Biogeochemistry (2011) 105:89–104
DOI 10.1007/s10533-010-9537-z

Fluxes of nitrogen and phosphorus in a gallery forest in the Cerrado of central Brazil

Lucilia Maria Parron · **Mercedes Maria Cunha Bustamante** · **Daniel Markewitz**

Received: 1 March 2010 / Accepted: 9 October 2010 / Published online: 28 October 2010

Abstract The Gallery forests of the Cerrado biome play a critical role in controlling stream chemistry but little information about biogeochemical processes in these ecosystems is available. This work describes the fluxes of N and P in solutions along a topographic gradient in a gallery forest. Three distinct floristic communities were identified along the gradient: a wet community nearest the stream, an upland dry community adjacent to the woodland savanna and an intermediate community between the two. Transects were marked in the three communities for sampling. Fluxes of N from bulk precipitation to these forests resulted in deposition of 12.6 kg ha^{-1} y^{-1} of total N of which 8.8 kg ha^{-1} was as inorganic N. The throughfall flux of total N was generally <8.4 kg ha^{-1} year^{-1}. Throughfall NO_3–N fluxes were higher (7–32%) while NH_4–N and organic N fluxes were lower (54–69% and 5–46%) than those in bulk precipitation. The throughfall flux was slightly lower for the wet forest community compared to other communities. Litter leachate fluxes differed among floristic communities with higher NH_4–N in the wet community. The total N flux was greater in the wet forest than in the dry forest (13.5 vs. 9.4 kg ha^{-1} year^{-1}, respectively). The stream water had total N flux of 0.3 kg ha^{-1} year^{-1}. The flux of total P through bulk precipitation was 0.7 kg ha^{-1} year^{-1} while the mean fluxes of total P in throughfall (0.6 kg ha^{-1} year^{-1}) and litter leachate (0.5 kg ha^{-1} year^{-1}) declined but did not differ between communities. The low concentrations presented in soil solution and low fluxes in stream water (0.3 and 0.1 kg ha^{-1} year^{-1} for N and P, respectively) relative to other flowpaths emphasize the conservative nutrient cycling of these forests and the importance of internal recycling processes for the maintenance and conservation of riparian and stream ecosystems in the Cerrado.

Keywords Biogeochemical processes · Bulk precipitation · Throughfall · Litter leachate · Soil solution · Riparian zones

L. M. Parron (✉)
Embrapa Florestas, Estrada da Ribeira km 111, Colombo, PR, Brazil
e-mail: lucilia@cnpf.embrapa.br

M. M. C. Bustamante
Depto Ecologia, Universidade de Brasília, Campus Darcy Ribeiro, Brasília, DF, Brazil

D. Markewitz
DB Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA, USA

Introduction

The savanna region in Brazil covers 24% of the country and encompasses a vegetation gradient from open savannas (5–20% tree cover) to gallery forests (70–95% tree cover) that dominate along stream corridors (Ribeiro and Walter 2008). These gallery forests represent about 5% of the Cerrado area but contain approximately 32% of its biodiversity (Felfili et al. 2001). Plant biodiversity of the gallery forests is particularly high (approximately 100 species ha^{-1}) (Santiago et al. 2005; Silva Júnior 2005).

Gallery forests also play an important role in the biogeochemical functioning of the Cerrado landscape. The presence of gallery forests, like riparian forests in general, reduces erosion and silting of streams, contributes to the maintenance of the quantity and quality of the water supply, and filters agrochemicals from adjacent cultivated areas preventing contamination of stream water (Felfili 1994; Silva Júnior et al. 1996). For these reasons, Brazilian environmental legislation considers gallery forests as permanently protected areas. Unfortunately, extensive changes in land use in the Cerrado region, particularly from intensification of agriculture, are increasingly disturbing these systems (Sano et al. 2009).

Despite being protected by law, gallery forests in the Cerrado biome are strongly affected by land use changes, especially in the southern part of the biome. In fact, 50% and 43% of the watersheds with areas between 10,000 and 200,000 ha, respectively, in the state of Goiás and in the Federal District, are already more than 70% converted from native vegetation (Bonnet et al. 2006). Within the Cerrado region, these conversion rates exceed the minimum area required to be maintained by the Brazilian Forest Code as legal forest reserves (20% in the core of the Cerrado region) and permanent protected areas (mean value of 10% in every property/basin assuming a buffer zone of 100m along the stream detected at the 1:250.000 scale). Although the importance of gallery forests is recognized relative to stream water quantity and quality, little information about nutrient cycling processes in gallery forests of the Cerrado region is available. Quantification of nutrient inputs and outputs through flowpaths (as bulk precipitation, throughfall, litter leachate, soil solutions, and stream water) is essential for understanding the functioning of gallery forests (Scatena 1990), particularly with regard to important agricultural fertilizer elements like N and P.

Chemical and physical properties of soils in gallery forests differ from upland Cerrado soils due to the soil hydrological regime and topography (Silva Júnior et al. 1996; Haridasan 1998). In these near stream areas, seasonally flooded hydromorphic soils (Gleissolos) with high contents of organic matter are often present (Reatto et al. 2008) as opposed to the well-aerated lateritic soils (Latassolos) of the uplands (Neufeldt 2006). Soil fertility and texture of these near-stream soils considerably affect the distribution of plant species in gallery forests (Oliveira-Filho et al. 1994; Souza et al. 2007). Microclimatic conditions below the closed canopy of gallery forests also provide shading for topsoil, which provides a quite different thermal regime than in the open savannas (Durigan 1994).

Distribution of tree species varies according to the position along the topographical gradient (Pinto et al. 2005) if nearest the stream or adjacent to the woodland savanna. The tall stature of gallery forest relative to upland Cerrado may also impact nutrient fluxes. The structure of the forest canopy itself (height and form of the trees, patterns of the branching, leaf area index) may influence rainfall partitioning into throughfall or interception with eventual evaporation (Tobón Marin et al. 2000). Other parameters, like amount and frequency of precipitation or size of gaps also impact the interception variability and the chemical composition of throughfall (Crockford et al. 1996; Rodrigo and Ávila 2001; Tobón et al. 2004; Perez-Marin and Menezes 2008). The species of arboreal vegetation in gallery forests also differ relative to upland Cerrado species with respect to their water requirements (Oliveira and Felfili 2005). In the uplands rooting depth is intimately related to the water balance of Cerrado ecosystems and it is likely to be shallower in gallery forests (Oliveira et al. 2005; Lopes and Schiavini 2007). In either case (uplands or gallery forests) the hydrological cycle of this biome will be affected by the conversion of woody vegetation to exotic grasses or agricultural crops.

Nutrient cycling studies in Cerrado ecosystems have quantified nutrient accumulation in the components of the aboveground biomass and the return of nutrients to the soil through litter decomposition and mineralization (Haridasan 1998; Nardoto and Bustamante 2003; Nardoto et al. 2006). However, studies quantifying nutrient fluxes in solution through the ecosystem or stream water fluxes are still very scarce (Resende 2001; Markewitz et al. 2006). As such, our objectives were to describe the fluxes of N and P in solutions along the topographic gradient from upland to stream in a gallery forest.

Materials and methods

Study area

The study was conducted in a gallery forest located near the headwater of the first-order Pitoco stream in the Ecological Reserve of the Brazilian Institute of Geography and Statistics (IBGE) (15°56′41″S and 47°53′07″W). The IBGE reserve is a 1500 ha conservation unit close to the city of Brasília in the Federal District, Brazil (Fig. 1). Silva Júnior et al. (1996) compared the floristic composition of different gallery forests in the region. They indicated the presence of three floristic communities according to the position along the topographical gradient in different forests: a wet community nearest the stream, a dry community adjacent to the woodland savanna (i.e., cerrado *strictu sensu*), and an intermediate

