 m layer were found in the

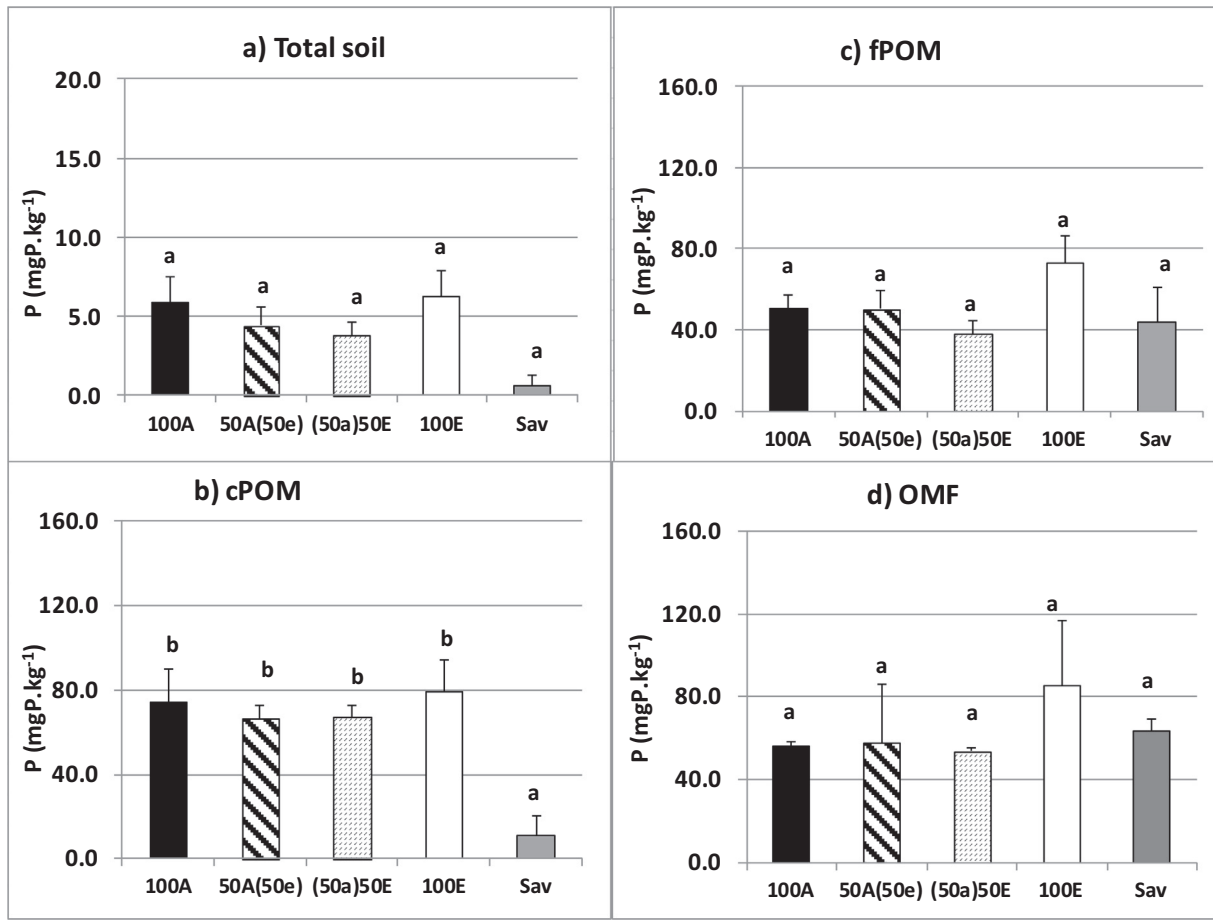
Table 2

Mean values (with standard errors) of the ratio of nitrogen to phosphorus concentrations (N:P) in the foliage of acacia trees in pure (100A) or mixed-species stands (50A) and of eucalyptus trees in pure (100E) and mixed-species (50E) stands at the end of the first rotation (EndR1, in Koutika et al., 2014,  $n = 8$ ) and at the age of 2 years of the second rotation (Y2R2,  $n = 4$ ). The different letters indicate that means are significantly different between the two species growing either in pure or in mixed-species stands, and stars indicate significant differences between the two ages ( $p < .05$ ). (adapted from Koutika et al., 2016).

