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Abstract

*The present paper is part of a comprehensive approach currently developed in Brazil to study biogeochemical cycles at the ecosystem level in **Eucalyptus grandis** plantations. It aims at assessing changes occurring in water chemical composition throughout their transfer in the soil, during the first year after planting. A lysimetry was installed in a 5-year-old **E. saligna** stand. Lysimeters were strategically positioned within a compartment of **E. saligna** prior to the clear felling of the stand that would allow the assessment of a fertilization experiment planned on the same site for the next rotation. About 180 zero-tension lysimeters were installed in the upper soil layers and 136 ceramic cups were setup horizontally down to a 3 m depth and connected to an automatic vacuum pump. After the harvest of the **E. saligna** stand, a fertilization experiment of **E. grandis** improved seedlings was initiated using a complete randomized block design, with 6 blocks and 5 treatments. The objective was to compare the influence of different amounts of ammonium sulphate and sewage sludge fertilizations on biogeochemical cycling. At the end of the rotation, nutrient concentrations in soil solutions were low whatever the depth and the lysimeter type. After clear felling, soil solution ionic balances were dominated by NO_3^- and Al^{3+}, whose concentrations increased substantially. No obvious change in concentrations was observed for all other elements. A proton unbalance, resulting from the interruption of NO_3^- uptake by plants after harvesting, might be responsible for the aluminium accumulation in soil solutions. After planting, fertilizer inputs were responsible for increasing concentrations of all elements applied until 1 m deep. Twelve months after planting **E. grandis**, the chemistry of soil solutions at 3 m deep had not developed. The monitoring of soil solution chemistry is going on in order to quantify the effects of these different fertilizations on deep drainage nutrient losses.*

Introduction

Fast growing *Eucalyptus* plantations cover approximately 3 millions hectares in Brazil. This sector is of great economical importance since the *Eucalyptus*-plantation production supplies the Brazilian cellulose and paper industry as well as the metallurgy industry through the production of vegetal charcoal. Due to several decades of research, the productivity of these plantations now ranges from 30 to 50 kg ha^{-1} year^{-1} according to soil characteristics and water availability (Gonçalves et al., 2004).

The ecological impact of *Eucalyptus* plantations has been widely discussed around the world (Cossalter and Pye-Smith, 2003). In particular, water consumption by eucalypt stands has been extensively investigated. But few studies have ever assessed the influence of silviculture on superficial water chemistry. Such studies are nonetheless necessary to identify and foster practices minimizing the silvicultural impact on the water table chemistry of afforested catchments.

A comprehensive approach is currently being conducted at the University of São Paulo to study the

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biogeochemical cycles of nutrients in *Eucalyptus grandis* plantations. This project is developed at the ecosystem level in an experimental stand representative of large areas of plantations in Brazil. The overall aim of the study is to assess the consequences of silviculture, and more particular of different fertilizer inputs, on water quality and long-term soil fertility by measuring water and nutrient fluxes throughout the ecosystem. The present paper focuses on changes occurring in soil solution chemical composition during the first year after planting.

Materials and methods

Site characteristics

The study was conducted at the ESALQ/USP experimental station of Itatinga (23º02′S, 48º38′W). The annual mean precipitation is 1,300 mm and the annual mean temperature is 20ºC. Figure 1 shows the time course of rainfall and temperature over the sampling period. The selected site is representative of the typical relief of the São Paulo Western Plateau. The maximum altitude of the area is 863 m. The slopes are flat to undulating (3%) in the experimental stand. The lithology is composed of sands, Marilia formation, Bauru group. The soils are "Latossolos Vermelho-Amarelo" according to Brazilian classification. Soil analysis showed that sand content was >75%, whatever the soil layer, down to >6 m.
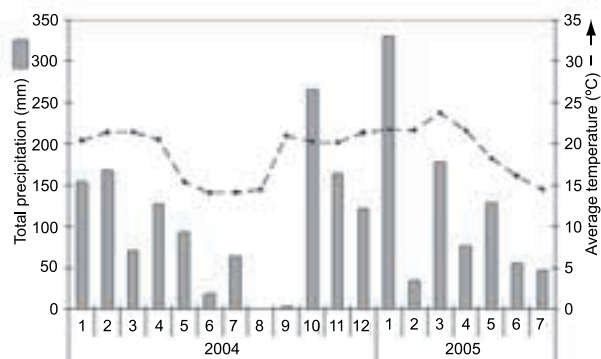