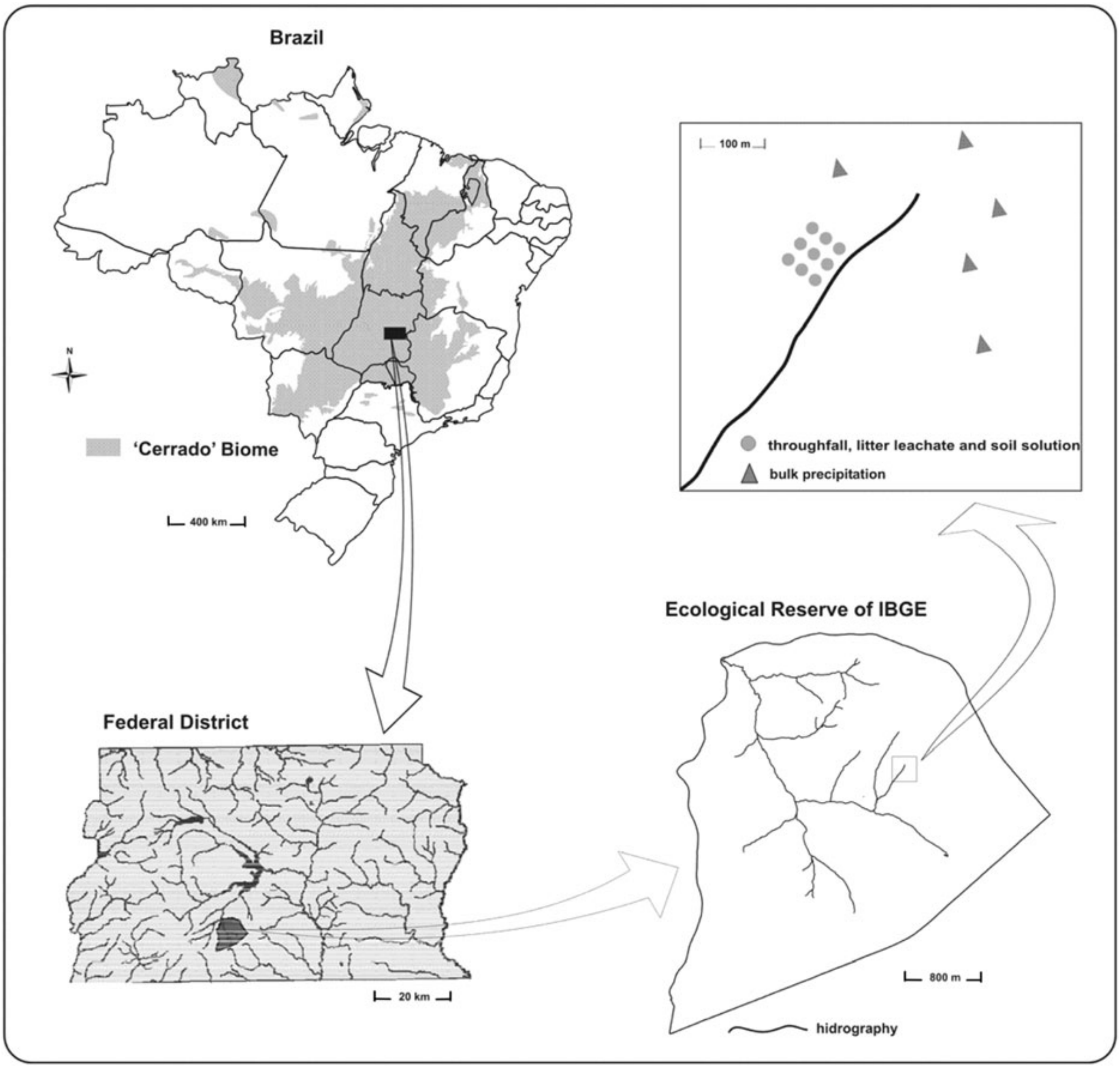


Fig. 1 Location of the study site in the gallery forest along the Pitoco stream at the IBGE Ecological Reserve, Brasília, Brazil

community between the two. The similarity among floristic composition of the same type of community in different forests was higher than that among the different types of communities in the same forest. In order to evaluate the nutrient fluxes as a function of the distance from the stream, we compared the three floristic communities within the Pitoco gallery forest as previously identified by Silva Júnior et al. (1996). The gallery forest of the Pitoco stream is wider at the stream head (160 m) and narrows downstream (120 m). Slope varies from 6 to 15 degrees. The IBGE Reserve is protected against fire and grazing, but after more than 20 years of protection, there was an accidental fire in 1994 that affected even the gallery forests. A vegetation survey recorded 99 tree species, distributed in 46 families with a density of 1914 trees ha^{-1} and basal area of 37.7 m^2 ha^{-1}, the diameter ranged from 8 to 23 cm for 90% of the trees and the maximum tree diameter was 78 cm (Silva Júnior 2005). The species with the highest Importance Value Indices (IVI = relative density + relative dominance + relative frequency) in each community are presented in Table 1.

The soils associated with each floristic community differ in physical and chemical characteristics varying from Gleissolo (Brazilian classification systems) in the wet community to a Red-Yellow Latossolo (Brazilian classification systems) in the intermediate and dry communities. Gleissolos are equivalent to Gleysols in the FAO classification and represent soils with hydromorphic features (i.e., low chroma colors). In US Soil taxonomy there is no similar order and classification of gleyed horizons would be associated with the Aquept, Aquult, or Aquox sub-orders. Red-yellow Latossolos are similar to Ferrasols in the FAO classification with Acric Ferrasols characteristic for the low-charge (<1.5 meq per 100 g clay in some part of the B horizon) soils in this area. In US Soil Taxonomy (Soil Survey Staff 1999) Oxisols are the nearest equivalent with the sub-order Ustox being appropriate because of the long dry season in the Cerrado that causes 90 days or more of soil dryness. Soil texture ranges from clayey at the surface (47.5–56.4% clay) to very clayey at deeper layers (10–100 cm, 59.7–74.7% clay).

The annual rainfall was around 1400 mm during the experimental period (April 18, 2001 and May 28, 2002) and its distribution was markedly seasonal with a pronounced dry season between May and September (Fig. 2). Temperatures are higher in the wet season than in the dry season.

Table 1 Plant species with highest Importance Value Indices (IVI = relative density + relative dominance + relative frequency) that are characteristic of the three floristic communities (wet, intermediate and dry) and species common to the three communities (Silva Júnior 1995)

Community	Species	Family
Wet	Protium almecega	Burseraceae
	Emmotum nitens	Icacinaceae
	Virola sebifera	Myristicaceae
Intermediate	*Copaifera langsdorffii*	Leguminosae
	Faramea cyanea	Rubiaceae
	Sclerolobium paniculatum var. *rubiginosum*	Leguminosae
	Tapura amazonica	Dichapetalaceae
Dry	Callistene major	Vochysiaceae
	Lamanonia ternata	Cunoniaceae
	Eriotheca pubescens	Bombacaceae
Common species	*Tapirira guianensis*	Anacardiaceae
	Copaifera langsdorffii	Leguminosae
	Maprounea guianensis	Euphorbiaceae

Soil sampling and analyses

Three 150 m transects (one in each floristic community) were established running parallel to the stream with 50 m between each transect. Soil samples from the three floristic communities (three replicates per community) were collected in May 2001 at the following depths: 0–5, 5–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, 70–80, 80–90 and 90–100 cm using a 10-cm diameter auger. Soils were air-dried and passed through a 2 mm sieve prior to chemical analysis. Samples were analyzed for pH in water (1:2.5), total nitrogen and carbon by dry combustion with a C/N Analyzer after ball mill grinding (Carlo Erba, Milan, Italy), and available phosphorus with the Mehlich I double acid extract. Bulk density samples for all depths were collected using Kopecky's ring composed of stainless steel rings with a height of 5.1 cm and volume of 100 cm^3. The rings were inserted in the walls of pits dug in the ground. Bulk density was determined as the oven-dry (110°C) weight of the soil per unit volume (cm^3).

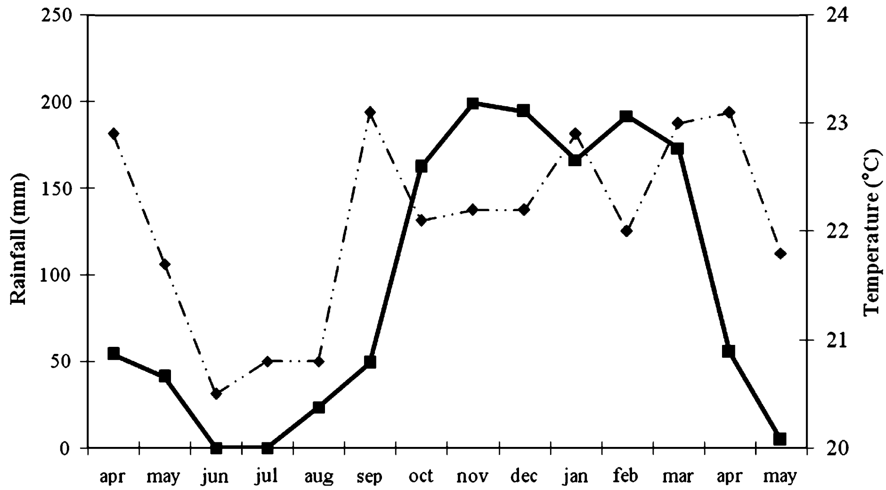


Fig. 2 Cumulative monthly rainfall and mean monthly temperature (°C) between April 2001 and May 2002 at IBGE Ecological Reserve, Brasília, Brazil

Solution sampling

Fluxes of N and P in bulk precipitation, throughfall, litter leachate, soil solution and stream water were measured along the topographic gradient. Solutions were sampled every 2 weeks between April 18, 2001 and May 28, 2002. Based on precipitation inputs, the sampling periods were divided into a distinct dry (May 30 and August 29, 2001), wet (September 04, 2001 and March 27, 2002), and transition (April 18 to May 30, 2001 and March 27, 2002 to April 24, 2002) seasons for statistical analysis. All the collectors were throughly acid-washed and rinsed with distilled water before installation in the field and rinsed with distilled water after each sample collection.

Bulk precipitation

Bulk precipitation collectors were made of polypropylene funnels (16 cm diameter, area = 0.0201 m^2) and 5 l glass bottles. Bottles were covered with aluminum foil to limit solar heating. Five collectors were installed at 2.3 m height in open areas of 'cerrado' within a 1 km radius of the study area. The height and density of the canopy in the gallery forest prevented the installation of precipitation collectors within the forest. The total volume of precipitation collected in each bottle was measured in the field with a graduated cylinder and an aliquot of 280 ml was subsampled.

