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Nutrient leaching and deep drainage under *Eucalyptus* plantations managed in short rotations after afforestation of an African savanna: Two 7-year time series

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ABSTRACT

African savannas developed an efficient strategy of nutrient uptake and control of nitrification making it possible to avoid large losses of nutrient by drainage. The conversion of native savanna into commercial forest plantations is an important global change driver that potentially impacts element cycles.

Afforestation of native Congolese savannas by *Eucalyptus* started 30 years ago. Large amounts of nutrients are removed through biomass harvesting every 6–7 years. Losses of nutrients by deep drainage might be a serious threat for the sustainability of these plantations, established on sandy soils with high hydraulic conductivities.

We compared the soil N-mineralisation, the nutrient fluxes and deep drainage beneath savanna and *Eucalyptus* plantation in Congo. Then, we discussed the strategy of nutrient recycling.

The water fluxes at a depth of 400 cm were approximately 20% higher in the savanna than in *Eucalyptus* plantation.

Although the nitrification rate and solution chemistry exhibited strong modifications during the first year following both savanna afforestation and the harvesting of the *Eucalyptus* stand, the losses of nutrients by deep drainage remained unexpectedly low. The largest fluxes of drainage at a depth of 6 m were found for NH_4^+-N, which reached a maximum of 0.4 g m^{-2} yr^{-1} in the second year following savanna afforestation and 1 g m^{-2} yr^{-1} in the first year after clear cutting. The deep drainage of NO_3^--N, Mg^{2+}, Ca^{2+} and K^+ did not exceed 0.2 g m^{-2} yr^{-1} in the savanna and at any stage of plantation development. These results are discussed regarding (i) the roots distribution in the soil of each ecosystem and (ii) the nutrient accumulation in biomass.

The limited changes between the nutrient fluxes in both ecosystems were the result of fast root growth in the deep soil layers after planting, combined with an intense uptake of the tree roots to satisfy the large nutrient and water requirements for the development of tree crowns.

Intense uptake and cycling of nutrients mitigated the risk due to clear cut and N fertilisation in this forest plantation. Nevertheless, forest managers must carefully fit fertilisation regimes to the nutrient requirements of new clone selected by breeding programmes and reduce as much as possible the delay between harvesting and re-planting to avoid high losses by deep drainage.

1. Introduction

Because native forest ecosystems are increasingly subject to zhuman pressures in tropical regions, forest plantations should play a growing role in the future to supply the population needs and to preserve native forests (Paquette and Messier, 2010). The overall area of forest plantations greatly increased during the last decade to reach 205 million ha, fulfilling one third of the world demand for wood products (FAO, 2010). Subtropical and tropical hardwood plantations are dominated by the *Eucalyptus* genus (FAO, 2010), which provides the raw material for pulp and particle boards and also large amounts of firewood for domestic uses. The rate of afforestation of native grasslands, particularly high in the

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Southern Hemisphere, may have a strong environmental impact both globally on the carbon and nutrient cycles and locally on hydrology, commonly reducing stream flows (Jackson et al., 2005; Nosetto et al., 2005; Jackson et al., 2008; Parfitt and Ross, 2011; Uri et al., 2011). The sustainability of those plantations in tropical regions is of concern because these plantations are usually established on low-fertility soils where large nutrient exports occur with biomass removal every 6–7 years. Afforestation and forest plantation management are likely to cause ecosystem degradation. Recent intensification of harvesting practices, introduction of more productive tree species, shortening of rotation lengths and mechanization of silvicultural practices impact the physical, chemical and biological properties of the soils (Bruijnzeel, 1998; Rosenqvist et al., 2011).

Increase in the nitrification and mineralisation rates after a disturbance due to changes in the soil microclimate and harvest residue deposition are likely to increase nutrient losses by deep drainage from the forest ecosystems (Vitousek and Melillo, 1979; Attiwill and Adams, 1993; Dahlgren and Driscoll, 1994; Ranger et al., 2007). In most cases, logging and burning increase the nutrient concentration in the top soil and in the soil solutions (Uhl and Jordan, 1984; Eden et al., 1991; Klinge, 1997) leading to an increase in nutrient concentrations in the stream waters. A concentration peak is often observed some months after a disturbance, followed by a slow return to pre-disturbance values. Little is known about nutrient losses by deep drainage following disturbances in tropical natural or plantation forests, particularly in Africa, when compared to temperate or boreal forests. While the effects of fertiliser applications on soil solution chemistry are well documented in forest plantations (Smethurst, 2000; Ring, 2004; Mitchell and Smethurst, 2008), studies on the effects of afforestation are scarce (Hansen et al., 2007). Nutrient drainage is most often high in commercial forest plantations linked to high levels of fertilisation (Mitchell and Smethurst, 2008), but drainage is most often measured in the first levels of the soil, while deep rooting is important in tropical forest plantations, even in young stands.

