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Water and element input into native, agri- and silvicultural ecosystems of the Brazilian savanna

JULIANE LILIENFEIN[1] and WOLFGANG WILCKE[1,2,*]
[1]*Institute of Soil Science and Soil Geography, University of Bayreuth, Bayreuth, D-95440, Germany;* [2]*Current address: Department of Soil Science, Institute of Ecology, Salzufer 11–12, Berlin University of Technology, Berlin, D-10587, Germany; *Author for correspondence (e-mail: wolfgang.wilcke@tu-berlin.de; phone: +49/30-31473538; fax: +49/30-31473548)*

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Abstract. The interaction of rain water with the vegetation canopy results in changes of the water quantity and quality. We examined these canopy effects in different ecosystems of the Brazilian savanna, the Cerrado. The ecosystems were 20 yr-old *Pinus caribaea* Morelet plantations (PI), productive (PP) and degraded *Brachiaria decumbens* Stapf pastures (DP), continuous corn-soybean rotation (CC), and native typical cerrado (CE). We collected rainfall, throughfall, and, in PI and CE, stemflow from three plots of each ecosystem. Dry deposition and canopy leaching were estimated with a Na-tracer method. Between May 1997 and April 1999, the mean annual rainfall was 1656 mm of which 145 mm fell during the dry season (May–September). The throughfall percentage of the rainfall increased in the order, PI (75–85%) < CC (76–89%) < CE (89–100%) < PP (90–100%) < DP (99–100%); stemflow was < 1% of the rainfall. The volume-weighted mean (VWM) pH in rainfall was higher in the dry (6.5) than in the rainy season (5.4). The VWM pH in throughfall decreased in the order, CC (rainy season: 5.9/dry season: 6.2) > PP (5.5/6.0) > CE (5.2/6.0) > DP (5.2/5.6) > PI (4.8/5.7). The rainfall deposition of the dry season contributed one third of the annual element input with rainfall because of higher element concentrations than in the rainy season. The mean Na deposition ratios, i.e. the ratio of throughfall (+ stemflow) to rainfall deposition as a measure for dry deposition, increased in the order, CE (1.5) = CC (1.5) < PP (1.7) < PI (1.9) < (DP 2.1). Total deposition (rainfall + dry deposition) accounted for 104–164% of the K and Ca fertilizer application in PP and for 6.1–12% of the K, Ca, and Mg fertilizer application in CC. The P concentrations were below the detection limit of 0.2 mg L^{-1} in all samples. Net canopy uptake, i.e. a smaller throughfall(+ stemflow) than rainfall + dry deposition, of Ca, K, Mg, S, Cu, and Zn in at least one of CE, PI, DP, and PP indicate that plant growth may be limited in part by these nutrients. During the vegetation period, between 28 and 50% of the applied K and Ca were leached from the canopy in PP and between 8.7 and 17% of the applied K, Ca, Mg, and S in CC. Our results demonstrate that PI causes larger water losses and enhanced acid inputs to the soil compared with all other ecosystems. However, the PI and pasture canopies scavenge more nutrients from the atmosphere than CE and CC.

Introduction

Large parts of the Brazilian savanna, the Cerrado originally covering approximately 2 million ha (Ribeiro and Walter 1998), are today used for agri- and silvicultural ecosystems with few intermixed remainings of the native vegetation. The land-use systems replaced a seasonal vegetation ranging from open grassland to dense forest with open woodland being most abundant (Ribeiro and Walter 1998). In the Cerrado, fires are common and are currently enhanced because of a rapid land-use change (Eiten 1972; Castro and Kauffman 1998). The most common land-use systems of the Cerrado region are pastures, continuous cropping, and forest plantations (Resck et al. 2000). The growth of the vegetation is water- and nutrient-limited because of the long dry season and the nutrient-poor soils. Furthermore, the predominant Oxisols are acid and rich in Al resulting in possible Al toxicity (Goedert 1983).