Throughfall and litter leachate

In this study we included nutrient fluxes in throughfall and litter leachate, but did not include stemflow measurements because its contribution to these fluxes in tropical ecosystems is small (Schroth et al. 2001).

Three throughfall and three litter leachate collectors were installed in each floristic community. The collectors were installed 50 m apart from each other along the three 150 m transects running parallel to the stream (see soil sampling section). Throughfall collectors were made of polypropylene funnels (16 cm diameter, area = 0.0201 m^2) and 5 l polyethylene bottles. Bottles were painted silver to avoid light penetration. Litter leachate collectors were made of PVC pipe that was cut into thirds lengthwise (32 cm length and 10 cm in diameter, area = 0.032 m^2). One end of the tube was capped and a Nalgene tube passed through the cap connecting to a collection bottle. Collectors were placed under the litter layer and bottles were placed in 50 cm depth pits to ensure gravity driven flow (Jordan 1968).

Soil solution and stream water

Two Superquarz® Prenart tension lysimeters (Denmark) were installed along the transects in each community at a 50 cm soil depth, which exceeded most of the rooting mass (Castro and Kauffman 1997) in these systems. Holes for installation were augered at an angle to leave soil above the lysimeter undisturbed. Holes were backfilled with soil and a tube extending to the surface was attached to a glass bottle. Bottles were evacuated to a pressure of 0.4 kPa at the time of sampling and a falling pressure-head was used for sampling (Titus and Mahendrappa 1996). Due to difficulties, samples were only recovered for one of the tension lysimeters in the wet community, with no samples obtained from either the intermediate or dry communities. Water samples of the perennial Pitoco stream, that flow year-round, were collected just downstream of the transects by submerging a polyethylene bottle (280 ml) below the stream surface.

Chemical analyses

The field samples were stored in polypropylene bottles and returned to the laboratory the same day and placed in cold storage (4°C) for later chemical analyses. After returning samples to room temperature, pH and electrical conductivity were analyzed within 24 h using an EC-sensor and glass pH electrode. Thereafter, samples were filtered through 0.45 µm polycarbonate membranes (Whatman), and stored in a freezer until analysis. Total dissolved N was determined after digestion with potassium persulfate by an Alpkem auto-analyzer (OI Analytical, College Station Texas), NH_4^+ was determined by colorimetry using the indophenol blue method, PO_4^- by the Murphy-Riley method (Clesceri et al. 1998) and NO_3^- by liquid chromatography (Dionex DX 500 Sunnyvale, CA). Total P was determined by ICP-MS (Elan 6200, Perkin Elmer). Organic N and P were calculated by the difference between total N and the sum of NH_4–N and NO_3–N and by the difference between total P and PO_4–P, respectively. Certified standards were used to quality assure all analyses (ERA Associates, Arvada CO). Detection limits were estimated according to Hulanicki (1995) and varied between 1 and 2×10^{-4} meq l^{-1} for anions and between 1 and 4×10^{-3} meq l^{-1} for cations.

Nutrient concentration (weighed by volume) and fluxes during the study period for each flowpath and each collector were found by multiplying their respective weighted concentrations by the estimated volumes as follows:

$$C = \sum (Ci \times Vi)/Vt$$

$$F = [C \times (Vt/A)]/1000$$

where C = concentration per collector (mg l^{-1}), C_i = concentration of sample i (mg l^{-1}), V_i = volume of sample i (L), V_t = sum of the volume of all the samples (L), F = nutrient flux (kg ha^{-1} year^{-1}), A = collector area. As the sites investigated by Markewitz et al. (2006) were close to the forest of the Pitoco stream, a rainfall:runoff ratio of 0.25 cm of runoff per cm of bulk precipitation was used to approximate total discharge of the stream (e.g., depth of runoff). The net return of nutrients from plant canopy was obtained by subtracting the inputs in bulk precipitation from those in throughfall while the total return was the sum of net return and litterfall, expressed per unit forest area. Litterfall details are presented in Parron et al. (2004). Nutrient inputs and fluxes were then compared over the three floristic communities for the various flowpaths.

Statistical analyses

The Shapiro–Wilk-Test (Shapiro and Wilk 1965) was used to evaluate the normality of the data. As most of the variables did not present normal distributions, nonparametric tests were used (Statistica software) (Statsoft Inc 2001). To verify differences in the nutrient concentrations among the three floristic communities during the study period ($n = 57$ per plot) the Kruskal–Wallis rank sum test ($p < 0.05$) was used and when there were significant differences in the nutrient concentrations the Mann–Whitney U test ($p < 0.05$) was used. Spearman rank correlation was used to examine correlation among variables.

Results

Soil nutrient concentrations and contents

Soil bulk density and pH increased with depth (Table 2) through the upper 1 m of soil and tended to increase moving upslope from the stream (wet < intermediate < dry community). Conversely, soil

Table 2 Bulk density, pH, concentrations and stocks of $_{total}N$ and $_{available}P$ in soils of the wet, intermediate and dry floristic communities of the gallery forest along the Pitoco stream at IBGE Ecological Reserve, Brasília, Brazil

Community	Depth	Bulk Density	pH	N		P	
				Conc.	Content	Conc.	Content
	cm	g cm^{-3}		%	kg ha^{-1}	μg g^{-1}	kg ha^{-1}
Wet	0–5	0.41	4.5	0.67	1367	4.9	1.0
	5–10	0.41	4.6	0.42	854	3.9	0.8
	10–20	0.45	4.5	0.32	1425	2.4	1.1
	20–30	0.55	4.6	0.23	1256	1.3	0.7
	30–40	0.55	4.6	0.19	1036	0.7	0.4
	40–50	0.55	4.6	0.16	862	0.5	0.3
	50–60	0.70	4.6	0.14	980	0.4	0.3
	60–70	0.70	4.6	0.13	910	0.3	0.2
	70–80	0.70	4.7	0.11	770	0.2	0.1
	80–90	0.70	4.7	0.11	787	0.1	0.1
	90–100	0.70	4.7	0.09	612	0.1	0.1
	Total				10,859		5.0
Intermediate	0–5	0.51	4.5	0.59	1513	3.8	1.0
	5–10	0.51	4.5	0.41	1033	3.3	0.8
	10–20	0.60	4.5	0.32	1900	2.1	1.3
	20–30	0.63	4.6	0.24	1512	1.2	0.7
	30–40	0.63	4.4	0.21	1302	0.7	0.4
	40–50	0.63	4.4	0.16	1029	0.4	0.3
	50–60	0.73	4.5	0.15	1083	0.3	0.2
	60–70	0.73	4.5	0.14	998	0.3	0.2
	70–80	0.73	4.7	0.13	949	0.3	0.2
	80–90	0.73	4.7	0.11	779	0.5	0.4
	90–100	0.73	4.8	0.09	669	0.1	0.1
	Total				12,766		5.7
Dry	0–5	0.67	4.8	0.36	1306	3.1	1.2
	5–10	0.67	4.7	0.29	1027	1.9	1.0
	10–20	0.70	4.7	0.21	1820	1.0	1.3
	20–30	0.70	4.7	0.18	1645	0.9	1.3
	30–40	0.70	4.7	0.13	1493	0.4	1.1
	40–50	0.70	4.8	0.10	665	0.2	0.1
	50–60	0.75	4.8	0.10	712	0.2	0.1
	60–70	0.75	4.9	0.08	562	0.1	0.1
	70–80	0.75	4.9	0.08	562	0.2	0.1
	80–90	0.75	4.9	0.08	619	0.2	0.1
	90–100	0.7	4.9	0.07	525	0.1	0.1
	Total				10,938		6.4

total N and available P concentrations decreased in an upslope direction from the stream for the 0–20 cm depths. Due to the combination of increasing bulk density and declining soil N and P concentrations, soil total N and available P stocks differed among the community soil profiles through 100 cm soil depth. Total N contents were greatest in the intermediate community (10,859, 12,766, and 10,934 kg–N ha^{-1} in wet, intermediate and dry communities, respectively) while available P contents increased continually from the wet to the dry community (5.0, 5.7 and 6.4 kg P ha^{-1}).

Electrical conductivity and pH of solution samples

Electrical conductivity and pH of bulk precipitation, throughfall, and litter leachate samples were negatively and significantly correlated with the volumetric water flux with the exception of pH in litter leachate (Table 3). Seasonality also affected conductivity with the highest values in bulk precipitation and throughfall observed during the transition from the dry to the wet season. Electrical conductivity in bulk precipitation varied from 1.9 μS cm^{-1} (January 30, 2002) to 75.5 μS cm^{-1} (September 27, 2001), with a mean (±1SD) of 14.1 ± 19.3 μS cm^{-1}. The pH VWM value was 5.6 ± 0.6.

In throuhgfall samples, the conductivity ranged from 4 μS cm^{-1} (February 13, 2002) to 168 μS cm^{-1} (September 27, 2001), with mean values of 17.5 ± 24.5, 23.2 ± 24.7, and 35.7 ± 40.4 μS cm^{-1} in the wet, intermediate and dry communities, respectively. The mean values for pH were 5.9 ± 0.1, 6.1 ± 0.1 and 6.3 ± 0.1 in the wet, intermediate and dry communities, respectively. For both variables, the values in the wet community were significantly lower ($p > 0.05$) than those from the intermediate and dry communities.