Figure 1. Time course of average temperature (ºC) and total precipitation (mm) at the experimental site

The Itatinga experimental station has been covered for 60 years with *Eucalyptus saligna* plantations. These stands were first planted in 1945 on pasture and have been managed in short rotation coppices for fire wood production since then. The experimental design was implemented in 2003 in a 6 ha coppice harvested in 1997, and planted in 1998 with *Eucalyptus saligna*. Tree spacing was 3 m × 2 m and only a NPK (10:20:10) starter fertilization of 300 kg ha^{-1} was applied.

Methodology

A lysimetric design was installed at the beginning of 2003 in the 5-year-old *E. saligna*. Lysimeters were positioned appropriately for a fertilization experiment planned on the same site for the next rotation, after the harvest. A 3 months period was left for soil stabilization, and then nutrient fluxes were monitored over a 9 month period prior to the harvesting of the stand (from July 2003 to February 2004). In February 2004, the stand was clear felled and the stumps killed using glyphosate. Improved *E. grandis* seedlings were planted on the same planting rows at half-distance between the stamps, without any soil preparation. The previous stocking density was maintained (2 m × 3 m spacing).

A nitrogen fertilization experiment was then initiated using a complete randomized block design, with 6 blocks, 5 treatments and 100 trees per plot. The fertilization treatments imposed were those classically used by Brazilian companies on these soil types: all mineral fertilizers but N (T1) (Control), all mineral fertilizers (T3), and sewage sludge fertilization (T$_5$). Nutrient fluxes were measured in these three treatments (T$_1$, T$_3$, T$_5$) in blocks 1, 2 and 3. Blocks 4, 5 and 6 were installed to sample trees at various ages without disturbing the lysimetry design (Table 1). T$_2$ and T$_4$ treatments were installed to help establish a response curve to N inputs. The fertilizations applied in each treatment are presented in Table 1.

The soil solution sampling equipment was installed in blocks 1, 2 and 3 of treatments T$_1$, T$_3$, T$_5$ according to a systematic constant scheme. Throughfall solutions were collected from 12 funnels systematically located beneath the trees in each one of the 9 experimental plots. In each plot, 3 sets of 9 narrow zero-tension lysimeters (40 × 2.5 cm) were installed beneath the forest floor, and zero-tension plate lysimeters (50 x 40 cm) were introduced at 15, 50 and 100 cm deep (5 at each depth) from pits backfilled after installation with the horizons in their natural arrangement. The litter and soil solutions were collected in polyethylene containers situated downhill in closed pits. Moreover, 4 replicates of tension lysimeters were installed horizontally at the depths of 15 cm, 50 cm, 1 m, and 3 m in each plot. They were connected to a vacuum pump and automatically maintained at a constant suction of -70 kPa. Ceramic-cup solutions were collected in glass bottles. All lysimeters were set up representatively near and between the trees to take into account spatial variability. In each plot, lysimeters of same type and depth were connected to one collector in order to

Table 1. Experimental treatments and fertilization strategies imposed

	Nitrogenous fertilization			Other fertilizers
	Amount	**Fertilizer type**	**Application type**	
		Control		
T1	0		4 equal partsat planting	■ Triple superphosphate (75 kg ha⁻¹ P₂O₅)
T2	40 kg ha⁻¹	Ammonium sulfate	6 months	■ KCl (30 kg ha⁻¹)
T3	120 kg ha⁻¹ (commercial fertilization)		12 months	■ Trace elements (45 kg ha⁻¹ FTE BR12)
				■ Boron (45 kg ha⁻¹ Borogran)
T4	360 kg ha⁻¹		18 months	■ Dolomitic limestone (2 t ha⁻¹)
T5	350 kg ha⁻¹ N$_{total}$	10 t ha⁻¹ sewage sludge (Barueri, SP)	2 equal parts at planting at 8 months	■ KCl (30 kg ha⁻¹ K₂O)

reduce the number of chemical analyses. Chemical analyses of solutions collected by each ceramic cup separately were performed in a few blocks and depths in order to estimate the spatial variability (data not presented). Rainfall solutions were collected in a 1 ha opened area, next to the experimental plots.