Water losses from ecosystems are associated with seepage to the groundwater, transpiration, and evaporation mainly from the canopy surface. Water losses by evaporation from the canopy are higher in coniferous than in deciduous forests (Parker 1983). The losses of intercepted water from the canopy of a corn field in the Cerrado, in contrast, are close to zero (Lilienfein and Wilcke 2001). In the uppermost 2 m of the soils under pasture and continuous cropping with conventional tillage, the mean water content is higher than under native Cerrado because of the lesser water use. In contrast, under continuous cropping with no-tillage and under *Pinus caribaea* Morelet plantations, the water content is decreased compared with the Cerrado because of the increased evapotranspiration. Thus, vegetation type and tillage practices control soil water content and seepage to the groundwater (Lilienfein et al. 1999).

Soil acidification may be enhanced by the effect of the canopy on the pH of throughfall and of stemflow in forested systems. Particularly coniferous forest canopies acidify the rain water (Parker 1983). Under *Pinus caribaea* in the Brazilian Cerrado, Lilienfein et al. (2000a) observed indications for enhanced soil acidification resulting in markedly increased Al concentrations in the soil solution. The Ca/Al concentration ratio in the soil solution under *Pinus* ranged between 0.1 and 1.1 and was near to or below the toxicity level of 1 (Rost-Siebert 1983). However, Al concentrations were much lower than known threshold values for Al toxicity. The soil acidification was mainly attributed to the acid litter.

Wet and dry deposition from the atmosphere may be an important additional nutrient source for plants. This is particularly true, when the soils are nutrient-poor as it is the case in the Brazilian savanna. In this region, the deposition of nutrients from the atmosphere is enhanced by the frequent biomass burning that releases a large part of the nutrients stored in aboveground biomass to the atmosphere (Pivello and Coutinho 1992; Kauffman et al. 1994). There are comparatively few studies on the chemical composition of rainfall and element deposition in tropical savanna regions (Lima 1985; Freydier et al. 1998; Galy-Lacaux and Modi 1998). We are not aware of any specific study on dry deposition in tropical savannas. In the temperate zone of the northern hemisphere, dry deposition including particle impaction and gaseous deposition may be as high as rainfall deposition. This has been shown for forests by Ulrich (1983) and Lindberg et al. (1986) and for grassland by Hesterberg et al. (1996). Dry deposition may be determined with micrometeorological methods requiring expensive technical equipment (Lindberg et al. 1986; Hesterberg et al. 1996). Alternatively, Ulrich (1983) proposed a simple estimation method for the dry particulate deposition to forest canopies. If it is assumed that uptake and leaching of Na and Cl^- in the canopy are negligible, the ratio of the rainfall deposition to the throughfall plus stemflow deposition of Na and Cl^-, the deposition ratio, is a measure for the extent of the dry deposition. If it is furthermore assumed, as an approximation, that all elements show similar ratios between wet and dry deposition rates, the deposition ratios of Na and Cl^- may also be used to estimate the dry deposition of other elements. Although this method only provides a rough estimate of dry deposition, it has been shown to produce similar results as micrometeorological methods (Ulrich 1983; Lindberg et al. 1986). It has also been successfully used to estimate element input with cloud water to a tropical montane ecosystem in Costa Rica (Clark et al. 1998). With Ulrich's model, canopy leaching of nutrients may be calculated as difference between throughfall + stemflow deposition and rainfall + dry deposition. These estimated leaching rates include unknown contributions of gaseous deposition of N and S. Using this method, Lilienfein and Wilcke (2001) estimated that dry deposition accounts for 50–55% of the total element input to corn fields in the Cerrado region contributing up to 46% of the plant's nutrient demand. They furthermore observed net canopy uptake of Cu and Zn and pronounced leaching of K indicating possible lack of micronutrients and considerable leaching losses of the applied fertilizers.

Up to now, most studies on the loss of intercepted water by evaporation, throughfall quantity and quality, dry deposition, and canopy leaching were restricted to forest ecosystems. We are not aware of any published comprehensive comparison of the water and element inputs to different native, agricultural, and silvicultural ecosystems in the tropics.

The objectives of our study were (i) to determine water losses by evaporation from the canopy, (ii) to assess the effect of the canopies on the acidity of throughfall and stemflow, (iii) to estimate total deposition including bulk and dry deposition, and (iv) to assess nutrient leaching from or uptake by the canopies as indication of possible nutrient limitations.