The conductivity and pH values of litter leachate showed the same pattern with the values from the wet community being significantly lower ($p > 0.05$) than those from the intermediate and dry community. The conductivity of litter leachate samples varied from 12.0 μS cm^{-1} (December 27th) to 135 μS cm^{-1} (September 18th), with mean values of 36.4 ± 22.9, 48.3 ± 29.4, and 70.2 ± 44.7 μS cm^{-1} in the wet, intermediate and dry communities, respectively. Mean pH values were 5.2 ± 0.6, 5.5 ± 0.8, and 6.2 ± 0.5 in wet, intermediate and dry communities, respectively. Only one of the lysimeters installed in the wet community worked properly during the study period. Soil solution data presented correspond to 29 collections made from this single lysimeter. Mean values of conductivity and pH were 5.7 ± 1.7 μS cm^{-1} and 5.0 ± 0.2, respectively. Mean conductivity and pH of stream water, which was also collected 29 times from a single location, was 3.1 ± 1.2 μS cm^{-1} and 5.2 ± 0.3.

Table 3 Spearman rank correlation coefficients ($p < 0.05$) between collected volume and electrical conductivity and pH in samples of bulk precipitation ($n = 100$), throughfall and litter leachate ($n = 171$ each) collected in the gallery forest along the Pitoco stream at IBGE Ecological Reserve, Brasília, Brazil

Flowpath	Electrical conductivity	pH
Bulk precipitation	−0.54	−0.57
Throughfall	−0.44	−0.47
Litter leachate	−0.29	−0.01

Nitrogen concentrations and fluxes

The highest total N concentrations in bulk precipitation were observed in samples of the first rain events after the dry season; consistent with the higher conductivities reported above. This peak in total N was driven largely by high NH_4–N and organic N with NO_3–N concentrations having no similar increase (Fig. 3). The total N concentration was <1 mg l^{-1} in most of the samples throughout the year while the highest value was 6.2 mg l^{-1} (September 27th).

Throughfall samples from the three communities had mean concentration of 1.0 mg total N l^{-1}, with a maximum value of 5.0 mg l^{-1} in the dry community on September 27th (data not shown). The total N, NH_4–N, NO_3–N and organic N concentrations from the intermediate community and total N and organic N from the dry community are significantly higher in throughfall ($p > 0.05$) than those from the wet community (Fig. 4).

Peaks of N concentration in litter leachate were observed over the course of the study period (Fig. 3). The total N mean concentration in the three communities was 1.8 mg l^{-1} in most of the samples with a maximum value of 4.0 mg l^{-1} in the dry community (data not shown). The mean total N concentration was higher than in throughfall. The concentration of NH_4–N in litter leachate decreased significantly from the wet community samples to the dry community samples while total N, NO_3–N and organic N concentrations did not significantly differ ($p > 0.05$) among the communities (Fig. 4).

The total N mean concentration in soil solution for the single wet community lysimeter was 0.09 mg l^{-1} with a maximum of 0.21 mg l^{-1} during the transition from dry to wet season (October 04th). The NH_4–N and NO_3–N mean concentrations were both 0.03 mg l^{-1} while maximum values were 0.05 and 0.09 mg l^{-1} FOR NH_4–N AND NO_3–N, respectively.

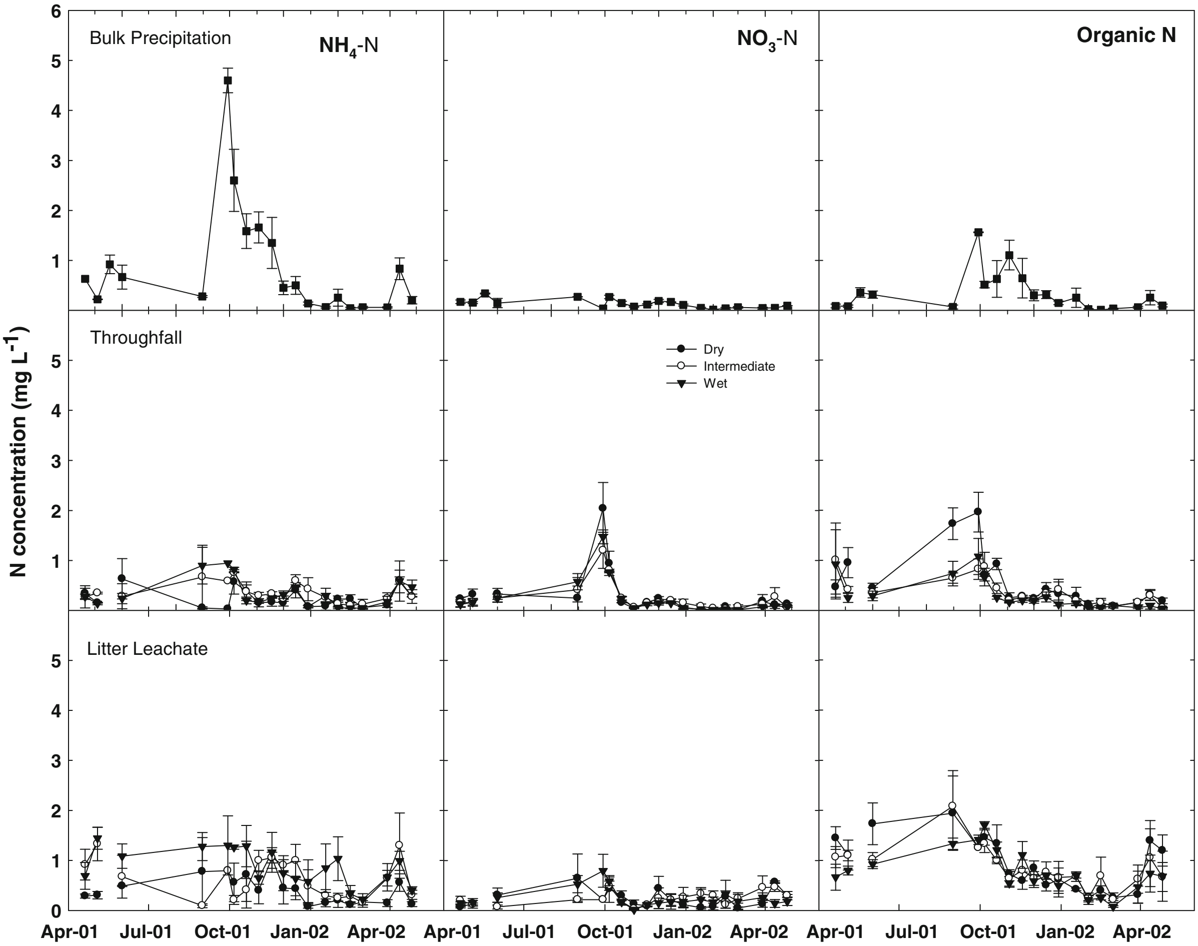


Fig. 3 Temporal variation (April 2001–April 2002) of concentrations of NH_4–N, NO_3–N and organic N in different flowpaths in the gallery forest along the Pitoco stream at IBGE Ecological Reserve, Brasília, Brazil. Data presented for wet, intermediate and dry floristic communities. Bars indicate standard deviations among collectors (5 for bulk precipitation, 3 each for throughfall and litter leachate)

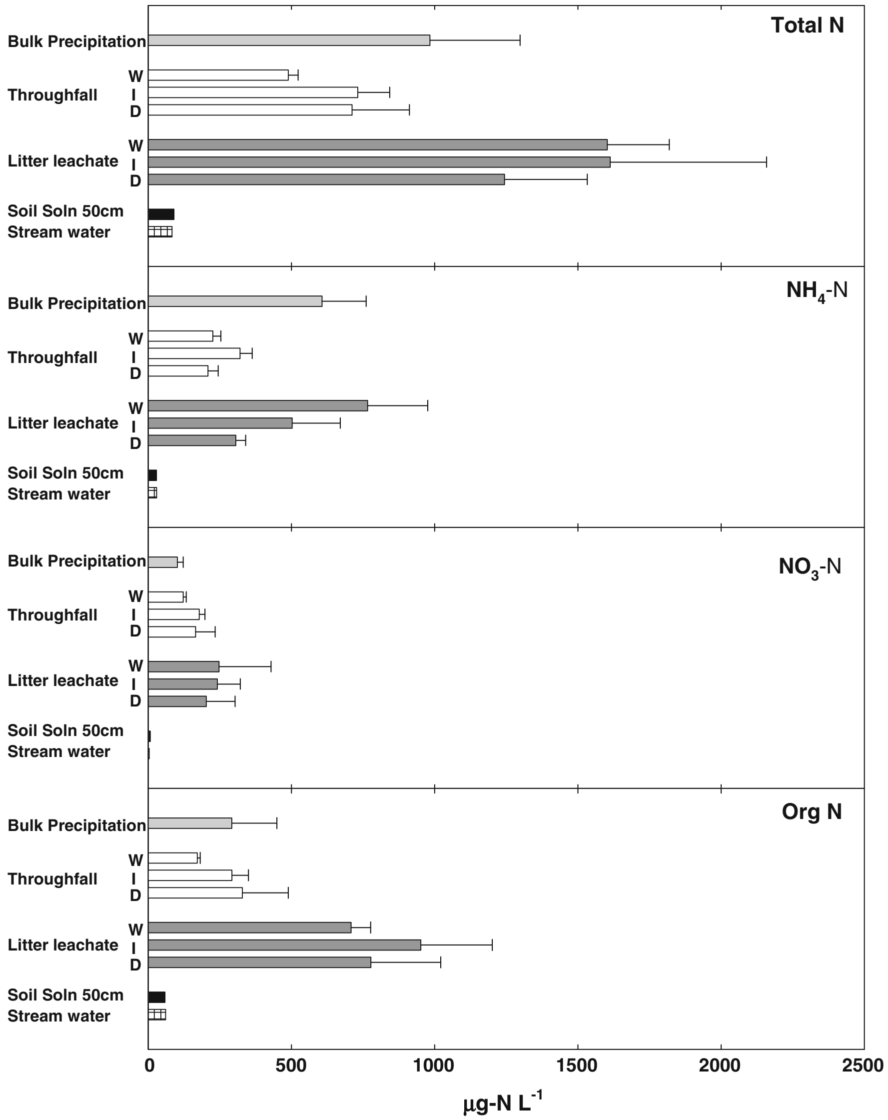
The stream water samples had mean total N concentration of 0.08 mg l^{-1} with a maximum of 0.15 mg l^{-1} in the dry season (July 11th). The mean NH_4–N concentration was 0.03 mg l^{-1} while NO_3–N was not detectable.

