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Low nutrient losses by deep leaching after clearcutting and replanting *Eucalyptus* plantations in Brazil

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ABSTRACT

Sustainable management of highly productive eucalypt plantations requires the application of fertilizers to balance nutrient exports associated with biomass removal every 6-7 years. Although deep leaching after clear-cutting is an important component of input-output budgets of nutrients in forest soils, accurate quantifications are rare in tropical plantations. Our study aimed to assess the consequences of management practices in highly productive eucalypt plantations on nutrient losses by deep leaching in two hillslope positions with contrasting soil types. Soil solutions were continuously collected using lysimeters down to a depth of 3 m, in the last year before the clear-cutting, then in the first 3.5 years after replanting. Concentrations of the main cations and anions were determined monthly and fluxes of gravitational solutions at the depths where the lysimeters were installed were estimated using the Hydrus 1D model, calibrated *in situ*. Stand productivity was high in both landscape positions with a mean basal area at harvest of 35 m^2 ha^{-1} at the bottom of the slope and 27 m^2 ha^{-1} at the top of the slope. Soil solution chemistry in the topsoil was highly responsive to management practices with sharp increases in ionic charges after clearcutting and fertilizer applications. While leaching fluxes of mobile ions (especially N-NO_3^-, K^+ and Mg^{2+}) reached values greater than 30 kg ha^{-1} yr^{-1} at a depth of 1 m after clear-cutting, they remained lower than 3 kg ha^{-1} yr^{-1} at a depth of 3 m both in the upper and lower hillslope positions throughout the rotation. Our study suggests that splitting fertilizer applications may not be necessary in tropical *Eucalyptus* plantations established in very deep tropical soils.

1. Introduction

Eucalypt plantations cover about 20 million hectares found in more than 90 countries around the world with a high diversity of management practices (Booth, 2013; Zhang and Wang, 2021). While the small woodlands commonly found in developing countries for firewood and charcoal uses commonly exhibit low productivities, commercial eucalypt plantations managed intensively to produce raw material for industry are among the highest gross primary productivity (GPP) forests in the world (Stape et al., 2008). Eucalypt plantations in Brazil provide pulp, paper, wood panels and charcoal for steel production. Therefore, companies are engaged in a continuous search for competitiveness and innovation. Research programs in genetic improvement and silviculture (with innovative techniques in site preparation, fertilization, spacing, weed control) over several decades, made it possible to triple the productivity of commercial plantations from the 1970s (Stape et al., 2010). The mean annual increment over the 5.7 million hectares of eucalypt plantations in Brazil was 37 m^3 ha^{-1} yr^{-1} in 2020, with an average close

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to 50 m^3 ha^{-1} yr^{-1} over 1.35 million ha in São Paulo state (IBÁ, 2021).

Plantations in the tropics are generally established on highly weathered soils with low fertility. In these poor soils, the sustainability of highly productive planted forests is a concern since large amounts of nutrients are exported over successive rotations via biomass removal. The period between clear-cutting of the previous stand and canopy closure of the re-planted stand is critical for the maintenance of soil fertility in tropical plantations (Cuevas et al., 2018; Perron et al., 2022). Soil solution chemistry has been extensively studied as an indicator of soil functioning (Schoenholtz et al., 2000; Rengasamy, 2016). Nutrient concentrations commonly increase after clearcutting in the soil solutions sampled in the topsoil as a result of changes in the soil microclimate and harvest residue accumulation at soil surface with a peak often observed some months after clear-cutting, followed by a slow return to pre-disturbance values (Versini et al., 2014). An interruption of water and nutrient uptake by tree roots after clearcutting, combined with an increase in mineralisation rates of organic matter resulting from an increase in soil temperature and moisture relative to the pre-harvest period, are likely to increase nutrient losses through deep drainage (Ranger et al., 2007; Shah and Nisbet, 2019).

Final standing biomass in eucalypt plantations is dependent on early growth rates and intensive management practices are needed to reach canopy closure as quickly as possible (Gonçalves et al., 2013). Fertilizers are commonly applied to balance nutrient exports in commercial plantations, considering the dynamics of nutrient demand by trees as well as the time-course of nutrient availabilities in the soil and the main components of the input-output budgets (Ranger and Turpault, 1999). Large amounts of nutrients applied as fertilizers can lead to high leaching losses in plantations (Cannavo et al. 2013; Mitchell and Smethurst, 2008; Lee and Jose 2005), but nutrient leaching is often measured down to a depth of 1 or 1.5 m, while nutrients can be taken up by eucalypt roots at a depth of 6 m only 1 year after planting (Pinheiro et al., 2019). While measurements of nutrient leaching at a depth of more than 1.5 m are rare (Wilcke and Lilienfein, 2005; Silva et al., 2013), a sharp decrease in nutrient concentrations has been shown throughout the transfer of gravitational solutions between the depths of 1 m to 3 m in eucalypt plantations (Mareschal et al., 2013; Versini et al., 2014). As far as we are aware, comprehensive studies quantifying nutrient leaching fluxes at depths greater than 2 m have only been performed in tropical forest plantations with low amounts of fertilizer application (< 50 kg ha^{-1} yr^{-1} for N, P and K). When large amounts of fertilizers are applied, nutrients could be lost through deep drainage following clear-cutting of tropical plantations because: i) the high annual rainfall concentrated in the rainy season can lead to high fluxes of gravitational water in deep soil layers, ii) nutrient retention considered low in highly weathered soils due to low amounts of reactive minerals and low organic matter content, although low ion exchange capacities over a large soil mass may lead to relatively high nutrient retention and iii) the rates of organic matter mineralisation are high during the rainy season (Cheng et al. 2014, Laclau et al., 2003; Shah and Nisbet, 2019). In addition, the soil texture is likely to greatly influence the velocity of water transfer throughout the soil profile (Williams et al., 1983; Landsberg and Sands, 2011), with a faster movement of nutrient-enriched solutions after fertilization in coarse-textured soils than in fine-textured soils. However, very deep rooting is common in tropical areas (Silva et al.; 2020; Tumber-Dávila et al., 2022), and the very fast growth in deep soil layers of tree roots can help prevent losses by deep drainage with an efficient 'safety net' (Suprayogo et al., 2002; Pinheiro et al., 2019). Estimates of potassium (K) and nitrogen (N) losses were greater than 10 kg ha^{-1} yr^{-1} at a depth of 1 m in the first year after planting eucalypts in tropical sandy soils (Silva et al., 2013; Versini et al., 2014; Binkley et al., 2018), but the rare quantifications at a depth of 3 m suggest that the losses are of the same order of magnitude as atmospheric inputs (Mareschal et al., 2013; Versini et al., 2014; Maquère, 2008).

Our study aimed at quantifying the effects of common management practices on nutrient losses by deep drainage in commercial eucalypt plantations established in deep tropical soils. We hypothesized that the amounts of nutrients leached in gravitational solutions are large in the upper soil layers but the losses at a depth of 3 m remain of the same order of magnitude as atmospheric inputs throughout the rotation.

2. Material And Methods

2.1. Study site

The study was carried out in an experimental area of 90 ha managed for more than 20 years as commercial eucalypt plantations in southeast Brazil (22°58'04 "S, 48°43'40" W) at 750 m above sea level (Eucflux project, https://www.ipef.br/eucflux2/). The relief was typical of the São Paulo Western Plateau, with a gently undulating topography (slope of about 5% in the experimental area, Campoe et al., 2012). The mean annual rainfall over the last 20 years was 1,360 mm (about 85% during the rainy season from October to May). The average annual temperature was 19.2°C, ranging from 13.3°C in the coldest months (June to August) to 27.2°C in the warmest months (December to February). The annual mean relative air humidity was 77%, with the lowest values in winter (~45%). Soils were very deep Ferralsols (FAO classification) developed on Cretaceous sandstone, Marilia formation, Bauru group. The depth of the water table ranged from a depth of 18 m before harvesting the eucalypt trees to 12 m at the end of the second rainy season after replanting (Christina et al, 2017). Clay contents down to a depth of 6 m ranged from 15% to 27% at the top of the hill and from 33% to 43% at the bottom of the toposequence (Table 1). The mineralogy was dominated by quartz, kaolinite and oxyhydroxides (Maquère 2008), with acidic soil layers (pH water between 4.3 and 5.7). Both hillslope positions were characterized by small amounts of nutrients (sum of base cations generally <10 $mmol_c$ kg^{-1}). Similar soil properties are found on hundreds of thousands of hectares covered by eucalypt plantations in Brazil.