	100A	50A50E		100E
		Acacia	Eucalyptus	
EndR1 <sup>a</sup>	$14.6 \pm 0.9^b$	$12.9 \pm 1.0^b$	$9.9 \pm 0.5^a$	$9.4 \pm 0.5^a$
Y2R2	$18.5 \pm 0.9^{b*}$	$15.2 \pm 2.2^{ab}$	$11.3 \pm 0.5^a$	$13.1 \pm 0.6^{a*}$

The different letters indicate that means are significantly different between the two species growing either in pure or in mixed-species stands and stars indicate significant differences between the two ages ( $p < 0.05$ ).





**Fig. 3.** Phosphorus (P) in (a) whole soil, (b) coarse fraction of particulate organic matter cPOM (4000–250  $\mu\text{m}$ ), (c) fine fraction of particulate organic matter fPOM (250–50  $\mu\text{m}$ ) and (d) organo-mineral fraction OMF (< 50  $\mu\text{m}$ ), 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% eucalyptus trees (50A(50e) or (50a)50E), pure eucalyptus (100E) stands and savanna ( $p < .05$ ). (Adapted from Koutika and Mareschal, 2017).

high P fixing of Malava in the Kenyan cropping systems (Ayaga et al., 2006, Table 3).

#### 4. Discussion

##### 4.1. P availability in the soils of the Congolese coastal plains

Anion exchange resin membranes are dynamic and sensitive to detect fluctuation in soil P availability even in very low concentrations (McGrath et al., 2000). From Table 3, Arenosols beneath the mixed-species plantations in Congolese coastal plains may be ranked between the

highly P fixing e.g., 2.1 mg kg<sup>-1</sup> P in the cropping Kenyan systems (Ayaga et al., 2006) and low P fixing soils e.g., 19.7 mg kg<sup>-1</sup> P in the eucalyptus plantation (Laclau et al., 2010). According to the resin P availability and low Fe oxide (< 1.5%) content (Mareschal et al., 2011); studied soils may therefore be defined as low P fixing soils (Laclau et al., 2010; Koutika et al., 2014, 2016). Nevertheless, large areas of Sub-Saharan Africa are covered by highly weathered soils, able to strongly fix P in Al and Fe oxides, resulting in low concentrations of labile P (Sanchez, 1976; Sanchez and Uehara, 1980). Some practices such as addition of organic residues (Nziguheba et al., 1998; Scott and Melendez, 2001), farm yard manure and inorganic fertilizers (Ayaga et

**Table 3**

Available P (mg kg<sup>-1</sup>) in the 0–0.05 m in the \*high and \*\*low P fixing soils in the Kenyan cropping systems (Ayaga et al., 2006), in forest plantations established on an Arenosols in the Congolese coastal plains (Mareschal et al., 2011\*\*\*), (Laclau et al., 2010\*), and (Koutika et al., 2014  $\Delta$ ; 2016  $\gamma$ ). EndR1 = End of the 7 year first rotation and Y2R2 = Year 2 of the second rotation.

	Kenya Malava*	Kenya Mau Summit**	Congo Kondi***			Brazil Itatinga*	Congo Kondi*	Congo Tchissoko $\Delta$ (EndR1)			Congo Tchissoko $\gamma$ (Y2R2)		
Land-use	Cropping systems		Eucalyptus plantations			Eucalyptus plantations		Mixed-species plantations					
Average rainfall (mm)	1300*/1025**		1200***			1390* 1200*		1200 $\Delta$					
Soils	Ferro-orthic-Acrisols* Mollic Andosols**		Arenosols***			Ferralsols* Arenosols*		Arenosols $\Delta$					
Stand/treatment			Plateau	Middle slope	Lower slope			100A	50A50E	100E	100A	50A50E	100E
P(mg kg <sup>-1</sup> )	2.1 $\pm$ 0.1	7.5 $\pm$ 0.2	8.3 –	3.5 –	4.6 –	4.0	19.7 –	8.07 $\pm$ 0.63	6.94 $\pm$ 0.45	8.46 $\pm$ 0.79	8.44 $\pm$ 1.13	14.05 $\pm$ 0.90	15.23 $\pm$ 1.21