The fluxes of NH_4–N and NO_3–N through bulk deposition were 7.4 and 1.4 kg ha^{-1} year^{-1}, respectively, resulting in an input of 8.8 kg ha^{-1} year^{-1} of inorganic N. The deposition of organic N was 3.8 kg ha^{-1} year^{-1}, resulting in 12.6 kg ha^{-1} year^{-1} of total N (Table 4). The NO_3–N flux in throughfall was 7–32% higher than that in bulk deposition for the three communities, indicating that NO_3–N is being leached from the canopy. On the other hand, NH_4–N and organic N fluxes in throughfall were 54–69% and 5–46% lower, respectively, than those in the bulk deposition, indicating retention of these N forms by the forest canopy. Fluxes through litter leachate were higher than that in throughfall and decrease from the wet community to the dry community. Stream water fluxes of total N were estimated to be lower than 0.3 kg ha year^{-1} (0.02% of bulk precipitation).

Phosphorus concentrations and fluxes

Total P mean concentration in bulk precipitation was 50 µg l^{-1} throughout much of the year with a maximum of 200 µg l^{-1} that was associated with the dry to wet season transition (September 27th) (Fig. 5). The PO_4–P concentration between November 2001

Fig. 4 Volume-weighted mean concentrations of N in different flowpaths. The throughfall and litter leachate were collected in the wet (W), intermediate (I) and dry (D) floristic communities in the gallery forest along the Pitoco stream at IBGE Ecological Reserve, Brasília, Brazil. *Bars* indicate standard deviations among collectors (5 for bulk precipitation, 3 each for throughfall and litter leachate, and 1 sample location each for soil solution and streamwater). Number of samples collected: bulk precipitation = 100, throughfall and litter leachate = 171 each, soil solution and stream water = 29 each. Samples were collected biweekly between April 2001 and April 2002



and March 2002 was 36 μg l^{-1}, which on average represents 67.0% of total P during this period. The organic P concentration was 17 μg l^{-1} (31.0% of $_{total}$P).

In throughfall samples, the total P mean concentration was 60 μg l^{-1} with a maximum of 110 μg l^{-1} observed in the wet community during the dry season (August 29th). The organic P concentrations in throughfall from the wet community (21.1 μg l^{-1}) were significantly higher ($p > 0.05$) than those from the dry (16.1 μg l^{-1}) while lower values were observed for the intermediate community (14.0 μg l^{-1}) (Figs. 5, 6). Finally, contrary to the seasonal pattern of high P concentration observed for bulk precipitation total P during the dry to wet season transition, concentrations of total P, organic P and PO_4–P in throughfall were similar in all seasons (Fig. 5).

Most values for total P concentration in litter leachate were lower than 100 μg l^{-1} with a maximum of 144 μg l^{-1} observed in the intermediate community. The PO_4–P (data not shown) and organic P mean concentrations were 58 and 17 μg l^{-1} (Fig. 5), respectively. There was no significant difference ($p > 0.05$) in total P and PO_4–P concentrations among the three communities (Fig. 6).

The total P mean concentration in soil solution for the wet community lysimeter was 30 μg l^{-1} with a maximum of 90 μg l^{-1} (September 27th). The PO_4–P

Table 4 Fluxes (bulk precipitation, throughfall, litter leachate and stream water) (kg ha^{-1} year^{-1}) and net and total returns of nitrogen and phosphorus in the three floristic communities (wet, intermediate and dry) in gallery forest along the Pitoco stream at IBGE Ecological Reserve, Brasília, Brazil. Values in brackets are standard deviations

Element	Community	Bulk precipitation	Throughfall	Litter leachate	Litterfall[a]	Net return[b]	Total return[c]	Stream output
		kg ha^{-1} year^{-1}						
N		12.6						0.3
	Wet		5.9 (0.1)	13.5 (5.0)	36.7	−6.7 (0.1)	43.4 (0.1)	
	Intermediate		8.3 (2.1)	12.4 (5.1)	42.3	−4.3 (2.1)	46.6 (2.1)	
	Dry		7.5 (2.4)	9.5 (2.3)	42.2	−5.1 (2.4)	47.3 (2.4)	
P		0.7						0.1
	Wet		0.6 (0.1)	0.5 (0.1)	1.5	−0.1 (0.1)	1.6 (0.1)	
	Intermediate		0.6 (0.1)	0.5 (0.1)	1.9	−0.1 (0.1)	2.0 (0.1)	
	Dry		0.6 (0.2)	0.5 (0.0)	1.6	−0.1 (0.1)	1.7 (0.2)	

BP Open-area bulk precipitation

[a] Foliar litterfall (Parron et al. 2004)

[b] Net returns = Throughfall − bulk precipitation

[c] Total returns = Net returns + Litterfall

and organic P mean concentrations were 20 and 10 µg l^{-1}, respectively (Fig. 6). In the stream water, most total P concentration values were lower than 40 µg l^{-1} (maximum of 188 µg l^{-1}) (October 04th).

The flux of total P through bulk precipitation was 0.7 kg ha^{-1} year^{-1} (Table 4). The mean fluxes of total P in throughfall (0.6 kg ha^{-1} year^{-1}) and litter leachate (0.5 kg ha^{-1} year^{-1}) did not significantly differ among the three communities ($p > 0.05$) and were lower than bulk precipitation inputs (Table 4) indicating a retention of P. Stream water flux was estimated to be lower than 0.1 kg ha^{-1} year^{-1} (15% of bulk precipitation).

Discussion

Soil characteristics evaluated in this gallery forest are generally consistent with previously reported data (Chapius Lardy et al. 2002; Lilienfein et al. 2003; Markewitz et al. 2006). Bulk density values differed somewhat, however, with values in the upper 0–10 cm surface of the wet community (i.e., ~0.4 g cm^{-3}) being low relative to the 0.56 g cm^{-3} reported for other gallery forests by Chapius Lardy et al. (2002). Decreasing total soil N and available P concentrations with depth are in accordance with previous measurements made in Cerrado soils (Roscoe et al. 2000; Alcântara et al. 2004). The N values at this site are also in the upper 75th percentile for Gleissolos in the database for Brazilian soils as summarized in Markewitz et al. (2006). The Gleissolos or hydromorphic soils do not occur in all gallery forests (Haridasan et al. 1996) and may represent as little as 10% of soils in these ecosystems (Silva Júnior 2005).