The experimental area (90 ha) was planted in December 2002 with *E. grandis* (W. Hill ex Maiden) seedlings (from Coffs Harbour in New South Wales) at a spacing of 3.75 x 1.60 m, after harvesting a previous *E. grandis* stand and herbicide application on the stumps. All seedlings received complete fertilization with 62 kg ha^{-1} N applied as ammonium sulfate, 52 kg ha^{-1} P, 131 kg ha^{-1} K, 1.5 Mg ha^{-1} of dolomitic lime (about 30% CaO and 18% MgO) and micronutrients. Fertilizers were applied at planting, then at 6, 12 and 24 months of age and a complementary application of KCl (53 kg K ha^{-1}) was broadcast at 42 months of age. Our study started at the end of the productive cycle, in November 2008, one year before the clear-cutting. In December 2009, a highly productive clone of *Eucalyptus grandis* was planted at a spacing of 3 m x 2 m, using standard management practices in Brazilian commercial plantations (Gonçalves et al., 2013). After clear cutting and removal of the stem from the previous rotation (leaves, branches and roots were left on site), 4 Mg ha^{-1} of dolomitic lime were applied. Standard fertilizations in commercial eucalypt plantations were applied with a total of 80 kg ha^{-1} N, 39 kg ha^{-1} P and 236 kg ha^{-1} K, the two first years after replanting (Table 2). Weeds were controlled by applications of glyphosate in the first few years after replanting.

2.2. Experimental design

Two study areas were selected within the same commercial plot (approximately 600 m apart, one at the top and the other at the bottom of a hill, at elevations of 755 and 725 m, respectively), which made it possible to study the effects of contrasting soil textures on the biogeochemical cycles of nutrients under the same management practices. However, this design confounded topographic position with soil type, even though the low slope (about 5%) probably resulted in low lateral flows. Four sub-plots containing 6 rows of 14 trees per row (84 trees, 504 m^2), spanning a range of basal area of 23–32 m^2 ha^{-1}, were set up at 6 years of age in the coarse-textured soil at the top of the hill, hereafter

Table 1
Main physico-chemical properties of the two types of soil studied in the upper (sandy soil) and lower (clayey soil) hillslope positions. There are $n = 4$ pits per hillslope position (mean values and standard deviations are shown).

Depth (cm)	Sand	Silt	Clay	pH $CaCl_2$	O.M. [a] (g kg^{-1})	*Presin* [b] (mg kg^{-1})	H + Al [b]	K [b]	Ca [b]	Mg [b]	Base cations [b]	CEC [b]
	Particle size distribution (%)						(mmol$_c$ kg^{-1})					
Sandy Soil												
0 - 25	82.3 ± 0.6	2.9 ± 0.6	14.8 ± 0.9	3.8 ± 0.2	20.5 ± 5.5	6.6 ± 1.2	74.1 ± 26.1	0.7 ± 0.1	6.2 ± 0.8	2.5 ± 0.6	9.5 ± 1.3	83.6 ± 27.1
25 - 50	80.3 ± 0.7	2.4 ± 0.2	17.4 ± 0.9	4.1 ± 0.1	13.0 ± 0.7	7.3 ± 0.2	44.4 ± 6.5	0.8 ± 0.1	5.9 ± 0.8	2.2 ± 0.0	8.9 ± 0.8	53.4 ± 6.0
50 - 100	78.0 ± 1.3	2.7 ± 0.5	19.3 ± 1.3	4.1 ± 0.1	11.2 ± 0.8	7.0 ± 0.6	37.9 ± 4.7	0.8 ± 0.2	5.4 ± 1.4	2.1 ± 0.0	8.4 ± 1.3	46.3 ± 3.4
100 - 200	74.4 ± 2.5	3.0 ± 0.5	22.6 ± 2.1	4.4 ± 0.2	14.5 ± 5.8	6.2 ± 0.7	25.8 ± 3.3	0.7 ± 0.1	6.6 ± 1.3	2.1 ± 0.0	9.3 ± 1.4	35.2 ± 3.1
200 - 400	71.4 ± 0.7	3.7 ± 0.5	24.9 ± 1.2	4.5 ± 0.1	7.6 ± 1.7	6.9 ± 0.5	17.2 ± 0.4	0.7 ± 0.1	5.6 ± 0.7	2.1 ± 0.0	8.3 ± 0.7	25.6 ± 0.3
400 - 600	68.4 ± 0.3	4.3 ± 0.5	27.3 ± 0.6	4.6 ± 0.1	6.0 ± 0.7	6.8 ± 0.6	16.2 ± 0.3	0.6 ± 0.0	5.0 ± 1.3	2.0 ± 0.0	7.7 ± 1.3	23.9 ± 1.4
Clayey Soil												
0 - 25	57.3 ± 4.9	9.4 ± 0.2	33.3 ± 4.7	4.2 ± 0.1	22.2 ± 4.1	8.5 ± 2.4	65.2 ± 20.5	0.7 ± 0.1	6.4 ± 1.8	2.0 ± 0.2	9.0 ± 1.9	74.3 ± 20.9
25 - 50	53.0 ± 0.8	11.4 ± 2.9	35.6 ± 2.8	4.2 ± 0.1	13.9 ± 1.9	6.3 ± 0.3	43.8 ± 6.9	0.7 ± 0.1	6.3 ± 1.8	2.0 ± 0.2	9.0 ± 1.6	52.8 ± 8.3
50 - 100	50.0 ± 3.8	10.9 ± 1.3	39.1 ± 3.0	4.3 ± 0.1	10.6 ± 2.6	5.8 ± 0.7	34.4 ± 2.3	0.7 ± 0.2	5.1 ± 0.7	2.2 ± 0.3	8.0 ± 0.8	42.4 ± 3.2
100 - 200	46.3 ± 4.1	11.0 ± 0.7	42.6 ± 3.4	4.6 ± 0.1	9.1 ± 2.1	5.7 ± 0.2	23.6 ± 1.5	0.6 ± 0.1	4.7 ± 0.0	2.2 ± 0.5	7.5 ± 0.6	31.1 ± 2.1
200 - 400	45.6 ± 2.5	11.9 ± 0.0	42.5 ± 2.5	5.0 ± 0.1	8.2 ± 4.1	6.3 ± 1.1	17.9 ± 0.6	1.5 ± 1.6	8.3 ± 5.0	2.8 ± 1.5	12.6 ± 8.1	30.6 ± 8.5
400 - 600	43.7 ± 3.4	20.3 ± 3.1	36.0 ± 0.8	4.7 ± 0.1	5.1 ± 0.2	6.0 ± 0.4	17.6 ± 0.5	0.7 ± 0.1	5.1 ± 1.4	1.9 ± 0.0	7.7 ± 1.3	25.3 ± 1.7

[a] Organic matter (O.M.) determined using sodium dichromate.
[b] The methodology described by van Raij et al. (2001) was used for resin extraction of phosphorus and exchangeable element determinations.

Table 2
Amounts of nutrients applied as fertilizer over the study period.