Materials and methods

Site description

The study area is located southeast of Uberlândia (State of Minas Gerais) about 400 km south of Brasília (Figure 1). Mean annual temperature in Uberlândia between 1981 and 1990 was 22 °C with only small variations between the coldest (June, July: 19 °C) and the warmest months (February: 24 °C). Mean annual precipitation during this period was 1550 mm with 130 mm during the dry season between May and September and 1420 mm during the rainy season between October and April (Rosa et al. 1991).

Within an area of about 100 km^2, three plots of each of the following five land-use and native systems were selected: (1) *Pinus caribaea* Morelet plantations (PI),

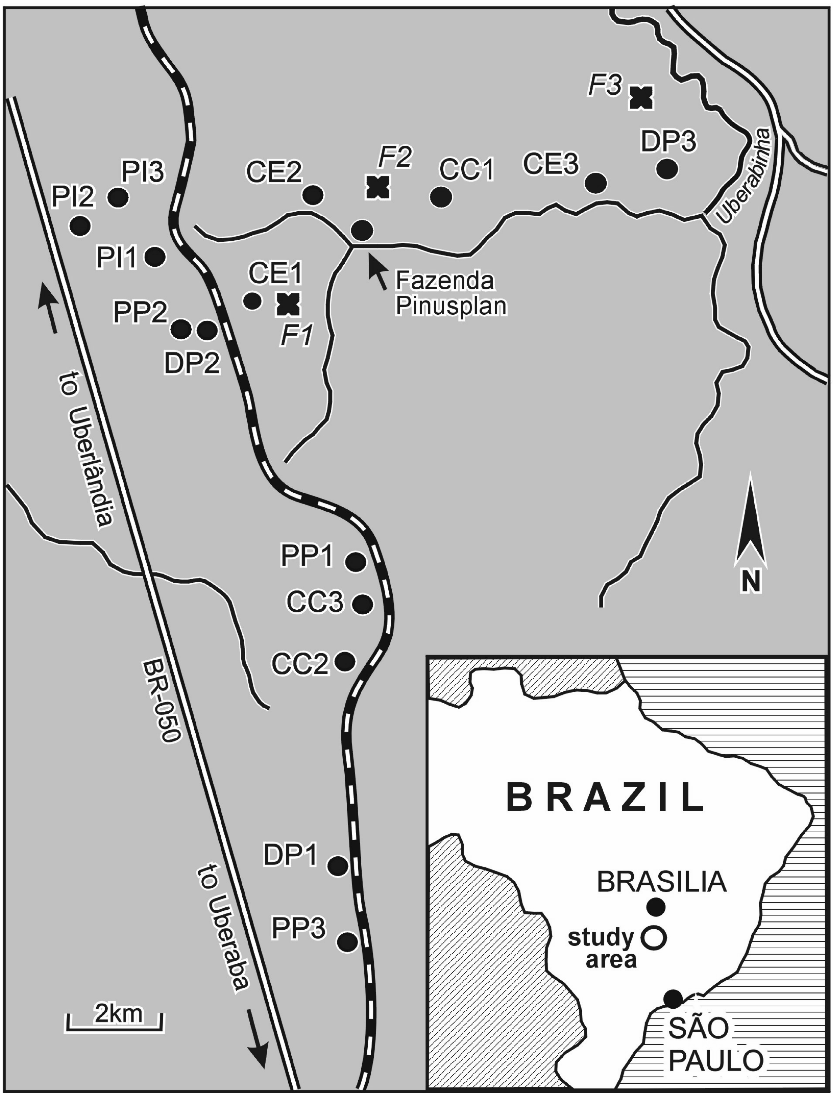


Figure 1. Location of the study sites. CE is Cerrado, PI is *Pinus caribaea* Morelet plantation, PP is productive *Brachiaria decumbens* Stapf pasture, DP is degraded *Brachiaria decumbens* pasture, CC is continuous cropping (corn-soybean rotation), and *F* is fallow with rain gauges.