The main characteristics of the bulk precipitation during the study period were a high level of acidity and higher nutrient concentrations in the first rains after the dry season with subsequent dilution throughout the wet season. The high concentrations of NH_4^+, and potentially other elements, in the first rain events may be due to biomass burning (Germer et al. 2007). Biomass burning is very common throughout the Cerrado during the long dry season and can be a biogenic source of nitrogen (Pinto et al. 2002). The chemical composition of precipitation was also studied intensively at the IBGE Reserve in 1999 (Resende 2001). Similar peak concentrations were observed during the dry to wet transition but the inputs through bulk precipitation were lower than those determined in the present study (NH_4–N = 2.34; NO_3–N = 1.36; organic N = 2.0; total P = 0.01 kg ha^{-1} year^{-1}). The lower annual rainfall (1206 mm) during 1999 can account for a portion of this decrease but clearly other mechanism must account for the observed considerable inter-annual variation. The growth of agricultural

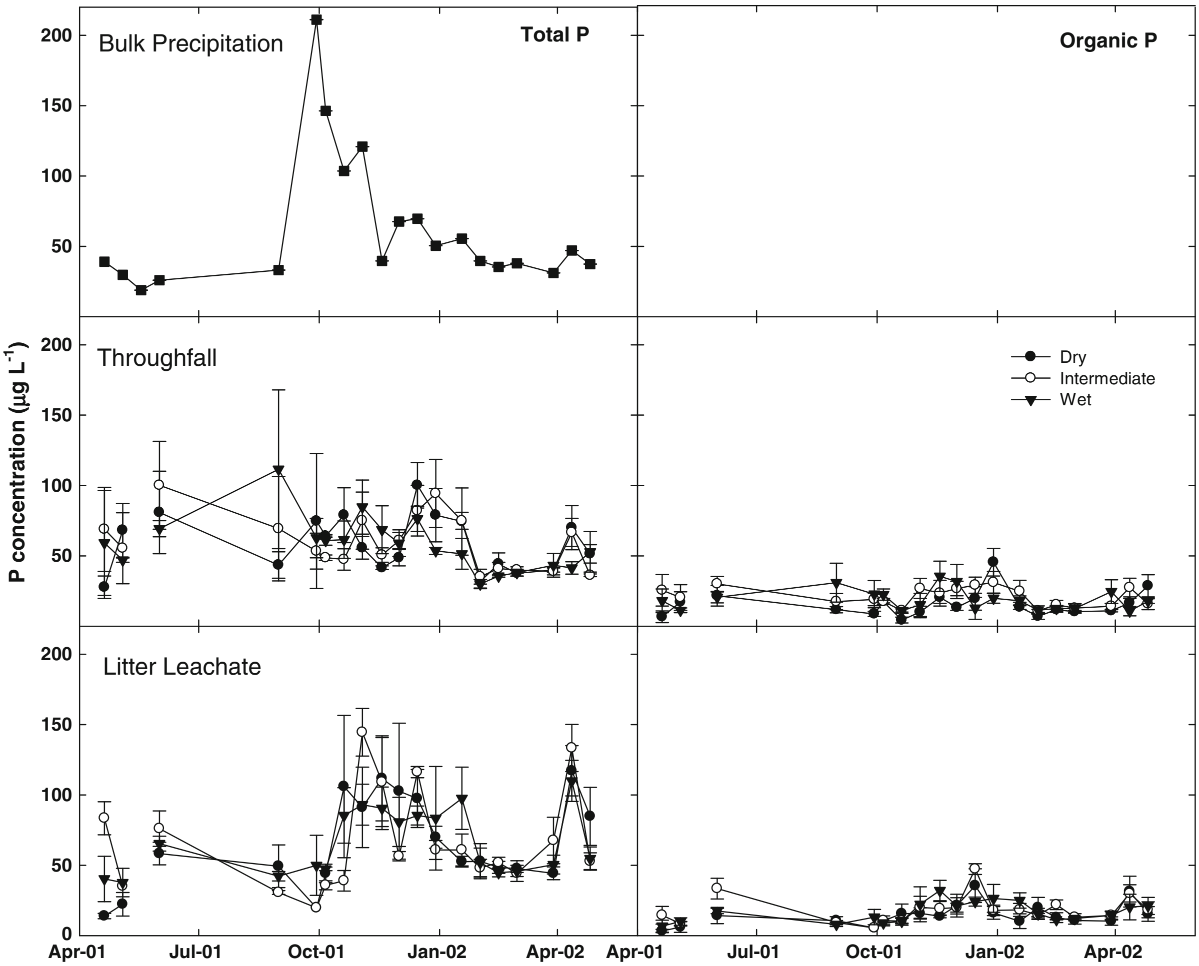


Fig. 5 Temporal variation (April 2001–April 2002) of the concentrations of total and organic P in in different flowpaths in the gallery forest along the Pitoco stream at IBGE Ecological Reserve, Brasília, Brazil. Data presented for wet, intermediary and dry floristic communities. *Bars* indicate standard deviations among collectors (5 for bulk precipitation, 3 each for throughfall and litter leachate)

activity in the Cerrado biome may also contribute to a higher atmospheric deposition of N (Lilienfein and Wilcke 2004). For example, soil emissions of NO from croplands after fertilization with urea (4.8 ng cm^{-2} h^{-1} N) (Carvalho et al. 2006) were higher than those from native Cerrado (1.2 ng cm^{-2} h^{-1} N) (Pinto et al. 2002).

As precipitation passes through the foliar canopy, nutrients are leached from leaves or retained by the canopy so that nutrient concentrations in throughfall usually differ from that in bulk precipitation. Rainfall is not only an important source of nutrients to the forests, but it also plays an important role in the transfer of nutrients from the forest canopy to the soil surface in the form of throughfall and/or stemflow. For example, Whitmore (1990) observed in a forest of New Guinea an increase of four-fold in N concentration in throughfall. In the Brazilian Atlantic forest, precipitation was acidic while throughfall was neutral and cation enriched (Silveira and Coelho Netto 1999). In a savanna ecosystem in the Congo, throughfall solutions showed an enrichment of PO_4^{-} through foliar leaching, although NH_4^{+} was absorbed. Changes in the chemical composition of bulk precipitation through the canopy in the present study indicated leaching of NO_3^{-} but retention of NH_4^{+} and organic N. Overall, there was a net decline in N flux through the canopy. Retention of N was observed previously by Zeng et al. (2005) and Umana and Wanek (2010). Fluxes of total P also declined

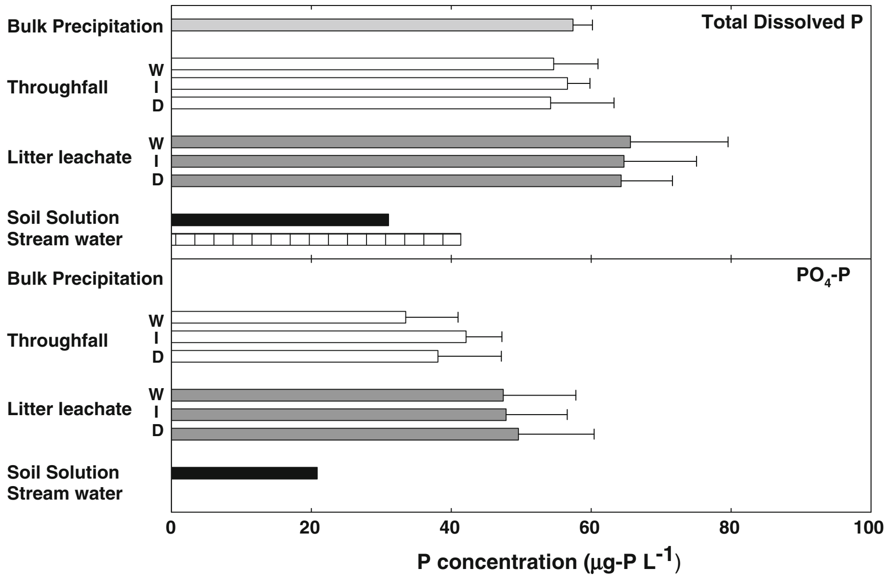


Fig. 6 Volume-weighted mean concentrations of P in flowpaths. The throughfall and litter leachate were collected in the wet (W), intermediate (I) and dry (D) floristic communities in the gallery forest along the Pitoco stream. *Bars* indicate standard deviations among collectors (5 for bulk precipitation, 3 each for throughfall and litter leachate, and 1 sample location each for soil solution and streamwater). Number of samples collected: bulk precipitation = 100, throughfall and litter leachate = 171 each, soil solution and stream water = 29 each. In stream water the PO_4–P concentration was below the detection limit. Samples were collected biweekly between April 2001 and April 2002

indicting some retention of P by the forest canopy. Comparing the nutrient fluxes in throughfall and bulk precipitation, it was observed that the net returns of N and P to the soil were negative (Table 4) because of the retention of NH_4, organic N and total P through the canopy. The litterfall return to the soil surface varies throughout the year and occurs mainly in the dry season in the three communities (Parron et al. 2004). The total return (net return plus litterfall) of N increased from the wet to the dry community. This is related to the higher inputs of N through canopy leaching and litterfall in the intermediate and dry communities. The same trend was observed for the total return of P although P fluxes did not differ significantly among the three communities.

The flux of N in litter leachate increased substantially relative to throughfall but this was not observed for P. Increases in litter leachate N are similar to results reported for Cerrado vegetation (Resende 2001) and lowland Amazonian rainforest (Markewitz et al. 2001) but these studies also demonstrated slight increases in P fluxes in litter leachate. Goller et al. (2006) working in a tropical montane rainforest demonstrated a decline in forms of dissolved organic P as solutions passed through the litter layer.