Months after replanting	N	P	K	Ca	Mg	S	B	Zn	Cu
			Nutrients (kg ha^{-1})						
0	18	39	25	321	162	9	0	1.5	1.5
5	31	0	30	0	0	34	1.2	1.9	0
12	31	0	56	0	0	39	1.4	0	0
24	0	0	125	0	0	0	2.8	0	0
TOTAL	80	39	236	321	162	82	5.4	3.4	1.5

called sandy soil, as well as in the fine-textured soil at the bottom of the hill, hereafter called clayey soil. Tree growth in the 8 sub-plots was assessed by measuring trunk circumference (1.3 m above ground level) every month over the last year before clear-cutting, and over the entire 6-year rotation after replanting.

Four pits were dug in each hillslope position to install 4 replicates of lysimeters in each soil layer, at different distances from trees in the planting row and in the inter-row. Soil solutions were sampled continuously using both zero tension lysimeters (ZTL) and tension lysimeters (TL). Gravitational solutions were collected weekly after three months of soil stabilization period, from December 2009 to June 2013. Four sets of nine thin ZTL lysimeters (40 cm x 2.5 cm), designed to limit the disturbance of the forest floor, were installed at the bottom of the litter layer in each hillslope position. At a depth of 15 cm, four replicates of ZTL (50 cm x 40 cm) were introduced horizontally in 4 pits (16 total in top of hillslope and 16 at bottom). Four replicates of tension lysimeters (TL) were also set up horizontally at depths of 15, 50, 100 and 300 cm in each hillslope position. The TLs were ceramic cups connected to a vacuum pump and maintained at a constant suction of about -60 kPa (checking automatically every 3 hours). At a depth of 15 cm, each replicate of ceramic cup was placed side by side with one replicate of ZTL. All pits were backfilled after installation with the horizons in their natural arrangement. The soil solutions sampled by TL were collected in glass bottles placed in closed pits where they were kept at +4 °C using refrigerators in the field. The soil solutions sampled by ZTL were collected in polyethylene containers in the same pits (at air temperature). Once a week, after volume measurements and sampling, the solutions were collected and carried to the laboratory where they were kept at +4°C.

2.3. Chemistry of soil solutions

A composite sample was prepared every four weeks for each lysimeter by adding the weekly solution proportionally to their collected volume. The composite samples were then filtered (0.45 µm) and the pH was measured. The concentrations of NO_3^-, NH_4^+, Cl^-, and $H_2PO_4^-$ were analyzed by colorimetry using FIA (Foss Tecator, FIASTAR 5000) and the concentrations of Ca, Mg, K, Na, S, Al, Fe and Si were determined by inductively coupled plasma optical emission spectrometry (ICP-OES, Jobin-Yvon Horiba Ultima 2). Dissolved organic C (DOC) and total dissolved N concentrations were determined using a Shimadzu TOC-VCPH Analyzer. The concentration of dissolved organic N (DON) was estimated for each sample by subtracting the concentration of inorganic N (nitrate + ammonium) from the concentration of total N.

2.4. Water balance modelling

Soil water contents were monitored every 30 minutes at the depths of 15, 50, 100, 200 and 300 cm using CS616 probes (Campbell Scientific Inc., Logan, UT, USA) horizontally buried at different distances from the planting row. Five probes per depth were installed in each hillslope position at the depths of 15, 50 and 100 cm. At the depths of 200 and 300 cm, three probes were set up at different distances from trees in each hillslope position. A home-made tensiometer was installed approximately 20 cm from a CS616 probe at depths of 15, 50, 100, 200 and 300 cm to establish in situ water retention curves (Appendix 1). A mechanistic model was used (Hydrus 1D), based on precipitation and evapotranspiration data, root water uptake and water movement through the soil using the Richards' equation (Šimůnek and Hopmans, 2008). This model was used to compute the vertical water fluxes at each lysimeter depth. The model was parameterized with climatic data, and the partitioning between soil evaporation and tree transpiration was estimated using both experimental data (eddy-flux measurements at our study site combined with soil water contents measurements) and a modelling approach using the MAESPA model (Christina et al., 2017). Fine root densities were measured before harvesting in the two hillslope positions counting intersects of fine roots on vertical trench walls down to a depth of 10 m (Laclau et al., 2013), and the dynamics of root development after replanting was measured in nearby plantations counting intersects of fine roots on vertical trench walls in 6-, 12-, 22-, 28-, 54-, 68- and 72-month-old *E. grandis* plantations (Maurice et al., 2010), as well sampling soils every metre with a cylindrical auger (diameter 7 cm) down to a depth of 10 to 16 m, and separating fine roots by hand picking (Christina et al., 2011; Pinheiro et al., 2016). An internal drainage experiment was performed in each soil type to calibrate *in situ* the water retention curves and the hydraulic parameters of each soil layer in the Hydrus 1D model following the approach of Laclau et al. (2005). In both sandy and clayey soils, 9 m^3 of water were poured into an area of 8 m^2, delimited by two concentric steel rings and equipped with TDR probes down to a depth of 3 m. A plastic sheet was used to prevent evaporation. Pressure heads and soil water contents were measured hourly on the first day and then daily for several weeks. We did not consider lateral flow in the Hydrus 1D model because the slope was low (5%) with a forest floor limiting surface runoff and high sand content in the upper hillslope leading to high infiltration rates. The best set of Hydrus 1D hydraulic parameters was found by adjusting the model simulations to the measurements of soil water content decline from saturation to residual soil water content at each depth.

2.5. Data analyses

The fluxes of dissolved elements were calculated monthly for each depth, multiplying mean concentrations in the soil solutions by the flux of gravitational water estimated from the Hydrus model. To estimate leaching beneath the forest floor (at 0 cm depth), we set the water fluxes equal to rainfall until an age of 6 months, thereafter we set them as the sum of throughfall and stemflow, estimated as 87% and 2.6% of rainfall, respectively (Maquère, 2008). Christina et al. (2017) showed that canopy closure was reached at about 16 months after planting in the same stand. LAI was already high at age 0.5 years (about 2 m^2 m^{-2}), which led to the consideration of crown interception from age 6 months. The amount of solution collected was about 5% of the time too small to allow chemical analyses, while a small water flux was predicted by the hydrological model. In these cases, we estimated the element concentrations as the mean of the closest dates at the same depth in the same landscape position.

Mean values and standard deviations were computed to quantify water and nutrient fluxes over 5 years down to a depth of 3 m in each soil type. The four replicates of lysimeters in each hillslope position were located in the same area and were therefore pseudo-replicates, which prevented from using ANOVAs to assess the effect of the hillslope position on nutrient leaching fluxes. However, nutrient leaching estimates are scarce in tropical forests and the detailed measurements carried out here provide new insights on the variability of nutrient losses through deep drainage in intensively-managed plantations established in tropical soils with contrasting textures.

3. Results

3.1. Tree growth

The effect of the hillslope position on tree growth was much higher in the last year before harvesting than after replanting (Figure 1). At the harvesting age (age 7 years), the mean basal area was about 30% higher in the clayey soil (35 m^2 ha^{-1}) than in the sandy soil (27 m^2 ha^{-1}). By contrast, tree growth was much less influenced by the hillslope position after replanting. The average basal area of the stand at the end of the monitoring of soil solution chemistry (3.5 years after replanting) was 23 and 21 m^2 ha^{-1} in the lower and upper position of the hillslope, respectively. At the end of the rotation (age 7 years) the average basal area of the re-planted stand was only 10 % higher in the lower hillslope position (32 m^2 ha^{-1}) than in the upper hillslope position (29 m^2 ha^{-1}).