(2) degraded (DP) and (3) productive pastures (PP), (4) continuous cropping (CC), and (5) native savanna (cerrado, CE). We considered these land-use systems the most important ones in the study region. To allow for statistical evaluation with variance analysis we aimed at selecting independent replicates of each system. As our objective was to conduct an on-farm experiment we had to select the experimental plots in existing land-use systems. Thus, an entirely randomized plot selec-

tion was not possible. However, we only chose replicate plots of each land-use and native system which were separated from each other by a distance of at least 300 m and, except for PI, by an area which was differently used between the replicate plots. The PI forest covered a large area without intermixed plots with different land-use. We assume that the prerequisites for variance analysis have been met by this experimental design.

The *Pinus caribaea* trees were planted in 1977 and fertilized with about 33 kg Ca, 13 kg P, and 20 kg S ha^{-1} (80 g of Superphosphate was applied to 1670 planted trees ha^{-1}) at the plantation date. There were no further fertilizer applications. At the time of our study (1997–1999), there were about 950 trees ha^{-1} with an average height of 21 m. The average diameter at breast height was 243 ± 38 mm at plot PI1, 261 ± 38 at PI2, and 234 ± 36 at PI3 (n = 30).

The PP was a pure grass pasture of *Brachiaria decumbens* Stapf with a closed vegetation cover. The DP system had decreased cover of *Brachiaria decumbens* Stapf compared with the productive pastures, followed by the invasion of Cerrado plants. All pastures under study were established around 1985. The most common procedure was to plant upland rice which was fertilized with about 40 kg P, 65 kg K, 32 kg N, and 1 t of dolomite ha^{-1}. The fertilizer was mixed with seeds of *Brachiaria decumbens*, an imported grass species from Africa. After the harvest of the rice, *B. decumbens* was already stabilized and grazing began. In 1996/97, we fertilized all PP replicates with 17 kg P and 33 kg K ha^{-1}. One of the three replicates of PP, PP1 in Figure 1, was an experimental pasture where the fertilizing rates are well known. The pasture PP1 received 17 kg P and 33 kg K ha^{-1} at 4-yr intervals (i.e. in 1988, 1992, and 1996). The other PP replicates received maintainance fertilizer applications at similar but unknown rates and application dates.

In the CC systems, a corn (*Zea mays* L.)-soybean (*Glycine max* (L.) Merr.) rotation had been grown for more than 10 years with a mean annual fertilizer rate of about 70 kg N ha^{-1}, 100 kg P ha^{-1}, and 160 kg K ha^{-1}. In the rainy season 1997/98, soybean was planted on 28 November 1997, fertilized with 60 kg P and 170 kg K ha^{-1}, and harvested on 16 April 1998. In the rainy season 1998/99, soybean was planted on 9 and 10 November 1998, fertilized on 29 October with 42 kg P ha^{-1} and 63 kg K ha^{-1}, and harvested on 15 April 1999. The fertilizer was applied as $Ca(H_2PO_4)_2$ and KCl. To control weeds 1.4 kg ha^{-1} glyphosate (Roundup, Monsanto) was applied.

The native vegetation was classified as a typical cerrado according to the definition of Eiten (1972). We conducted an extensive vegetation survey and determined the cerrado biomass (Lilienfein et al. 2001). The studied cerrado was characterized as an open woodland with a 15–40% cover of 3–5 m high trees. The density of woody plants was 6487 ha^{-1} with only 602 trees ha^{-1} taller than 2 m. Dominant tree species in the layer > 2 m were *Pouteria torta* (Mart.) Radlk., *Ouratea spectabilis* (Mart.) Engl., *Roupala montana* Aubl., *Byrsonima coccolobifolia* H.B. et K., *Dalbergia miscolobium* Benth., *Kielmeyera coriacea* Mart., and *Caryocar brasiliense* Cambess. which together represented 70% of the biomass of the > 2-m layer. In the 0.5–2 m tall layer, many different species were found of which *Ouratea hexasperma* (St.-Hil.) Baill. representing 33% of the biomass in the 0.5–2 m layer was most abundant. The dominant shrub species were *Miconia holosericea* DC., *Hortia brasiliana* Vand. ex DC., *Myrcia rostrata* DC., *Parinari obtusifolia* Hook. f., and *Campomanesia velutina* Blume, contributing 93% to the total shrub biomass. Among the grass species we most frequently found *Andropogon minarum* Kunth, *Axonopus barbigerus* (Kunth) Hitchc., *Tristachya chrysothrix* Nees, and *Echinolaena inflexa* (Poir.) Chase of the family *Poaceae* which comprises the highest number of species; among the herbaceous species, members of the families *Asteraceae*, *Rubiaceae*, *Fabaceae*, and *Mimosaceae* are most abundant.