Outputs to streams for both N and P were small relative to inputs. Total N and P outputs represent, respectively, 2% and 15% of inputs. In both cases, these limited outputs indicate retention of N and P in the Cerrado landscape. The fluxes of N and especially of P through bulk precipitation are critical components of the biogeochemical cycle since these are inputs to the ecosystem rather than aspects of nutrient recycling as quantified by net throughfall, net litter leachate, or litterfall. The flux of total N input through bulk precipitation (12.6 kg ha^{-1} $year^{-1}$) represents only 0.9% of the stock of total N in the 0–5 cm topsoil (1395 kg ha^{-1} on average in the three communities) and 0.1% of the stock of total N in the soil up to 100 cm depth (11,012 kg ha^{-1} average in the three communities) (Tables 2, 4). Soil N availability is largely determined, however, by mineralization rates of the soil organic matter estimated at about 45 kg-N ha^{-1} $year^{-1}$ (average for the three communities) in the studied area (Parron et al. 2003). Rainfall thus corresponds to 28% of this value. Additionally around 40 kg ha^{-1} $year^{-1}$ of N is returned through litterfall (Table 4) and in this ecosystem the half-life of litter mass is approximately 2 years (Parron 2004). The flux of total P through bulk precipitation (0.7 kg ha^{-1}

year^{-1}) represents 73.0% of the available P (Mehlich I) stock in the topsoil (1.0 kg ha^{-1} average in the three communities) and 14.9% in the 0–100 cm depth interval (4.9 kg ha^{-1} average in the three communities) (Tables 2, 4). Litterfall flux of P (1.7 kg ha^{-1} year^{-1}) is 2.5 fold greater than atmospheric inputs.

As the throughfall and litter leachate solutions pass from the surface into the soil there are clearly additional changes that occur in the chemical composition (Chaves et al. 2009). Although soil solution was collected at only one point in the wet community a general characteristic was the very low concentrations of N and P, which are clearly related to the ion-exchange complex in the soil and requirements for plant uptake. Soil solutions collected in savanna ecosystems (Laclau et al. 2003) and planted forests (Lilienfein et al. 2000; Laclau et al. 2003) were also low in concentrations of nutrients. In another study in the IBGE reserve that used a similar network of lysimeters as utilized here but in an upland position beneath Cerrado vegetation the mean N and P concentrations of soil solutions at 25 cm depth were 6 µg l^{-1} of $_{total}$P, 34.0 µg l^{-1} of NH_4–N and 109.0 µg l^{-1} of NO_3–N (Resende 2001). These low concentrations indicate that the filtering capacity of preserved gallery forests for runoff of N and P from agricultural activities should be relatively high.

Additionally, the low concentrations of N and P in streamwater support the above contention. Although stream fluxes were estimated based on a fixed runoff percentage of bulk precipitation rather than direct measurements of discharge, the low concentrations of N and P, largely as base flow, indicate that fluxes should be lower than rates of N and P input through bulk precipitation (i.e., the system is not leaching excess N or P). Even though soil solution concentrations are low it might be possible that some amount of N can leave the ecosystem through groundwater flow as was estimated for an open tropical rainforest by Germer et al. (2009). The concentrations presented, however, in soil solution and stream relative to bulk precipitation, throughfall and litter leachate water emphasize the conservative role of these gallery forests in terms of nutrients. This nutrient retention within the gallery forests likely serves an important role in filtering surface runoff inputs to the stream and reinforces the value of maintaining and conserving these critical functional components of the Cerrado ecosystems.

The above results indicate links between the patterns in biogeochemical processes, especially for N, in the floristic communities (i.e., wet, intermediate, and dry) within the gallery forest and the patterns of tree species distribution (Silva Júnior et al. 1996), foliar nutrient concentrations of the more important tree species (Silva and Haridasan 1997), as well as physical and chemical soils characteristics and drainage conditions (Pinto et al. 2005). These patterns vary according to community position along the topographical gradient, if nearest the stream or adjacent to the woodland savanna. In agreement with our results, deforestation and replacement by croplands or pastures can led to a modification in N and P cycling and compromise the soil conservation of uplands and the quality of water in streams.

The gradient of community types in the gallery forest from wet to dry demonstrated differences in soils with bulk density, pH, and P contents increasing from wet to dry communities. Dissolved ion loads (i.e., conductivity) also increased in throughfall and litter leachate solutions from the wet to dry communities. Patterns in solution N and P concentration were not as clear with the wet community having lower N concentrations in throughfall but higher NH_4–N in litter leachate and greater organic P in litter leachate. The wet community appeared to have slightly lower internal fluxes than the intermediate or dry community. Relative to stream water outputs, however, all three communities were conservative, retaining N and P. The studied gallery forests, like many riparian forests, were effective in retaining N and P with inputs through bulk precipitation exceeding outputs to stream waters. This nutrient conservation in an undisturbed state offers a degree of protection for water resources. A continued improvement in understanding of biogeochemical processes can have implications for management practices and conservation polices of gallery forests in the Cerrado biome. This is, presently, of particular importance considering the revision of the Forest Act (Metzger et al. 2010), the main Brazilian environmental legislation affecting private land, including mandatory levels of restoration of previously cleared gallery forest.

Acknowledgments The authors acknowledge the Recor-IBGE for the logistic support, the financial assistance of the Embrapa, NASA (project LBA ND-07) and USEPA (Assistance Agreement 827291-01). We are grateful to César Prado for his help with the field and laboratory work.

References

Alcântara FA, Buurman P, Furtini Neto AE, Curi AE, Roscoe R (2004) Conversion of grassy cerrado into riparian forest and its impact on soil organic matter dynamics in an Oxisol from southeast Brazil. Geoderma 123:305–317

Bonnet BRP, Ferreira LG, Lobo FC (2006) Sistema de Reserva Legal Extra-Propriedade no Bioma Cerrado: Uma Análise Preliminar no Contexto da Bacia Hidrográfica. Rev bras Cartogr 58(2):129–137

Carvalho AM, Bustamante MMC, Kosovits AR, Miranda LN, Vivaldi LJ, Sousa DM (2006) Emissão de óxidos de nitrogênio associada à aplicação de uréia sob plantio convencional e direto. Pesq Agrop Bras 41(4):679–685

Castro EA, Kauffman JB (1997) Ecosystem structure in the Brazilian Cerrado: a vegetation gradient of aboveground biomass, root mass and consumption by fire. J Trop Ecol 14:263–283

Chapius Lardy L, Brossard M, Lopes Assad ML, Laurent JY (2002) Carbon and phosphorus stocks of clayey Ferralsols in Cerrado native and agroecossystems. Brazil Agric Ecossyst Environ 92:147–158

Chaves J, Neill C, Germer S, Gouveia Neto S, Krusche AV, Bonilla AC, Elsenbeer H (2009) Nitrogen transformations in flowpaths leading from soils to streams in Amazon forest and pasture. Ecosystems 12:961–972

Clesceri LS, Greenberg AE, Eaton AD (1998) Standard methods for the examination of water and wastewater, 20th edn. American Public Health Association, Washington

Crockford RH, Richardson DP, Sageman R (1996) Chemistry of rainfall, throughfall and stemflow in a eucalyptus forest and a pine plantation in South-Eastern Australia: stemflow and total inputs. Hydrol Process 10:25–42

Durigan G (1994) Florística, fitossociologia e produção de folhedo em matas da região oeste do Estado de São Paulo. Thesis, University of Campinas

Felfili JM (1994) Floristic composition and phytosociology of the gallery forest alongside the Gama stream in Brasilia, DF, Brazil. Rev Bras Bot 17(1):1–11

Felfili JM, Mendonça RC, Walter BMT, Silva Júnior MC, Nóbrega MGG, Fagg CW, Sevilha AC, Silva MA (2001) Flora fanerogâmica das matas de galeria e ciliares do Brasil Central. In: Ribeiro JF, Fonseca CEL, Souza-Silva JC (eds) Cerrado: Caracterização e recuperação de matas de galeria. Embrapa Cerrados, Planaltina, DF, p 19

Germer S, Neill C, Krusche AV, Gouveia Neto SC, Elsenbeer H (2007) Seasonal and within-event dynamics of rainfall and throughfall chemistry in an open tropical rainforest in Rondônia, Brazil. Biogeochemistry 86:155–174

Germer S, Neill C, Vetter T, Chaves J, Krusche AV, Elsenbeer H (2009) Implications of long-term land-use change for the hydrology and solute budgets of small catchments in Amazonia. J Hydrol 364:349–363

Goller R, Wilcke W, Fleischbein K, Valarezo C, Zech W (2006) Dissolved nitrogen, phosphorus, and sulfur forms in the ecosystem fluxes of a montane forest in Ecuador. Biogeochemistry 77:57–89

Haridasan M (1998) Solos de Matas de Galeria e nutrição mineral de espécies arbóreas em condições naturais. In: Ribeiro JF (ed) Cerrado: matas de galeria. Embrapa Cerrados, Planaltina, DF, p 17

Haridasan M, Felfili JM, Silva MC Jr, Rezende AV, Silva PEN (1996) Gradient analysis of soil properties and phytosociological parameters of some gallery forests on the Chapada dos Veadeiros in the cerrado region of central Brazil. In: Proceedings of the international symposium on assessment and monitoring of forests in tropical dry regions with special reference to gallery forests. November 4–7, 1996, Brasília, Brazil. University of Brasília, Brasília, p 259

Hulanicki A (1995) International Union of Pure and Applied Chemistry (IUPAC Recommendations). Absolute methods in analytical chemistry. Pure Appl Chem 67(11): 1905–1911

Jordan CF (1968) A simple, tension-free lysimeter. Soil Sci 105:81–86

Laclau JP, Ranger J, Bouillet JP, Nzila JD, De leporte P (2003) Nutrient cycling in a clonal stand of Eucalyptus and an adjacent savanna ecosystem in Congo 1. Chemical composition of rainfall, throughfall and stemflow solutions. For Ecol Manage 176:105–119