3.2. Water fluxes throughout the soil profiles

The mean annual rainfall over the study period ranged from 1,365 mm (for the hydrologic year between September 2009 and August 2010) to 1,737 mm (between September 2008 and August 2009) with an average of 1,596 mm per year (Figure 2A). Soil water contents were much more influenced by seasons at a depth of 15 cm than at a depth of 3 m, for both soil textures. During the rainy season (from November to

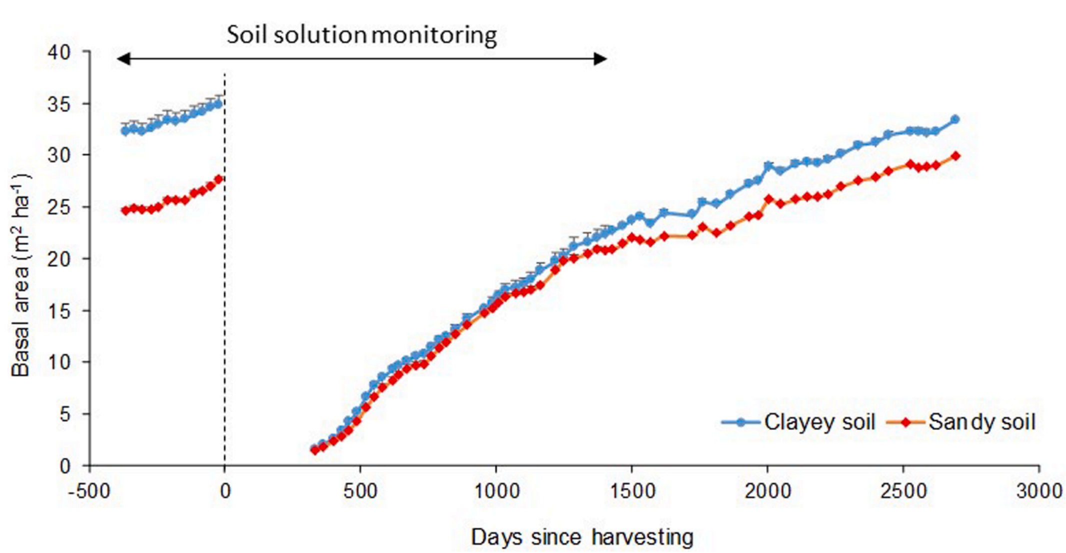

Figure 1. Mean values of stand basal area (m^2 ha^{-1}) measured monthly the last year before clear-cutting at age 7 years (dashed line) and over the rotation after replanting in the clayey soil (lower hillslope position) and in the sandy soil (upper hillslope position). Standard deviations between 4 sub-plots in each soil type are indicated.

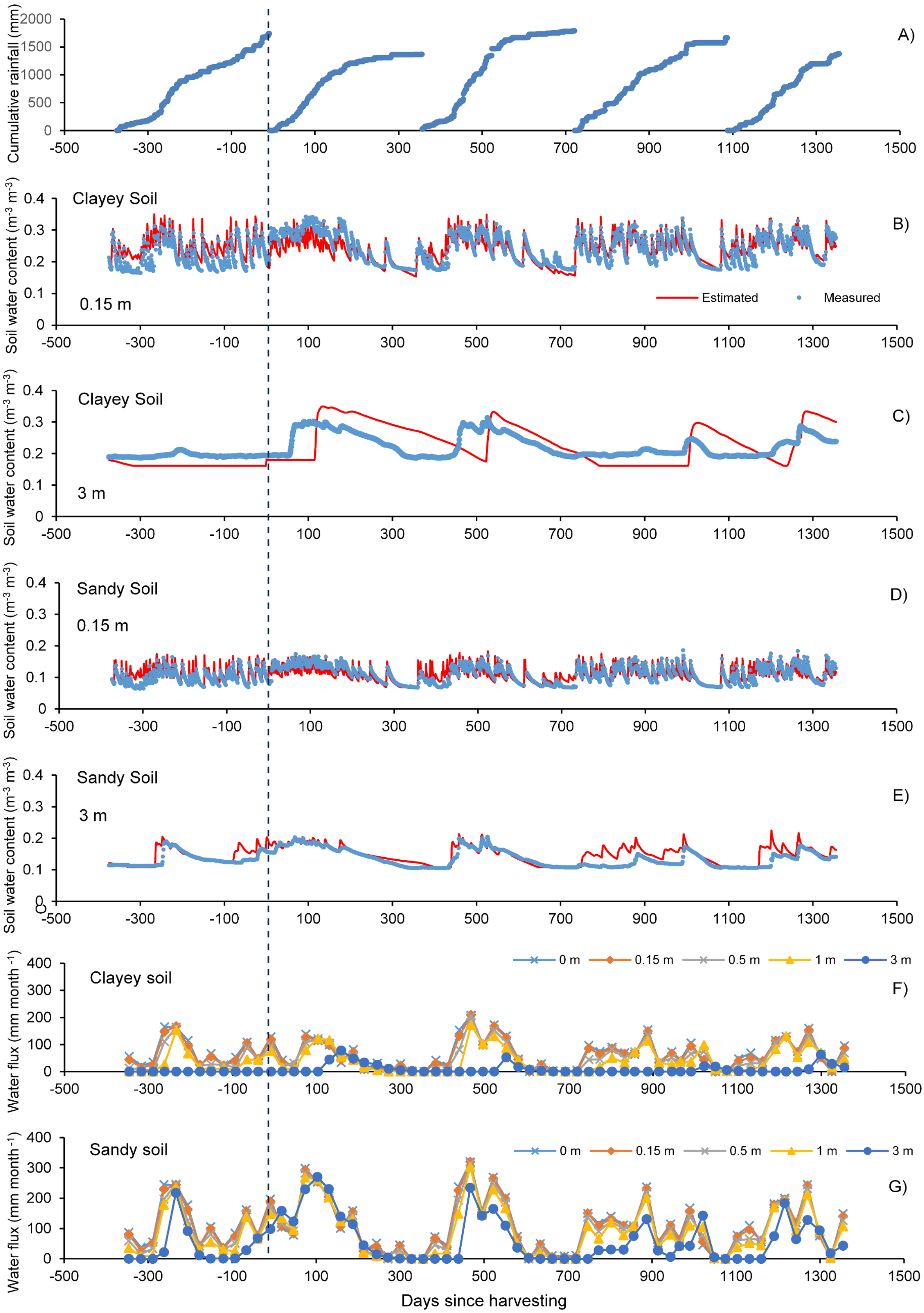

Figure 2. Cumulative annual rainfall A), soil water contents estimated by the Hydrus model and measured by TDR probes in the clayey soil at a depth of 15 cm B) and 300 cm C) and in the sandy soil at a depth of 15 cm D) and 300 cm E). Water fluxes estimated monthly with the Hydrus model at depths of 0, 15, 50, 100 and 300 cm in the clayey soil F) and in the sandy soil G). The vertical dashed line shows the clear-cutting date (November 2019).

April), the mean volumetric water content at a depth of 15 cm was about 25% in the clayey soil and 12% in the sandy soil, while at a depth of 3 m it was 21% in the clayey soil and 15% in the sandy soil. At the end of the dry seasons, the lowest soil water contents were approximately 20% throughout the soil profile (from the soil surface to a depth of 10 m) in the clayey soil and 10% in the sandy soil.

Despite some discrepancies, the sharp increases in soil water content at a depth of 3 m resulting from the arrival of gravitational water from the upper soil layers detected by the CS616 probes were predicted using the Hydrus model in both soil types, sometimes with a delay of 1 to 2 weeks (Figure 2). The root mean square errors between predicted and measured soil water contents over the entire study period were 0.03 and 0.05 at depths of 0.15 m and 3.0 m in the clayey soil, respectively, and 0.02 at both depths in the sandy soil. The water fluxes throughout the soil profiles were much higher in the sandy soil than in the clayey soil during the rainy season, which led to a drainage at a depth of 3 m ranging from 0 to 250 mm yr^{-1} in the clayey soil and from 541 to 1,332 mm yr^{-1} in the sandy soil over the study period. Gravitational water flux were highly variable over the study period (Appendix 2). The dry season was less pronounced the last year before the clear-cutting than the following years, which led to a lower seasonality of water fluxes throughout the soil profiles (Figure 2A).

