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Effects of litter manipulation in a tropical *Eucalyptus* plantation on leaching of mineral nutrients, dissolved organic nitrogen and dissolved organic carbon

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ABSTRACT

Although many studies have shown that soil solution chemistry can be a reliable indicator of biogeochemical cycling in forest ecosystems, the effects of litter manipulations on the fluxes of dissolved elements in gravitational soil solutions have rarely been investigated. We estimated the fluxes of NH_4-N, NO_3-N, K, Ca, Mg, Na, Cl, dissolved organic nitrogen (DON) and dissolved organic carbon (DOC) over the first two years after re-planting *Eucalyptus* trees in the coastal area of Congo. Two treatments were replicated in two blocks after clear-cutting 7-year-old stands: in treatment R, all the litter above the mineral soil was removed before planting, and in a double slash (DS) treatment, the amount of harvest residues was doubled. The soil solutions were sampled down to a depth of 4 m and the water fluxes were estimated using the Hydrus 1D model parameterized from soil moisture measurements in 4 plots. Isotopic and spectroscopic analytical techniques were used to assess the changes in dissolved organic matter (DOM) properties throughout the transfer in the soil. The first year after planting, the fluxes of NH_4-N, K, Ca, Mg, Na, Cl and DOC in the topsoil of the DS treatment were 2–5 times higher than in R, which showed that litter was a major source of dissolved nutrients. Nutrient fluxes in gravitational solutions decreased sharply in the second year after planting, irrespective of the soil depth, as a result of intense nutrient uptake by *Eucalyptus* trees. Losses of dissolved nutrients were noticeably low in these *Eucalyptus* plantations despite a low cation exchange capacity, a coarse soil texture and large amounts of harvest residues left on-site at the clear cut in the DS treatment. All together, these results clarified the strong effect of litter manipulation observed on eucalypt growth in Congolese sandy soils. DOM fluxes, as well as changes in $\delta^{13}C$, C:N and aromaticity of DOM throughout the soil profile showed that the organic compounds produced in the litter layer were mainly consumed by microorganisms or retained in the topsoil. Below a depth of 15 cm, most of the DOC and the DON originated from the first 2 cm of the soil and the exchanges between soil solutions and soil organic matter were low.

1. Introduction

Planted forests are expanding rapidly worldwide to meet the increasing demand in forest products (FAO, 2010). Plantation forests designed to meet social, economic, and environmental objectives are likely to provide key ecosystem services and can therefore contribute to preserving natural forests (Paquette and Messier, 2010). However, the sustainability of tropical plantations is of concern since large amounts of nutrients are exported with biomass harvesting in highly weathered soils (Gonçalves et al., 2013; Nambiar, 2008). The management of organic residues at harvesting in tropical forests can strongly impact ecosystem functioning with direct consequences on soil physical properties, nutrient stocks, carbon (C) cycling, plant growth, microbial communities and soil fauna (Sayer, 2006). Saint-André et al. (2008) showed in a network of tropical experiments that the poorest was the soil, the highest was tree response to harvest residue manipulations. This pattern might reflect a key role of the nutrients released throughout residue decomposition on tree growth in nutrient-poor soils (Laclau et al., 2010; Versini et al., 2013). Although the chemical composition of soil solutions is recognized as highly sensitive to management practices, the effects of litter manipulation on dissolved nutrient fluxes have, surprisingly, received little attention in forest ecosystems (Laclau et al., 2003a; Piirainen et al., 2009; Smethurst et al., 2001).