Lilienfein J, Wilcke W (2004) Water and element input into native, agri- and silvicultural ecosystems of the Brazilian savanna. Biogeochemistry 67:183–212

Lilienfein J, Wilcke W, Ayarza MA, Vilela L, Lima SC, Zech W (2000) Soil acidification in *Pinus caribaea* forests on Brazilian savanna oxisols. For Ecol Manage 128: 147–157

Lilienfein J, Wilcke W, Vilela L, Ayarza MA, Lima SC, Zech W (2003) Soil fertility under native Cerrado and pasture in the Brazilian savanna. Soil Sci Soc Am J 67:1195–1205

Lopes SF, Schiavini I (2007) Dinâmica da comunidade arbórea de mata de galeria da Estação Ecológica do Panga, Minas Gerais, Brasil. Acta bot bras 21(2):249–261

Markewitz D, Davidson EA, Figueiredo RO, Victoria RL, Krusche AV (2001) Control of cation concentrations in stream waters by surface soil processes in an Amazonian watershed. Nature 410:802–805

Markewitz D, Resende JCF, Parron L, Bustamante M, Klink CA, Figueiredo RD, Davidson EA (2006) Dissolved rainfall inputs and streamwater outputs in an undisturbed watershed on highly weathered soils in the Brazilian Cerrado. Hydrol Process 20:2615–2639

Metzger JP, Lewinsohn TM, Joly CA, Verdade LM, Martinelli LA, Rodrigues RR (2010) Brazilian law: full speed in reverse? Science 329:276–277

Nardoto GB, Bustamante MC (2003) Effects of fire on soil nitrogen dynamics and microbial biomass in savannas of Central Brazil. Pesq Agrop Bras 38:955–962

Nardoto GB, Bustamante MMC, Pinto AS, Klink CA (2006) Nutrient use efficiency at ecosystem and species level in savanna areas of Central Brazil and impacts of fire. J Trop Ecol 122(2):191–201

Neufeldt H (2006) Geoecological drivers of cerrado heterogeneity and ^{13}C natural abundance in oxisols after land-use change. R Bras Ci Solo 30:891–900

Oliveira ECL, Felfili JM (2005) Estrutura e dinâmica da regeneração natural de uma mata de galeria no Distrito Federal, Brasil. Acta bot bras 19(4):801–811

Oliveira RS, Bezerra L, Davidson EA, Pinto F, Klink CA, Nepstad DC, Moreira A (2005) Deep root function in soil water dynamics in cerrado savannas of central Brazil. Funct Ecol 200:574–581
Oliveira-Filho AT, Vilela EA, Gavilanes ML, Carvalho DA (1994) Effect of flooding regime and understorey bamboos in the physiognomy and tree species composition of a tropical semideciduous forest in Southeastern Brazil. Vegetatio 133:99–124
Parron LM (2004) Aspectos da ciclagem de nutrientes em função do gradiente topográfico em uma mata de galeria no Distrito Federal. Thesis, University of Brasília
Parron LM, Bustamante MMC, Prado CLC (2003) Mineralização de nitrogênio e biomassa microbiana em solos de mata de galeria: efeito do gradiente topográfico. Boletim de Pesquisa, vol 88. Embrapa Cerrados, Planaltina, DF, pp 1–26
Parron LM, Bustamante MMC, Prado CLC (2004) Produção e composição química da serapilheira em um gradiente topográfico em Mata de Galeria no bioma Cerrado. Boletim de Pesquisa, vol 128, Embrapa Cerrados, Planaltina, DF, pp 1–20
Perez-Marin AM, Menezes RSC (2008) Ciclagem de nutrientes via precipitação pluvial total, interna e escoamento pelo tronco em sistema agroflorestal com *Gliricidia sepium*. Rev Bras Cienc Solo 32:2573–2579
Pinto AS, Bustamante MMC, Kisselle K, Burke R, Zepp R, Viana LT, Varella F, Molina M (2002) Soil emissions of N_2O, NO and CO_2 in Brazilian Savannas: effects of vegetation type, seasonality, and prescribed fires. J Geoph Res 107:8089–8095
Pinto JRR, Oliveira-Filho AT, Hay JD (2005) Influence of soil and topography on the composition of a tree community in a central Brazilian valley forest. Edinb J Bot 62(1and 2):69–90
Reatto A, Correia JR, Spera ST, Martins ES (2008) Solos do bioma cerrado: aspectos pedológicos. In: Sano SM, Almeida SP, Ribeiro JF (eds) Cerrado: ecologia e flora, Embrapa Informação Tecnológica, Brasília DF. Embrapa Cerrados, Planaltina, DF, p 109
Resende JCF (2001) A ciclagem de nutrientes em áreas de Cerrado e a influencia de queimadas controladas. Thesis, University of Brasília
Ribeiro JF, Walter BMT (2008) As principais fitofisionomias do bioma Cerrado. In: Sano SM, Almeida SP, Ribeiro JF (eds) Cerrado: ecologia e flora, Embrapa Informação Tecnológica, Brasília DF. Embrapa Cerrados, Planaltina, DF, p 153
Rodrigo A, Ávila AA (2001) Influence of sampling size in the estimation of mean throughfall in two Mediterranean holm oak forests. J Hydrol 243:216–227
Roscoe R, Buurman P, Velthorst EJ, Pereira JAA (2000) Effects of fire on soil organic matter in a cerrado "sensu-stricto" from Southeast Brazil as revealed by changes in $d^{13}C$. Geoderma 95:141–160
Sano EE, Rosa R, Brito JL, Ferreira LG (2009) Land cover mapping of the tropical savanna region in Brazil. Environ Monit Assess 1:1–12. doi:10.1007/s10661-009-0988-4
Santiago J, Silva Júnior MC, Lima LC (2005) Fitossociologia da regeneração arbórea na Mata de Galeria do Pitoco (IBGE-DF), seis anos após fogo acidental. Scientia Forestalis 67:64–77
Scatena FN (1990) Watershed scale rainfall interception on two forested watersheds in the Luquillo Montains of Puerto Rico. J Hydrol 113:89–102
Schroth G, Elias MEA, Uguen K, Seixas R, Zech W (2001) Nutrient fluxes in rainfall, throughfall and stemflow in tree-based land use systems and spontaneous tree vegetation of central Amazonia. Agric Ecosyst Environ 87(1): 37–49
Shapiro SS, Wilk MB (1965) An analysis of variance test for normality (complete samples). Biometrika 52:591–611
Silva PEN, Haridasan M (1997) Foliar nutrient concentrations of tree species in four gallery forests in central Brazil, pp 309–321. In: Proceedings of the international symposium on assessment and monitoring of forests in tropical dry regions with special reference to gallery forests. November 4–7, 1996, Brasília, Brazil. University of Brasília, Brasília, 378 pp
Silva Júnior, MC (1995) Tree communities of the gallery forest of the IBGE Ecological Reserve, Federal District, Brazil. Thesis, University of Edinburgh
Silva Júnior MC (2005) Fitossociologia e estrutura diamétrica na Mata de Galeria do Pitoco, na Reserva Ecológica do IBGE, DF. Cerne 11:147–158
Silva Júnior MC, Furley PA, Ratter JA (1996) Variations in tree communities and soils with slope in gallery forest Federal District, Brazil. Adv Hills Process 1:451–469
Silveira CS, Coelho Netto AL (1999) Hydrogeochemical responses to rainfall inputs in a small rainforest basin: Rio de Janeiro, Brazil. Phys Chem Earth A: Solid Earth Geodesy 24(10):871–879
Soil Survey Staff (1999) Soil taxonomy-a basic system of soil classification for making and interpreting soil surveys. US Government Printing Office, Washington, DC
Souza JP, Araújo GM, Haridasan M (2007) Influence of soil fertility on the distribution of tree species in a deciduous forest in the Triângulo Mineiro region of Brazil. Plant Ecol 191:253–263
Statsoft Inc (2001) Statistica (data analysis software system), version 6. http://www.statsoft.com
Titus BD, Mahendrappa MK (1996) Lysimeter system designs used in soil research: a review. Series Information Report N-X-301 (Canadian Forest Service. Newfoundland and Labrador Region); N-X-301. St. John's, Newfoundland
Tobón Marin C, Boutenand W, Sevink J (2000) Gross rainfall and its partitioning into throughfall, stemflow and evaporation of intercepted water in four forest ecosystems in western Amazonia. J Hydrol 237(1–2):40–57
Tobón C, Sevink J, Verstraten JM (2004) Solute fluxes in throughfall and stemflow in four forest ecosystems in northwest Amazonia. Biogeochemistry 70:1–25
Umana NHN, Wanek W (2010) Large canopy exchange fluxes of inorganic and organic nitrogen and preferential retention of nitrogen by epiphytes in a tropical lowland rainforest. Ecosystems 13:367–381
Whitmore TC (1990) An introduction to tropical rain forests. Clarendon Press, Oxford
Zeng GM, Zhang G, Huang GH, Jiang YM, Liu HL (2005) Exchange of Ca^{2+}, Mg^{2+} and K^+ and uptake of H^+, NH_4^+ for the subtropical forest canopies influenced by acid rain in Shaoshan forest located in Central South China. Plant Sci 168:259–266