3.3. Chemical composition of soil solutions

Negative and positive charges were well balanced throughout the study period, in both sandy and clayey soils (Figure 3). The charge imbalance ranged from -20 to +30% across the soil solution samples. The average values at each soil depth were generally positive (i.e., greater positive charge). While the ionic charges changed little throughout the transfer of gravitational soil solutions from the surface to a depth of 3 m in the last year before clearcutting, a sharp increase occurred in the first year after replanting in the upper 1 m of the soil profiles. The order of magnitude of anionic and cationic charges in soil solutions sampled at a depth of 3 m remained unchanged in the two soil types throughout the study period that covered most of the rotation (commonly 6-7 years in tropical eucalypt plantations).

Prior to clearcutting, anion concentrations were dominated by Cl^- in both hillslope positions. N-NO_3^- and S-SO_4^{2-} concentrations remained low in the upper 3 m for both hillslope positions (< 100 $\mu mol_c\ l^{-1}$, except for N-NO_3^- in the clayey soil at a depth of 15 cm). Cations exhibited comparable concentrations prior to clearcutting in both hillslope positions. Over the first year after replanting, Cl^- and N-NO_3^- were the dominant anions between the depths of 15 and 300 cm, while Mg^{2+} was the dominant cation, in both hillslope positions. Cation and anion concentrations decreased during the transfer of gravitational solutions from the forest floor to a depth of 15 cm, except for Mg^{2+} and N-NO_3^- in the clayey soil which peaked at a depth of 15 cm (462 and 675 $\mu mol_c\ l^{-1}$, respectively) and S-SO_4^{2-} in the sandy soil which peaked at a depth of 15 cm (174 $\mu mol_c\ l^{-1}$). Mean concentrations of N-NO_3^-, Al^{3+} and Mg^{2+} at a depth of 1 m were much higher in the sandy soil than in the clayey soil the first year after clear-cutting. Between 2 and 4 years after replanting, average ionic charges remained high (of the same magnitude compared to the first year after replanting) for soil solutions sampled below the litter and at depths of 15, 50, and 100 cm in the clayey soil, while they decreased in the upper layer of the sandy soil. The dominant anions and cations were the same as in the first year after replanting, with the exception of N-NO_3^- whose concentrations decreased sharply in the upper layers in both hillslope positions.

3.4. Fluxes of dissolved elements throughout soil profiles

While the fluxes of some nutrients dissolved in soil solutions sharply increased in the upper meter of the soil profiles after the clear-cutting, the fluxes of most nutrients at a depth of 3 m remained below 3 kg $ha^{-1}\ yr^{-1}$ throughout the study period (Figure 4). Mean N-NO_3^-, N-NH_4^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, S-SO_4^{2-} and DOC fluxes at a depth of 3.0 m over the study period were 0.3, 0.2, 0.6, 0.4, 0.2, 0.8, 0.2, and 1.8 kg $ha^{-1}\ yr^{-1}$ in the clayey soil and 0.9, 1.2, 1.9, 2.7, 1.1, 6.6, 2.3 and 24 kg $ha^{-1}\ yr^{-1}$ in the sandy soil, respectively. N-NO_3^- fluxes peaked the first year after the clear-cutting at about 70 kg $ha^{-1}\ yr^{-1}$ between the depths of 15 and 100 cm in the sandy soil and at about 50 kg $ha^{-1}\ yr^{-1}$ between the depths of 15 cm and 50 cm in the clayey soil, then they decreased sharply in deeper horizons in both hillslope positions. The fluxes of N-NH_4^+ in gravitational solutions were much lower than the fluxes of N-NO_3^- in the upper layers of both soil types and remained roughly constant throughout the soil profiles (generally lesser than 5 kg $ha^{-1}\ yr^{-1}$ between the depths of 15 and 300 cm). Ca^{2+} and Mg^{2+} fluxes ranged from 20 to 50 kg $ha^{-1}\ yr^{-1}$ in both hillslope positions beneath the forest floor and Ca^{2+} fluxes decreased more sharply in the topsoil than Mg^{2+} fluxes which reached high values down to a depth of 1.0 m, in particular in the sandy soil. S-SO_4^{2-} fluxes were of the same order of magnitude as Ca^{2+} and Mg^{2+} fluxes in the topsoil and peaked at 25 kg $ha^{-1}\ yr^{-1}$ at a depth of 15 cm in the clayey soil and at 37 kg $ha^{-1}\ yr^{-1}$ at a depth of 50 cm in the sandy soil.

Contrary to most of the other dissolved elements, which exhibited the highest fluxes in the upper soil layers the first year after the clear-cutting, the K^+ and Cl^- fluxes sharply increased in the third year after replanting, reaching 163 kg $ha^{-1}\ yr^{-1}$ at a depth of 15 cm in the clayey soil and 122 kg $ha^{-1}\ yr^{-1}$ beneath the forest floor in the sandy soil. In deeper horizons, K^+ fluxes decreased gently in the clayey soil and sharply in the sandy soil to reach very low values at a depth of 300 cm. The Cl^- fluxes behaved similarly to the K^+ fluxes and peaked the third year after replanting at a depth of 15 cm in the clayey soil (about 316 kg $ha^{-1}\ yr^{-1}$) and at a depth of 100 cm in the sandy soil (about 140 kg $ha^{-1}\ yr^{-1}$). DOC fluxes were little influenced by stand age and exhibited similar patterns in both hillslope positions, with a sharp decrease from the forest floor to a depth of 100 cm. Over the study period, mean DOC fluxes beneath the forest floor were 160 kg $ha^{-1}\ yr^{-1}$ in the clayey soil and 260 kg $ha^{-1}\ yr^{-1}$ in the sandy soil, while they amounted to only 14 and 44 kg $ha^{-1}\ yr^{-1}$ at a depth of 100 cm, respectively.

4. Discussion

4.1. Tree growth

The difference in tree growth between the upper and the lower hillslope positions observed before harvesting has been shown in other Brazilian eucalypt plantations (e.g. Gonçalves et al., 2012). Forest productivity is generally higher on clay soils than on sandy soils because the soil's fertility and water-holding capacity are inherently higher (Cavalli et al., 2020). Stand productivities at our study site are representative of commercial eucalypt plantations in areas with favourable temperature and precipitation in Brazil (Binkley et al., 2017). However, the low effect of the soil texture on tree growth after replanting a highly productive clone is surprising. The effect of hillslope position on tree growth does not appear until the second half of the rotation in the replanted stand and to a lesser extent than in the previous rotation. Low fertilizer inputs from 2002 to 2009 and a higher soil fertility in the clayey soil than in the sandy soil, inherited from the previous land use might account for the difference in stand basal area at the harvest in 2009. A complete water recharge of the soil profile led to a rise of the water table from 18 m depth after clear-cutting to 12 m depth at age 2 years in the re-planted stand, which suggests that water was not strongly limiting tree growth in both soil textures the first years after replanting (Christina et al., 2017). In addition, the amounts of fertilizers applied after replanting were sufficient to prevent nutrient shortage for tree growth, whatever the hillslope position. The change of clone between the 2 rotations probably also had an impact on the productivity of the stand according to the hillslope position. The high growth rates at our study site led to high nutrient requirements the first months after replanting in particular to build the crown and the fine root biomass (Laclau et al., 2010), and the large amounts of nutrients taken up by tree roots in soil solutions after