All study sites had slopes below 1°; they have been continuously used for the same purposes for 12 (DP, PP, CC) or 20 (PI) years and passed directly from natural vegetation to the current land-use system. All study soils were very-fine isohyperthermic Anionic Acrustoxes (Soil Survey Staff 1998) developed from fine limnic sediments of the lower Tertiary. The soils were homogeneously weathered to a depth of > 2.5 m to which we opened trenches. We did not observe substantial changes in the state of weathering in the uppermost 2.5 m of the soil and therefore assume that the weathered layer extended to a depth of several m.

Equipment and sampling

On each of the 18 plots a 10 × 10 m area was fenced and equipped with five rain collectors consisting of a 2-L sampling bottle and a funnel both made of polyethylene with a diameter of 115 mm to measure soil water input at 0.3 m height above the soil surface in April 1997. In October 1998, we installed additional 15 rain collectors at each of the CE1 and PI1, as the assumed end members of canopy homogeneity, to improve the representativity of sampling. Each sampling bottle was protected against larger particles and small animals with a polyethylene net (0.5 mm mesh width). A table-tennis ball was used to reduce evaporation. The collectors were cleaned with deionized water prior to installing in the field and, if necessary, after each sampling. Furthermore, they were replaced by new clean collectors in 6–12 months intervals. Additionally, on the three DP plots five rain collectors were installed at 1 m above the soil surface in October 1998. Between October 1997 and April 1998, we considered the throughfall of the DP plots as representing the rainfall precipitation because we did not observe substantial differences in water volume collected with the samplers at 1 and at 0.3 m above the surface after April 1998 (Table 1). During the dry seasons, rainfall was measured on fallow soils (F1–3 in Figure 1) at 0.3 m above the soil surface. To compare rainfall and throughfall for each system, we used the rainfall measurements at the stations next to the individual plots of each system. These were during the rainy seasons the rain gauge at DP1 for DP1 and PP3, that at DP2 for CE1, CE2, PI1–3, DP2, PP1–2, CC1–2, and that at DP3 for CE3, DP3, and CC3. During the dry seasons the rain gauge at F1 was assigned to CE1, PI1–3, DP1–2, PP1–3, and CC1, that at F2 to CE2 and CC2, and that at F3 to CE3, DP3, and CC3 (Figure 1). Means and ranges of rainfall were calculated for all rain gauges we assigned to each individual plot.

In October 1997, five tall trees were equipped with stemflow collectors in each of the CE and three trees in each of the PI plots (slightly modified from Likens and

Table 1. Ranges of rainfall (RF), throughfall (TF), stemflow (SF), and interception losses (IL) in Cerrado (CE), *Pinus* (PI), degraded (DP) and productive pasture (PP), and continuous cropping (CC) during a) the dry seasons 1997 and 1998 and b) rainy seasons 1997/98 and 1998/99.

System	RF	TF	SF	IL	RF	TF	SF	IL
	a) Water fluxes during the dry seasons (mm)							
	May–September 1997				May–September 1998			
CE	47–193	153–211		0	146–173	139–169	1.5	0–14
PI	193	116–157		36–77	173	116–143	0.7–2	29–55
DP	47–193	33–175		14–69	154–173	166–184		0–5
PP	193	83–174		19–110	173	111–188		0–62
CC	156–193	111–115		41–82	146–173	144–169		0–29
	b) Water fluxes during the rainy seasons (mm)							
	October 1997–April 1998				October 1998–April 1999			
CE	1336–1403	1259–1475	13	0–130	1387–1594	1132–1574	13	7–242
PI	1403	1086–1278	5–10	120–290	1594	1189–1279	4–12	311–394
DP	1320–1403	1320–1403		0	1387–1944	1362–1977		0–25
PP	1320–1403	1166–1321		48–237	1594–1944	1575–1883		0–74
CC	1320–1403	1138–1344		0–265	1594–1944	1357–1633		237–479