al., 2006), or chemical fertilizer and either cow manure or rice straw (Lan et al., 2012), reduced Fe associated to periodic C inputs or labile C (Chacon et al., 2006; Pandey and Srivastava, 2009), may increase soil P mobile and available to plant and microorganisms. The presence of legume within savanna or forest ecosystems enhances biological activities through higher P cycling and availability (Oberson et al., 1999, 2001; Santos et al., 2017) and changes bacterial composition and communities (Pereira et al., 2017). Growing crops may also enhance microbial interactions in the P cycle in highly weathered subtropical soils (Tiecher et al., 2012), while green manure increases the most labile P pool (Resin—P + NaHCO<sub>3</sub>—P) and accentuates the P incorporation into biological cycle (Xavier et al., 2009). However, in addition to P deficiency due to its occlusion in the Fe and Al oxides in the highly weathered soils (Sanchez and Uehara, 1980; Bunemann et al., 2004), the symbiotic fixation of atmospheric N<sub>2</sub> by nitrogen fixing species (NFS), may intensify P deficiency, and thereafter limit P availability for crop or tree growth (Binkley, 1992; Crews, 1993; Crème et al., 2016).

#### 4.2. Nitrogen fixing species may affect soil P availability

However, disregarding P occluded in Fe and Al oxides (Sanchez, 1976; Oberson et al., 1999, 2001), this practice may also negatively impact soil P availability in the weathered soils, as NFS requires P to sustain symbiotic N<sub>2</sub> fixation process (Inagaki et al., 2011). Furthermore, the increase in N availability may also lead to a decrease in P availability (Binkley, 1992; Kaye et al., 2000; Resh et al., 2002). Soil P availability was lower in the studied soil (0–0.05 m) in the mixed-species ( $6.94 \pm 0.45 \text{ mg kg}^{-1}$ ) stands relative to the pure acacia ( $8.07 \pm 0.63 \text{ mg kg}^{-1}$ ) and eucalyptus ( $8.46 \pm 0.79 \text{ mg kg}^{-1}$ ) at the end of the first rotation (Fig. 2). This result highlights the link between soil P availability and soil C accretion in accordance with other findings (Binkley, 1992; Kirkby et al., 2013; Lal, 2014). For instance, C stock down to 0.25 m was higher in the mixed-species ( $17.8 \pm 0.7 \text{ t.ha}^{-1}$ ) relative to pure acacia ( $16.7 \text{ t.ha}^{-1} \pm 0.4$ ) and eucalyptus ( $15.9 \text{ t.ha}^{-1} \pm 0.4$ ) stands (Koutika et al., 2014), i.e., P demands by trees were increased, induced by higher C accretion and accompanying increase of soil P availability in the mixed plantations.

High P requirement of acacia was confirmed by the decrease in resin available P in the 0.25 m in pure acacia relative to pure eucalyptus stands and soil readily available inorganic P (resin and Pi—HCO<sub>3</sub>) at year 2 of the second rotation e.g.,  $1.7$  vs  $2.17 \text{ mg kg}^{-1}$  for Pi—HCO<sub>3</sub> (Koutika et al., 2016). Along with C accretion, the decrease in soil P availability in acacia stands is probably also enhanced by the higher P uptake by acacia trees, i.e., high P stock in acacia foliage related to high leaf biomass (Koutika et al., 2016). This is well illustrated by both the biomass of leaves and branches at 24 months e.g., 0.67 and 0.51 for acacia vs 0.19 and 0.77  $\text{kg m}^{-2}$  for eucalyptus, respectively (Table 1), and previous findings at the end of the first rotation (Epron et al., 2013). Higher ratio of N: P concentrations in foliage of acacia stand at juvenile stage suggested that N is less limiting than P early in the rotation, due to more active photosynthesis and highlighting the high P demand at that stage (Table 2). This also may suggest that P limitation may eventually occur in pure acacia stands in longer term and threaten the equilibrium in soil N and P content and inhibit plant growth in the Congolese coastal plains. Currently, studies are in progress to confirm this tendency at year 5 of the second rotation.

Nevertheless, additional study on available P of particulate organic matter (POM) fractions at year 3 of the second rotation compared to natural savannas showed that P availability increased in all afforested stands relative to savannas (Koutika and Mareschal, 2017). This is probably due to the greater amount of P immobilized in the foliage biomass of afforested stands relative to savannas (Trouvé, 1992; Lata et al., 1999; Koutika and Mareschal, 2017). In commercial plantation located in western Brazilian Amazonia, P availability was lowest where litter accumulation was minimal (McGrath et al., 2000). Overall studies conducted in the Congolese coastal plains are highlighting the improvement in