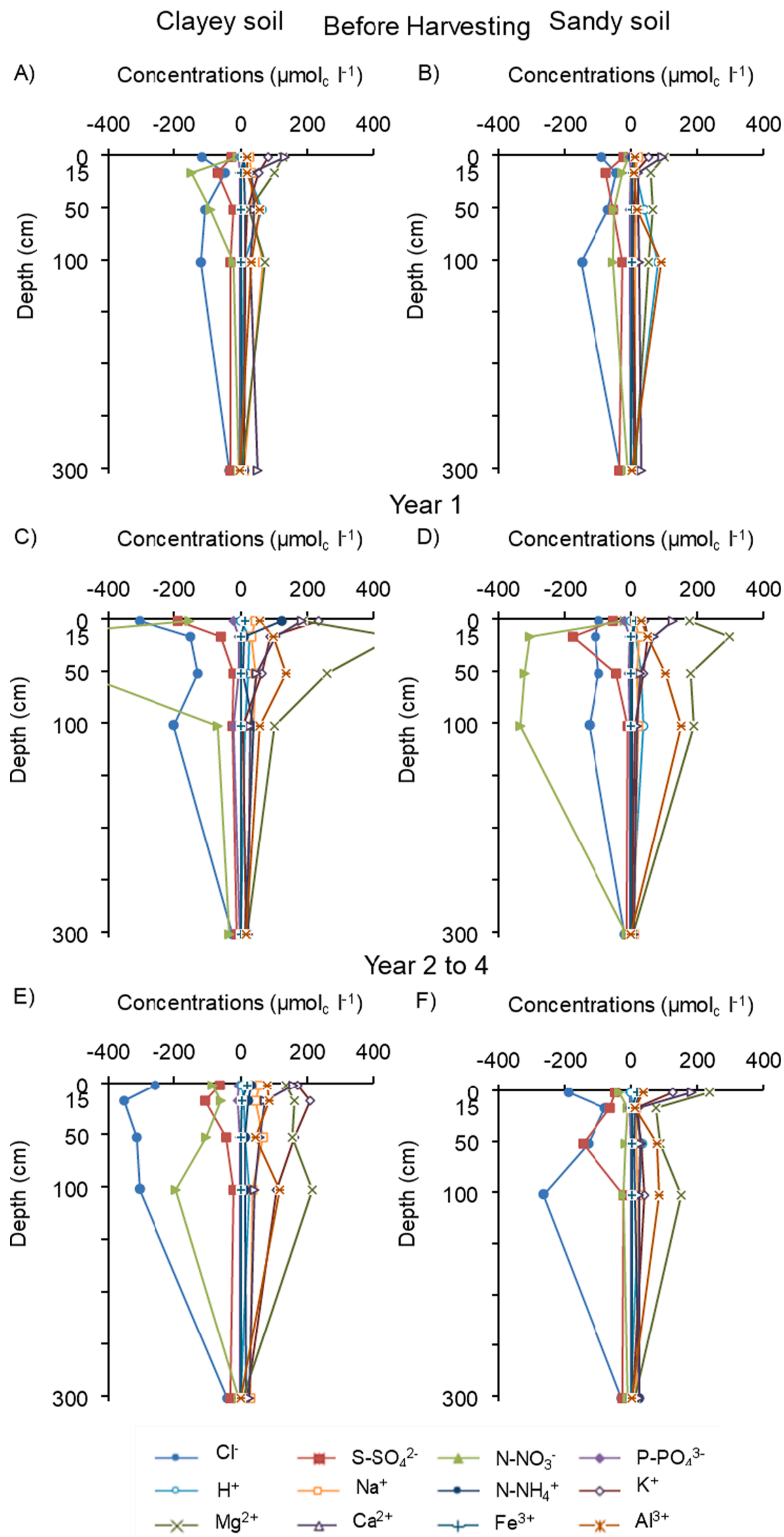

Figure 3. Charge balance of the solutions (mean concentrations expressed in µmol$_c$ l^{-1}) during their transfer before clear-cutting in the clayey soil A) and in the sandy soil B); the first year after clear-cutting in the clayey soil C) and in the sandy soil D); and from year 2 to year 4 in the clayey soil E) and in the sandy soil F).

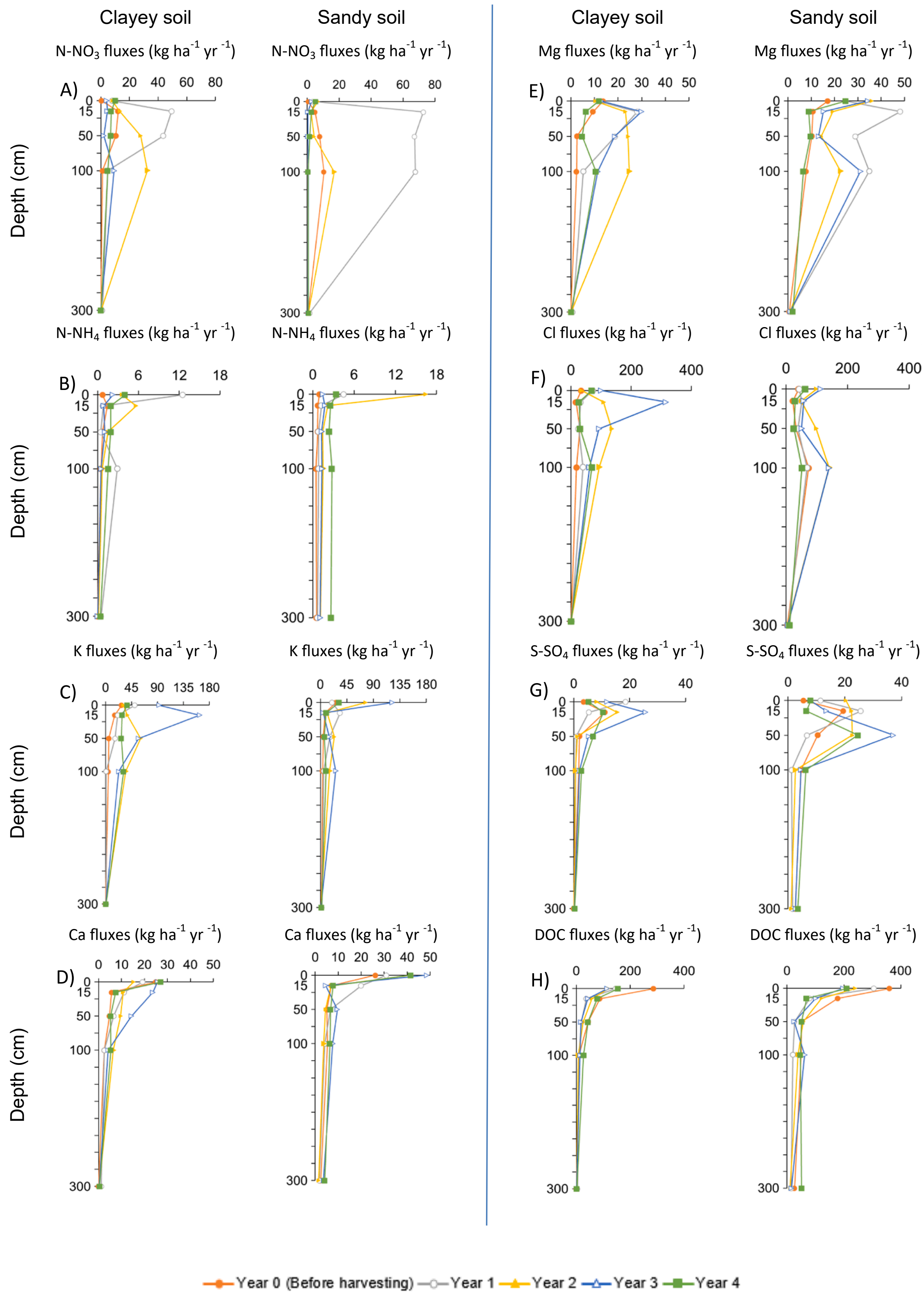

Figure 4. Fluxes of N-NO_3^- A), N-NH_4^+ B), K^+ C), Ca^{2+} D), Mg^{2+} E), Cl^- F), S-SO_4^{2-} G), and DOC H) in gravitational soil solutions sampled in clayey and sandy soils before and after harvesting *Eucalyptus* trees.

replanting probably greatly influenced the dynamics of the chemical composition of soil solutions in both hillslope positions. In nearby *E. grandis* plantations with the same soil type (20% clay) and similar management practices, Laclau et al. (2010) estimated that the amounts of N, P, K, Ca and Mg taken up by the trees from the soil averaged 126, 7, 37, 71, and 29 kg ha^{-1} yr^{-1} during the first 4 years after planting, respectively.