Eaton (1970)). In October 1998, after the dominant tree and shrub species in the CE vegetation had been determined (Lilienfein et al. 2001), 13 additional stemflow collectors were installed in plot CE1 to collect stemflow from the four dominant tall tree (*Pouteria torta*, *Ouratea spectabilis*, *Roupala montana*, *Byrsonima coccolobifolia*), the dominant small tree (*Ouratea hexasperma*), and the dominant shrub species (*Miconia holosericea*). Thus, in the rainy season 1998/99 stemflow was collected from the most abundant four tall tree, one small tree, and one shrub species in threefold replication.

Precipitation, throughfall, and stemflow samples were taken weekly during the rainy seasons (October–April 1997/98 and 1998/99) and every two weeks during the dry seasons (May–September 1997 and 1998). The samples of each plot or rainfall measurement station were bulked except for the 20 rain collectors in CE1 and PI1 on 28 October 1998, during the transition from the dry to the rainy season, and on 31 March 1999, at the end of the rainy season, to assess spatial variability of the quantity and quality of throughfall. During the first dry season, we only recorded the precipitation volume but did not collect samples for chemical analyses.

Chemical analyses

Precipitation, throughfall, and stemflow samples were filtered through ashless white ribbon filters (pore size, 4–7 μm; Nr. 300111, Schleicher and Schuell, Dassel, Germany) and all solution samples were frozen for storage on the day of sampling. We did not add any preservatives. The samples were kept frozen (except that some samples thawed during the export to Germany but remained near to 0 °C) until the analysis that was conducted within 6 months after sampling. We checked the influence of sample storage in the field by comparing pH and element concentrations (including N forms and organic C) of samples taken in 1–3 day intervals with those in samples that remained for 1 week in the collectors and did not observe significant differences.

In all samples, the following parameters were determined: solution pH with a glass electrode (U 402-S7, Orion, Boston, MA, USA); the measurement was conducted in a subsample which was afterwards discarded because of the contamination with K released by the pH electrode, Cl^- with a Cl^--specific ion electrode (Orion, Boston, MA), NH_4^+ and NO_3^- with a rapid flow analyzer (RFA-300, Alpkem Corporation, Clackamas, OR, USA). Total N concentrations were only determined in bulked monthly samples with a total N-analyzer (ABIMED TN-05, Abimed Healthcare Products, South Plainfield, NJ, USA) because the analysis required a large sample volume of 40 mL.

To check the contribution of the larger particles that remained in the filter to bulk deposition, we extracted the filter papers including the retained particles of two sampling dates in the rainy season (28/10/98 and 31/03/99) and combined filters of the dry season 1998 with a 4:1 mixture of concentrated HNO_3 and concentrated $HClO_4$ (Zeien and Brümmer 1989). For the extractions, the filter papers of the five rain collectors were combined for each plot.

Calcium, K, Mg, and Na concentrations were analyzed with flame atomic absorption spectrometry (Varian SpectrAA 400, Varian, Mulgrave, Australia). Aluminum, Mn, and Zn concentrations were measured with inductively-coupled plasma mass spectroscopy (VG PlasmaQuad PQ2 Turbo Plus, VG Elemental, Windsford, UK), Cu with atomic absorption spectrometry – graphite tube technique (Varian SpectrAA 400Z), total S and P with inductively-coupled plasma-atomic emission spectroscopy (ICP-AES, GBC Integra XMP, GBC Scientific Equipment Pty, Ltd., Dandenong, Victoria, Australia), and total organic C (TOC) with an automatic TOC analyzer (TOC-5050, Shimadzu, Tokyo).