The factors driving dissolved organic matter (DOM) fluxes in the soil are of immense importance since DOM has been recognized to play a

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fundamental role in soil functioning and C sequestration. However, studies dealing with DOM (and particularly dissolved organic nitrogen, DON) dynamics are still scarce in tropical forests (Chantigny, 2003; Fujii et al., 2009, 2013; Möller et al., 2005). Decomposing litter is a potential source of DOM (Currie et al., 1996; Riaz et al., 2012) and litter manipulations at the soil surface are therefore likely to modify the inputs of organic matter (OM) into the mineral soil (Kalbitz et al., 2007; Klotzbücher et al., 2012; Park and Matzner, 2003). The forest floor is an organic layer (O horizon) consisting of organic material in various stages of decomposition, above the mineral soil, and is therefore expected to be a major source of DOM for the mineral soil. Some studies suggested that fresh litter was the major source of DOM entering into the mineral soil (Currie and Aber, 1997; Michalzik and Matzner, 1999) while recent research provided evidences that the main source of DOM can be the most humified part (Oa) of the O horizon (Fröberg et al., 2005; Kalbitz et al., 2007; Klotzbücher et al., 2012). DOM can be transferred trough gravitational soil solutions in deep soil layers or can interact with soil organic matter (SOM) along the soil profile (Fröberg et al., 2006; John et al., 2003; Sanderman et al., 2008). Sandy soils, that are characterized by low adsorption capacities and high infiltration rates, are usually considered as large exporters of litter-derived DOM in tropical regions (Aitkenhead-Peterson et al., 2007; Sanderman et al., 2008).

Clonal *Eucalyptus* plantations have been set up in the coastal plains of Congo since the 70s for pulpwood production purpose. Even though several decades of breeding and researches in silviculture increased the productivity of these commercial plantations, the low amounts of fertilizers applied make their sustainability highly sensitive to nutrient losses by leaching during the post-harvest phase (Laclau et al., 2005; Mareschal et al., 2013). After afforestation of the native savanna, clonal *Eucalyptus* stands are harvested every 6–9 years in Congo, before a sharp decrease in annual increment. Mean productivity is about 20 m^3 ha^{-1} $year^{-1}$, which is at the lower range of commercial plantations worldwide (Gonçalves et al., 2013). Most of the plots are replanted after harvesting and the silvicultural practices are similar to other tropical commercial plantations managed to produce high amounts of biomass.

The objective of this study was to investigate the effects of litter manipulations at the harvest of tropical *Eucalyptus* plantations on the chemistry of soil solutions and the losses of nutrients, dissolved organic carbon (DOC) and DON by leaching. Soil solutions were acidic at this study site and a minor contribution of inorganic carbon to total carbon fluxes was therefore expected. Two contrasting treatments (removal vs addition of harvest residues at the soil surface) were compared to estimate the contribution of the O horizon to the input of DOM and dissolved nutrients into the mineral soil. Isotopic and spectroscopic analytical techniques were used to assess changes in DOM chemical properties throughout their transfer from the topsoil to deep soil layers.

The hypothesis of the study were that i — the O horizon was a major source of DOM and nutrients, highlighting the role of litter management on *Eucalyptus* growth in Congolese plantations and ii — harvesting led to large losses of nutrients and DOM by leaching when fresh residues were added at the soil surface.

2. Material and methods

2.1. Study site description

The study site of Kondi was located on the coastal area of Congo (4° 34′ S, 11° 54′ E, 100 m elevation). The climate is sub-equatorial with a rainy season from October to May and a dry season from June to September. Mean annual rainfall is about 1220 mm, and mean annual temperature is 25.5 °C with seasonal variations of about 5.0 °C. The soil is classified as Ferralic Arenosols (FAO). Briefly, this soil is characterized by a homogeneous sandy texture down to more than 10 m, a moderately acidic soil pH, and very low amounts of exchangeable 'base' cations and organic matter (Table 1). The soil mineralogy is dominated by quartz and kaolinite and nutrient bearing minerals are very scarce (Mareschal et al., 2011). The vertical distribution of SOM in these soils was characterized by high variations of $\delta^{13}C$ along the soil profile as a consequence of C_3–C_4 type vegetal successions. Before the afforestation of savanna with *Eucalyptus* trees, the upper 40 cm of soil was entirely composed of C_4-derived OM ($\delta^{13}C$ of −13‰) from the savanna (Trouvé et al., 1994), the proportion of this OM decreased progressively down to the depth of 3 m where the SOM was entirely composed of old and stable C_3-derived OM ($\delta^{13}C$ of −25‰) originating from a forest replaced 3000 years ago by the herbaceous savanna (Schwartz et al., 1992). The afforestation with *Eucalyptus* ($\delta^{13}C$ of −30.5‰) led to a progressive substitution of C_4-SOM by C_3-SOM in the upper 50 cm of the soil profile and to an exponential $\delta^{13}C$ decrease in SOM relative to time since afforestation (Epron et al., 2009; Trouvé et al., 1994) (Table 1).