4.2. Soil solution chemistry

The clear-cutting led to a sharp increase in nitrate concentrations in the upper soil layers, which can be explained by an interruption in root uptake in this planted forest without understory, whereas soil organic matter mineralization continues (Laclau et al., 2010). Soil solution composition in an individual soil layer is a result of complex processes, with in particular: (i) element inputs from gravitational solutions (rainfall, stemflow and throughfall) and fertilizer application at soil surface, (ii) element releases by weathering of soil minerals and organic matter mineralization, (iii) ion-exchange equilibriums between the soil solution and the soil solid phase, and (iv) element outputs by leaching as well as uptake by roots and microbiota. The conceptual scheme identifying the main factors influencing the soil solution chemistry throughout the soil profile proposed by Laclau et al. (2003) in a Ferralic Arenosol soil in the Congo remains valid in the Ferralsols with contrasting textures studied here. Before clear-cutting, the total cationic charges in the solutions collected by TL at a depth of 15 cm were lower in the sandy soil (< 150 μmol_c l^{-1}) than in the clayey soil (< 300 μmol_c l^{-1}). Those concentrations were low for both soil textures and of the same order of magnitude as in *Eucalyptus* plantations established in a sandy soil in the Congo (Mareschal el al., 2013). The total cationic charges reported in soil solutions collected in *Eucalyptus* native forests in Australia were much higher (> 1000 μmol_c l^{-1}, Adams and Attiwill, 1991), as is observed in most studies in temperate forest ecosystems (e.g. Legout et al., 2016; Paul et al., 2022). The main biogeochemical processes controlling the soil solution chemistry were similar for both soil textures in our study. In addition to the interruption of nutrient uptake due to tree harvesting, large amounts of dolomitic lime and fertilizers applied at replanting contributed to the sharp increase in cation concentrations the first year after the clear-cutting (up to 500 μmol_c l^{-1} in the sandy soil and 800 μmol_c l^{-1} in the clayey soil). The sensitivity of soil solution chemistry to environmental changes made it possible to detect the fertilizer applications in the upper soil layers, with a clear increase in K^+ and Cl^- concentrations the first months after each KCl addition.

4.3. Nutrient leaching

In agreement with our hypothesis, the amounts of nutrients leached in gravitational solutions were large in the upper soil layers but the losses at a depth of 3 m remained low throughout the rotation for both soil textures. The sharp increase in anion and cation concentrations (in particular $N\text{-}NO_3^-$, Ca^{2+}, Mg^{2+}, K^+, Cl^-, $S\text{-}SO_4^{2-}$) in soil solutions the first year after the clear-cutting led to an increase in nutrient leaching in the 0-1 m soil layer. The higher hydraulic conductivity in the sandy soil than in the clayey soil led to higher gravitational water fluxes (Lilly, 2006; Zhang and Schaap; 2019), which also contributed to higher cation and anion leaching fluxes in the upper soil layers. While most of the studies quantifying nutrient leaching in forest ecosystems and plantations of perennial crops sample soil solutions down to a maximum depth of 1 m (or 1.5 m), our study points out the importance of measuring nutrient fluxes in gravitational soil solutions at a depth of 3 m (at least) in deep soils. The fluxes of $N\text{-}NO_3^-$ at a depth of 1 m peaked the first year after replanting in the sandy soil (at 68 kg ha^{-1} yr^{-1}) and the second year after planting in the clayey soil (at 33 kg ha^{-1} yr^{-1}) and the assessment of nutrient losses by deep leaching would be different if the deepest lysimeters were installed at a depth of 1 m or 3 m. Leaching fluxes peaked at about 40 kg ha^{-1} yr^{-1} for K^+ and 30 kg ha^{-1} yr^{-1} for Mg^{2+} at a depth of 1 m in both hillslope positions, while losses by deep drainage were very low (< 3 kg ha^{-1} yr^{-1}) at a depth of 3 m and generally lower than atmospheric deposition measured in a nearby area (Laclau et al., 2010). The low nutrient fluxes at a depth of 3 m measured here throughout the rotation suggest that an installation of lysimeters more deeply would not greatly change the assessment of nutrient losses by deep drainage, as shown comparing leaching fluxes at depths of 3 m and 6 m in eucalypt plantations in the Congo (Mareschal et al, 2013).

Highly productive eucalypt plantations managed in short rotations are remarkably conservative of small nutrient pools, taking up nutrients before they are lost below the root front in very deep tropical soils. While the ability of tropical savannas to avoid nutrient losses through a conservative biogeochemical cycling is well documented (Yé et al., 2015; Pinheiro et al., 2021), nutrient losses through deep drainage can be large in intensive oil palm, coffee or banana plantations where high amounts of fertilizer are applied annually (Armour et al. 2013; Cannavo et al. 2013; Formaglio et al., 2020). Low nutrient losses by deep leaching both in the coarse and fine textured soils in our study, with fertilizer applications representative of commercial plantations, are a result of: i) a fast development of the crowns, leading to high nutrient requirements and high water uptake by *Eucalyptus* trees, from age 6 months onward (Laclau et al., 2010), as shown for instance for K cycling (Cornut et al. 2021), ii) various degrees of ion adsorption on the soil solid phase (oxides, organic matter and clay minerals), which slows down the transfer of ions in the deep soil layers to maintain the charge balance in the gravitational solutions (Duwig et al., 2003; Harmand et al., 2007; Jankowski et al., 2018), iii) a very fast development of fine roots both in the topsoil and in deep soil layers, making it possible to take up nutrients in the deeper layers (Laclau et al., 2004; Pinheiro et al., 2016) and iv) a release of nutrients by the decomposition of harvest residues relatively slow in comparison with other tropical forests (Ferreira et al., 2016). In addition, some of the nutrients in gravitational solutions at a depth of 3 m may be taken up deeper by tree roots, as suggested by a recent study focusing on nitrogen in very deep aquifers (Smethurst et al., 2022).

Low nutrient losses by deep drainage suggest that splitting fertilizer applications is not necessary in tropical eucalypt plantations established in deep tropical soils. We set up a throughfall exclusion experiment in 2010 in a nearby area (same soil type with 20% clay, Guillemot et al., 2021) where we monitored soil solution chemistry to 3 m depth in the first three years after replanting *E. grandis* trees with a single fertilizer application 3 months after replanting. Productivity and nutrient leaching fluxes in this experiment were similar to those in the present study (unpublished data). Although it was not a direct comparison between a single application and a split application of fertilizer, these results suggest that it may be possible to reduce the number of fertilizer applications on very deep soils. Even though the sand content reached only 80% in our sandy soil, very low nutrient leaching fluxes were also found in soils with 90% sand in the Congo (Mareschal et al., 2013). These results, combined with the understanding of the dynamics of nutrient requirements by eucalypt trees before canopy closure and the capacity of the roots to take up nutrients down to a depth of 6 m at age 1 year, suggest that a single fertilizer application at planting (or a few months later) could possibly be made in all soil types where commercial eucalypt plantations are established, provided they are very deep. This conclusion is supported by another field experiment established in a sandy soil in Brazil (> 90% sand) showing that splitting the fertilizer application in *E. grandis* plantations could not raise biomass production the first 2 years after planting compared to a single fertilizer application at age 3 months (Silva et al., 2013). Reducing the number of fertilizer applications in commercial eucalypt plantations could significantly decrease the cost of silvicultural practices by strongly reducing the use of tractors in the plots, which would also contribute to the reduction of GHG emissions.