Calculations and statistical evaluation

Element deposition was calculated as the product of the volume-weighted mean concentrations of each dry and rainy season and the total water volume. The concentrations of organic N in our solutions (*TON*, filtered < 4–7 μm) was calculated with Equation 1.

$$TON = TN - (NO_3 - N) - (NH_4 - N) \tag{1}$$

where *TN* is the total N concentration.

To estimate the dry deposition and the crop leaching we used the model of Ulrich (1983) which has been proposed for forest canopies. The total deposition (*TD*) of an element *i* was calculated with Equation 2.

$$TD_i = RD_i + DD_i \tag{2}$$

Here, *RD* is bulk rainfall deposition measured above the canopy and *DD* is dry deposition estimated with Equation 3. This estimate of *DD* does not include gaseous deposition.

$$DD_i = \frac{TFD_{Na} + SFD_{Na}}{RD_{Na}} RD_i - RD_i \tag{3}$$

where TFD_{Na} represents the throughfall deposition of Na and SFD_{Na} the stemflow deposition of Na; the quotient $(TFD_{\mathrm{Na}} + SFD_{\mathrm{Na}})/RD_{\mathrm{Na}}$ is called deposition ratio. Crop leaching (*LEA*) was calculated with Equation 4.

$$LEA_i = TFD_i + SFD_i - RD_i - DD_i \tag{4}$$

These leaching rates include an unknown contribution of dry gaseous deposition of N and S.

Means of the concentrations and element fluxes were compared among the land-use and native systems with Tukey's honestly significant difference (HSD) mean separation test (Hartung and Elpelt 1989). Differences in element concentrations among the systems were tested with the nonparametric Wilcoxon matched pairs test. Significance was set at $P < 0.05$. Statistical analyses were performed with STATISTICA for Windows 5.1 (StatSoft 1995, Hamburg, Germany).

Results

Water input

The mean annual rainfall between 1 May 1997 and 28 April 1999 was 1815 mm at DP1, 1682 at DP2, and 1472 at DP3. On average, it was higher in the second year (1815 mm) than in the first year (1497). Mean weekly precipitation during the dry seasons was 6 mm and during the rainy seasons 50 mm, five weeks had > 100 mm of rainfall (Figure 2). The mean annual rainfall at the three rain gauge stations showed a small variation (coefficient of variation (CV): 10%) in spite of a distance of 5.7–8.9 km between the gauge stations. The variation of the mean cumulative rainfall of the two dry seasons among the three gauge stations (CV: 29%) was higher than that of the two rainy seasons (9%). The different ranges of rainfall for the different systems in Table 1 result from the fact that we considered only the rain gauges which were located next to the study plots of a given system as representative for this system. This was necessary because the spatial variation of the weekly rainfall among the three rain gauges that was used to calculate the means of the water budget components was much larger (CV up to 154%).

In CE1 and PI1, the mean throughfall on 28 October 1998 and 31 March 1999 collected with the first five collectors deviated by < 12% from the mean of all 20 collectors (Table 2).

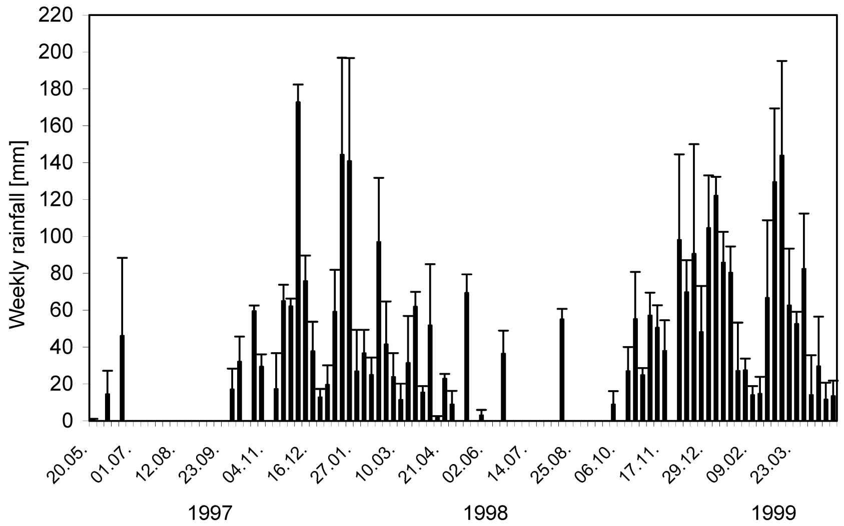


Figure 2. Course of weekly rainfall in the Cerrado region near the city of Uberlândia in Brazil between 11 April 1997 and 28 April 1999. Error bars represent standard deviations of three replicate plots.