The present study was carried out in two adjacent stands (A and B considered as two blocks in this study) planted on native savanna with the same clone of a *Eucalyptus* hybrid (PF1, unknown species, clone 1-41). The A stand was afforested in 1992 and the B stand in 2001, at a stocking density of 532 trees per ha. The A stand was harvested in 2001, the stumps were killed by glyphosate application and the stand was re-planted with a more productive clone (18-52) from the hybrid *Eucalyptus urophylla* (ST Blake) × *Eucalyptus grandis* (Hill ex Maid.), at a stocking density of 800 trees per ha. The soil properties and the chemistry of soil solutions were studied in these two stands over this period (Laclau et al., 2003b, 2005; Mareschal et al., 2013). The two stands were harvested in March 2009 and two treatments were immediately replicated in each stand (i.e. 4 plots):

R (Removed): the O horizon was removed from the plot (litter from the previous rotation as well as harvest residues),

DS (Double Slash): only debarked commercial-sized boles (top-end over-bark diameter > 2 cm) were removed. Harvest residues of the R plots were added in the DS and uniformly distributed on the ground. This treatment left on the soil surface 6.4 kg m^{-2} of dry matter in stand A and 4.5 kg m^{-2} in stand B, of which about 35% was fresh leaves.

Table 1
Soil properties and stocks of total C, total N, exchangeable nutrients, Fe and Al oxy-hydroxide down to a depth of 4 m calculated from concentrations measured at the same site (Laclau et al., 2003b; Mareschal et al., 2011).

Soil layer	Particle size distribution (%)			$\delta^{13}C$ (‰)[a]		Concentrations (g kg^{-1})								Stocks of element (g m^{-2})							
cm	Clay	Silt	Sand	Plot A	Plot B	C	N	K	Ca	Mg	Na	Fe	Al	C	N	K	Ca	Mg	Na	Fe	Al
0–5	7.7	2.1	87.7	−23.7	−19.2	8.90	0.53	0.01	0.02	0.01	0.01	13.00	25.00	627	37	1	2	1	1	917	1763
5–15	7.1	2.1	88.6	−19.9	−16.7	4.87	0.29	0.01	0.01	0.01	0.01	13.15	26.09	682	40	1	2	1	1	1842	3652
15–50	7.0	2.1	89.1	−15.0	−13.7	2.71	0.17	0.01	0.01	0.00	0.00	13.31	27.72	1328	81	3	3	1	1	6521	13,584
50–100	9.9	2.2	86.6	−19.0	−19.0	1.79	0.11	0.01	0.01	0.00	0.00	14.52	30.59	1386	87	5	4	1	4	11,254	23,705
100–200	10.3	2.4	86.1	−24.0	−24.0	1.27	0.08	0.01	0.01	0.00	0.01	15.53	34.94	1964	125	10	9	3	11	24,066	54,152
200–400	11.3	2.7	85.1	−25.0	−25.0	0.90	0.06	0.00	0.01	0.00	0.01	16.53	40.94	2801	182	14	16	7	23	51,580	127,723

[a] $\delta^{13}C$ was measured in the 0–5 and 5–15 cm soil layers just before clear-cutting in stands A and B (Derrien, unpublished data), values in the 15–50 cm soil layer were measured in the same plots in 2006 (Epron et al., 2009) and values below a depth of 50 cm were measured by Trouvé et al. (1994) in the same soil type under a nearby savanna.