Some studies on African savannas have evidenced a strong control of nitrogen cycling by herbaceous vegetation. The inhibition of nitrification in such an ecosystem is considered as an important strategy to reduce nitrogen losses by deep drainage (Bernhard-Reversat, 1996; Lata et al., 1999; Lata et al., 2000; Subbarao et al., 2007). Indeed, diffusion coefficient of NH_4^+ being much lower than NO_3^-, because preferentially held on soil cation exchange site (Veresoglou et al., 2011). Afforestation of tropical savannas could likely impact this process and potentially induce a rise in nitrogen leaching. The ecological consequences of the afforestation of native herbaceous savannas with *Eucalyptus* plantations have been intensively studied for 2 decades in the Congo. The risks of nutrient losses following a disturbance are high in those plantations because (i) the high annual rainfall concentrated over 6 months may lead to high water fluxes in the soil, (ii) the soil is sandy (85–90% of sand) with high hydraulic conductivities, (iii) the retention capacities of the nutrients are low in those highly weathered soils (low amounts of reactive minerals, mainly quartz and kaolinite, and low organic matter content) (Mareschal et al., 2011) and (iv) the rates of organic matter mineralisation are high due to the favourable climatic conditions of the wet season (Versini et al., 2012). Soil solutions have been monitored over 7 years in two adjacent stands, leading to a diachronic sequence of 14 years: a native savanna monitored over 3 years, followed by the first 4 years after planting *Eucalyptus* trees on this savanna, and the last 3 years before clear-cutting an adjacent *Eucalyptus* stand (6–9 years after afforestation), followed by the first 4 years after replanting *Eucalyptus* trees after the harvest. Our study aimed to assess the consequences of replacing a native African savanna by an exotic tree species on nutrient losses by deep drainage. We hypothesized that (i) the shift in vegetation impacts N mineralisation, leading to a qualitative and quantitative change in nitrogen forms both in soils and soil solutions, and (ii) major disturbances (afforestation and clear-cutting) modify the nutrient concentrations in the soil solutions, leading to large nutrient losses by deep drainage in this tropical sandy soil.

2. Materials and methods

2.1. Study site

The study was performed at the Kondi site in a clonal *Eucalyptus* stand and in a native savanna located 10 km from the sea. *Eucalyptus* plantations have been established near the city of Pointe Noire on the Atlantic coast of the Congo and approximately 90 km inland (4°S, 12°E). The ecological situation was described in Laclau et al. (2003). In brief, the climate is characterised by high atmospheric humidity (85% on average) with low seasonal variations (2%). The mean annual rainfall reaches approximately 1300 mm with a marked dry season from May to October. The mean annual temperature is high (25 °C) with seasonal variations of approximately 5 °C. The topography is slightly undulating. On the plateau, where most of the plantations are located, the altitude ranges from 80 to 120 m. The bedrock is composed of thick detritic layers (down to 100 m) of continental origin and the soils are deep Ferralic Arenosols (Mareschal et al., 2011). The native vegetation established on these soils consists of herbaceous savanna which has occupied this area since the Upper Holocene (Schwartz et al., 1995; Trouvé, 1992). This tropical grassland was dominated by *Loudetia arundinacea* which was burned each year at the beginning of the dry season. The dynamics of the biomass and nutrient accumulations in the savanna species after burning were studied at our study site (Laclau, 2001).

2.2. Plant material and stand management

A clonal *Eucalyptus* stand (from a natural hybrid selected in the Congo) was planted on the savanna in January 1992 and was 6 years old at the onset of our study (1998). Lysimeters were installed in 1997 in an adjacent savanna (plot A) located 300 m apart and in the studied *Eucalyptus* plantation (plot B) (Laclau et al., 2003). The trees in stand B were harvested in 2001. Only debarked, commercial-sized boles and coarse branches (diameter >4 cm) were removed from the clear-cut area for pulpwood (boles) or charcoal production (coarse branches). The leaves, bark, bole tops and small branches were left on the ground, following the silvicultural practices in commercial plantations. A more productive clone of *E. urophylla* (ST Blake) × *E. grandis* W. Hill ex Maiden was replanted after clear cutting.

The savanna was planted in 2001 with the clone planted in 1992 in plot B. Before planting, glyphosate was applied to kill the stumps in the *Eucalyptus* stand and the plants in the savanna. Fertilisation was applied 3 months after planting using 10 kg N ha^{-1}, 5 kg P ha^{-1} and 14 kg K ha^{-1} in both stands.

The soil solution chemistry and soil water contents were monitored continuously from January 1998 to December 2004 (Fig. 1). The consequences of the main disturbances resulting from forest management (afforestation of the native savanna and clear cutting) were studied over a 14-years time series.

2.3. Soil properties

The soil properties and soil mineralogy of the experimental site have been described in detail by Mareschal et al. (2011). The particle size distributions of the soil showed the predominance of