both N and P status in the soils of all afforested stands relative to inherently nutrient-poor soil of natural savanna counterpart (Trouvé, 1992; Laclau et al., 2010; Mareschal et al., 2011), probably as result of using an appropriate practice (Binkley, 1992; Crews, 1993). This is in accordance with the findings of Deng et al. (2017). The authors used a global meta-analysis of soil P dynamics after afforestation, and argued that available P increased after afforestation with time relative to native vegetation, even though total P did not. Acacia trees have ability of accessing P from deeper soil layers and probably also utilizing organic forms more efficiently than grass (Sitters et al., 2013). In Arid-zone, acacia species may access P in iron phosphate probably due to carboxylate exudation and rhizosphere acidification (He et al., 2012). However, in some cases, the afforestation of savannas may threaten the sustainability of the ecosystems, as in the Chinese semi-arid region, where artificial plantations reduced the total P relative to natural elm savanna (Zhao et al., 2008).

#### 4.3. Replenishing soil P availability in natural savannas of the coastal Congolese plains

Therefore, via replenishing P availability in Arenosols of the Congolese coastal plains, the large use of inorganic fertilizers may be avoided to ensure fuel energy for rural population and secure forest productivity and sustainability. Because in the case of the over fertilization in the Congolese coastal plains, as in most parts of Sub-Saharan Africa, the government would not afford the cost of restoring the polluted lands and rivers. Sub-Saharan African countries should learn from mistakes made elsewhere and seek for new technologies and practices that will not damage the environment and compromise the health of their inhabitants (Barrow and Debnath, 2014; Scholz et al., 2014). In addition to the high cost of fertilizers which cannot be afford by most of farmers, the tropical weathered soils of Africa are very fragile and mainly nutrient-poor (Sanchez, 1976; Sanchez and Uehara, 1980; Laclau et al., 2010; Mareschal et al., 2011). Special care must be taken when adopting the use of inorganic fertilizers, which must be linked to improved agronomic strategies to avoid the over fertilization (Scholz et al., 2014). So, how African countries will manage to restore their lands and environment if by bad luck, they reach such level? However, no regarding its ability to improve nutrient cycling, the potential invasiveness of *A. mangium* has been already observed in some parts of the world (Koutika and Richardson, 2019). To preserve the biodiversity of ecosystems, the use of local nitrogen fixing species must be considered in the future planting.

It seems that the best option for the studied area, as for most other African areas, to avoid the large use of inorganic P fertilizers and secure crop and wood production, is to 'elaborate' their own way, taking into account all constraints (natural resources, financial, social economic, geographical and climatic) but also existing practices and improved agronomic strategies. Addition of combined inorganic fertilizers and organic nutrients (e.g. crop residues or manure) to soil helps to saturate part of the P-fixing capacity i.e., to minimise P fixation, and allow an increase in soil microbial biomass, with further slow release for crop uptake (Nziguheba et al., 1998; Scott and Melendez, 2001; Cu et al., 2005; Ayaga et al., 2006; Lan et al., 2012). To enhance P release and availability, Yerokun (2008) argued that releasing non-labile P, or minimizing immobilisation (application of agricultural lime and incorporation of organic matter) lead to an enhancement of optimum native P availability in uncultivated soils in Zambia. Soil P may be more effectively used in the mixed culture of a 'P-mobilizing' species (e.g., white lupin) with a more competitive 'P-utilizing' species (e.g. wheat) (Cu et al., 2005).

## 5. Conclusions

Introduction of nitrogen-fixing trees as a way to improve soil fertility led to an increase in standing wood biomass, soil C and N accretion in

the mixed-species stands. It also resulted in a decrease of soil P availability relative to pure eucalyptus and acacia stands at the end of the first 7-year rotation on the Arenosols of the Congolese coastal plains. Even then, it must be noticed that overall soil P availability in afforested stands was still higher than those of natural savannas at year 3 of the second rotation. This study is showing that in the low input systems; such as the studied experimental site, afforesting savannas increases P availability of inherently nutrient-poor but low P fixing soil, along with an increase in N stock and a potential C sequestration in both soil and biomass. This also indicates that inherently low soil P availability can be improved by using an appropriate practice e.g. mixed-species acacia and eucalyptus plantations. Current findings may also be relevant for the similar areas in Central Africa, extending around 6 million ha (Schwartz and Namri, 2002). However, practices leading to a decrease in P availability in the weathered soils inherently poor in available P, such as introducing nitrogen-fixing species in plantations or cropping systems, must be used with extreme caution. The risk of invasiveness of exotic species must always be considering before planting, preference must be given to local species.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:<https://doi.org/10.1016/j.geodrs.2019.e00207>. These data include the Google map of the most important areas described in this article.

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