5. Conclusion

Our study shows low nutrient losses through deep drainage throughout the rotation in *Eucalyptus* plantations, in agreement with previous studies on fast-growing plantations established in deep tropical soils. While many studies sample soil solutions to a depth of 1 m (or 1.5 m), our results demonstrate that estimating leaching losses at these depths greatly exceeds that observed at 3 m. The chemical composition of soil solutions in the topsoil is strongly influenced by management practices with a large increase in nutrient concentrations in the first few years after replanting but these early surface increases did not result in leaching losses beneath 3 m. Our study shows that a better understanding of biogeochemical cycles in deep soil horizons (i.e., 100 to 300 cm) can help improve management practices. As an outcome, we suggest that the number of fertilizer applications might be reduced in eucalyptus plantations grown on deep tropical soils, which would save money, reduce greenhouse gas emission, and have no impact on deep leaching to local waterways.

CRediT authorship contribution statement

Alberto Caldeira: Formal analysis, Visualization, Writing – original draft. **Alex Vladimir Krushe:** Methodology, Resources, Writing – review & editing. **Louis Mareschal:** Writing – review & editing. **Paulo da Silva:** Writing – review & editing. **Yann Nouvellon:** Methodology, Writing – review & editing. **Otavio Campoe:** Writing – review & editing. **Jose Luiz Stape:** Writing – review & editing. **Alexandra Montebelo:** Methodology. **Greta Formaglio:** Writing – review & editing. **Guerric le Maire:** Writing – review & editing. **Joannès Guillemot:** Writing – review & editing. **Jacques Ranger:** Writing – review & editing. **Jean-Paul Laclau:** Conceptualization, Methodology, Investigation, Supervision, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Appendix 1. Hydraulic properties of the two soil types used in the Hydrus model.

Soil layer (m)	Qr	Qs	Alpha (1/m)	n	Ks (m d^{-1})	l
			Sandy soil			
0.00 – 0.33	0.07	0.35	38.23	1.73	11.49	0.35
0.33 – 0.66	0.07	0.32	38.23	1.72	13.65	0.32
0.66 – 1.00	0.07	0.32	7.01	1.69	11.95	0.32
1.0 – 1.5	0.08	0.32	6.25	1.79	9.83	0.32
1.5 – 2.0	0.09	0.32	5.19	1.95	7.07	0.32
2.0 – 2.5	0.1	0.33	3.96	2.14	4.1	0.33
2.5 – 3.0	0.1	0.34	3.16	2.19	1.73	0.34
			Clayey soil			
0.00 – 0.33	0.09	0.37	5.9	1.45	0.347	0.374
0.33 – 0.66	0.09	0.36	5.9	1.42	0.346	0.364
0.66 – 1.00	0.1	0.36	5.9	1.45	0.346	0.364
1.0 – 1.5	0.11	0.37	5.9	1.49	0.347	0.374
1.5 – 2.0	0.12	0.37	6.1	1.46	0.317	0.371
2.0 – 2.5	0.13	0.38	6.3	1.44	0.27	0.38
2.5 – 3.0	0.14	0.39	4.76	1.46	0.17	0.39

Appendix 2. Fluxes of gravitational water (mm yr^{-1}) and dissolved elements (kg ha^{-1} yr^{-1}) in gravitational solutions at depths of 15 cm, 100 cm and 300 cm in the sandy soil and in the clayey soil.

Stand age	Depth	Water	N-NO_3	N-NH_4	P-PO_4	K	Ca	Mg	Na	Cl	S	DOC
Sandy soil												
Before harvest												
6th year	15 cm	1476	4.93	0.74	0.08	8.01	7.07	10.72	4.56	22.57	19.5	178.75
	100 cm	1066	10.53	0.47	0.08	3.91	5.31	7.75	3.35	73.79	4.55	50.33
	300 cm	541	0.54	0.54	0.02	1.77	2.36	0.56	1.36	4.39	2.56	26.84
After harvesting												
1st year	15 cm	1319	72.76	1.25	0.37	33.56	20.07	48.25	7.65	51.38	25.66	79.77
	100 cm	1263	67.72	0.83	0.17	5.61	4.15	34.95	7.44	67.81	1.26	20.48
	300 cm	1332	1.63	0.7	0.09	2.73	1.83	0.9	2.75	7.17	1.61	15.15

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(*continued*)

Stand age	Depth	Water	N-NO_3	N-NH_4	P-PO_4	K	Ca	Mg	Na	Cl	S	DOC
2nd year	15 cm	1408	2.35	2.2	0.11	11.39	6.9	19.19	4.27	49.32	22.34	121.82
	100 cm	1105	16.93	1.47	0.08	15.57	3.68	22.6	7.17	139.54	2.58	38.93
	300 cm	693	0.88	1.1	0.04	1.44	1.47	0.86	2.32	5.58	1.06	11.44
3rd year	15 cm	1282	0.36	1.78	0.05	5.01	4.55	15.24	5.53	57.78	12.44	100.76
	100 cm	1064	0.79	1.34	0.04	26.3	7.64	31.18	7.28	139.95	4.49	62.45
	300 cm	563	0.54	1.07	0.02	1.34	3.59	0.9	2.3	5.59	2.6	15.73
4th year	15 cm	1186	2.68	2.56	0.2	10.17	7.82	8.89	6.54	29.25	6.49	68.62
	100 cm	1002	0.53	2.76	0.08	9.67	6.39	6.57	4.7	51.68	6.21	47.42
	300 cm	608	0.81	2.62	0.05	2.26	4.12	2.07	1.95	11.28	3.49	51.25
Clayey soil												
Before harvest 6th year	15 cm	911	12.19	1.44	0.05	15.97	5.68	0.94	6.86	16.67	11.1	87.42
	100 cm	452	1.28	0.51	0.01	4.74	2.58	0.24	9.16	18.77	1.87	9.74
	300 cm	0	0	0	0	0	0	0	0	0	0	0
After harvesting												
1st year	15 cm	592	49.54	0.83	0.1	21.37	11.1	2.81	4.11	32	5.42	37.9
	100 cm	463	4.78	2.91	0.4	1.16	2.44	0.52	5.47	40.6	0.76	9.97
	300 cm	250	1.11	0.52	0.01	1.43	1.22	0.08	0.98	1.94	0.35	4.39
2nd year	15 cm	912	13.26	5.64	0.06	38.05	10.77	2.31	7.46	108.56	15.55	57.94
	100 cm	553	32.57	0.67	0.04	34.93	6.37	2.48	6.99	93.44	0.55	7.8
	300 cm	82	0.09	0.15	0.01	0.41	0.26	0.01	0.22	0.83	0.09	1.18
3rd year	15 cm	883	4.51	0.9	0.02	163.24	23.7	2.99	15.19	315.8	25.59	42.6
	100 cm	530	9.32	0.55	0.02	23.02	4.21	1.14	7.01	61.55	2.06	14.46
	300 cm	45	0.02	0.03	0.01	0.58	0.32	0.01	0.48	0.2	0.25	0.98
4th year	15 cm	773	7.27	1.95	1.7	28.72	7.48	0.64	7.73	27.01	10.58	77.61
	100 cm	538	4.73	1.57	0.4	31.46	5.3	1.06	3.69	69.71	2.79	27.43
	300 cm	120	0.07	0.42	0.1	0.76	0.42	0.01	0.58	0.88	0.34	2.25

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