Solutions were collected each week from July 2003 to June 2005. A composite sample for each type of collectorwas prepared every 4 weeks. The solutions were filtered (0.45 µm) and the pH was measured. SO_4^{2-}, NO_3^-, NH_4^+, Cl^-, $H_2PO_4^-$, K^+, Ca^{2+}, Mg^{2+}, Na^+ were analysed by chromatography (Dionex). Al, Fe, Si and dissolved organic carbon (DOC) were determined by ICP and Shimadzu equipment for each depth, treatment and collector type on a three-block composite sample.

Soil solution ionic balances were computed considering the species: SO_4^{2-}, NO_3^-, NH_4^+, Cl^-, H_2PO_4, K^+, Ca^{2+}, Mg^{2+}, Na^+, H^+. NO_2 and Fe concentrations were very low so that they were neglected in the calculations. As the pH of soil solutions were between 4 and 5 until 1 m deep, aluminium was considered as Al^{3+} in this first preliminary approach.

The whole study will help to relate the soil solution characteristics to the dynamics of biomass and nutrient accumulation in the stands, as well as of nutrient returns to the soil with litter fall and forest floor decomposition.

Results and discussion

Nutrient concentrations in soil solutions were low (<100 µmol$_c$ L⁻¹) over the 9 months of monitoring at the end of stand rotation, whatever the depth and the type of lysimeter (Laclau et al., 2004). A similar behaviour was observed in other tropical forest plantations. This confirms the species ability to prevent deep drainage nutrient losses as soon as the root system is completely developed (Lilienfein et al., 2000; Laclau et al., 2003a).

Clear felling sharply increased nitrate concentrations in surface (0-50 cm) soil layer solutions, and this, without any fertilizer application (Figure 2). This pattern suggests that the sudden interruption of N uptake by plants resulting from herbicide application, combined with the production of mineral N by the mineralization of soil organic matter and forest residues, led to an accumulation of mineral N in these soil layers.

Soil solution ionic balances were dominated by NO_3^- and Al^{3+}, and the concentrations of other elements were little influenced by clear felling during the first months (data not shown). The accumulation of NO_3^- in soil solutions was thus linked with the release of Al^{3+} in soil solutions. The hypothesis formulated to explain such behaviour was that the interruption of NO_3^- uptake by plants leaded to a proton unbalance which might be responsible for the accumulation of aluminium in soil solutions. Indeed, after clear felling, the protons released during the nitrification were no more removed from soil solutions by plant anion uptake and thus, accumulated in the soil solution (Van Breemen et al., 1984). The H^+ may then have desorbed the Al^{3+} on the ion-exchange sites and solid phase dissolution, leading to an increase of aluminium concentrations in soil solutions. As an increase of Si concentration in soil solutions was also observed after clear cutting, some mineral weathering may also have occurred under H^+ influence, releasing mineral Si and Al in soil solutions.

After the planting, fertilizer inputs were responsible for an increase in surface layer concentrations in all elements applied (K^+, Cl^-, NH_4^+, SO_4^{2-}, Ca^{2+}, Mg^{2+}). It resulted in increasing sums of cations and anions as well as the predominance of the elements brought by fertilization in the ionic balance, as for NH_4, Mg and Ca regarding cations (Figure 3). The sum of cations was then very high (>7,000 µmol$_c$ L⁻¹) but declined with depth and time until reaching more common values at 3 m deep. At this depth, the sum of cations was approximately 200 µmol$_c$ L⁻¹, that