During the monitored period, the mean proportion of the rainfall at the stations next to the respective study plots that reached the soil as throughfall increased in the order, PI (75–85%) < CC (76–89%) < CE (89–100%) < PP (90–100%) < DP (99–100%, Table 1). In CE and PI, stemflow accounted for < 1% of rainfall. The PI stands had the highest interception losses. They accounted for 9–25% of rainfall during the rainy season and for 17–40% during the dry season. In CE, 0–9% of the rainfall were evaporated from the canopy during the rainy season, and no evaporation of intercepted water was observed during the dry seasons. In all studied systems, the mean weekly throughfall correlated significantly with the mean weekly rainfall (r = 0.85–0.99). In CE and PI, the mean weekly stemflow correlated significantly with the mean weekly rainfall (r = 0.81 and 0.77).

Chemical composition of solutions

pH

The volume-weighted mean (VWM) pH in rainfall was lower during the rainy season than during the dry season (Table 3). During the rainy season, the VWM pH in throughfall remained almost unchanged in CE and DP, decreased in PI, and increased in PP and CC compared to that in rainfall. During the dry season, the VWM pH in throughfall was lower than in rainfall in all systems except for the unvegetated CC and the differences among the systems were small. In CE and PI, the stemflow was more acid than the throughfall. The pH in stemflow did not vary much among the seasons and was significantly lower in PI than in CE.

Table 2. Means, standard errors as measure for the error of the mean, and coefficient of variations as measure for the variation of the data of the water volume, TN, K, and Cu fluxes during one week measured with 5 versus 20 throughfall collectors in Cerrado and *Pinus* on 28 October 1998 and 31 March 1999.

	Cerrado				*Pinus*			
	Volume (mm)	TN (kg ha^{-1} wk^{-1})	K (kg ha^{-1} wk^{-1})	Cu (g ha^{-1} wk^{-1})	Volume (mm)	N_{tot} (kg ha^{-1} wk^{-1})	K (kg ha^{-1} wk^{-1})	Cu (g ha^{-1} wk^{-1})
28 October 1998[a]:								
5 collectors	30	0.57	0.21	1.7	28	0.29	0.30	1.8
Standard error	1.5	0.17	0.05	0.3	1.7	0.02	0.03	0.4
Coefficient of variation[b]	12	68	55	43	14	16	23	48
20 collectors	27	0.39	0.13	1.5	27	0.31	0.27	1.4
Standard error	1.0	0.06	0.02	0.3	0.89	0.02	0.02	0.2
Coefficient of variation	17	66	64	79	13	29	29	44
31 March 1999:								
5 collectors	62	0.47	0.15	2.0	31	0.11	0.17	1.0
Standard error	1.9	0.31	0.04	1.0	2.4	0.03	0.03	0.2
Coefficient of variation	6.7	148	64	109	17	62	43	37
20 collectors	64	0.18	0.93	1.2	34	0.09	0.16	0.9
Standard error	1.8	0.08	0.02	0.3	1.4	0.01	0.01	0.1
Coefficient of variation	13	206	71	96	18	47	39	43

[a]In *Pinus* only 15 collectors.; [b]Cofficient of variation = standard deviation $(mean)^{-1} \times 100$.

Table 3. Volume-weighted mean element concentrations in rainfall, throughfall, and stemflow in Cerrado (CE), *Pinus* (PI), degraded (PP) and productive pasture (PP), and continuous cropping (CC) during two rainy (RS) and one dry seasons (DS). Different letters indicate significant differences among the ecosystems according to Tukey's HSD test ($p < 0.05$).

	Al			TOC			Ca			Cl^-			Cu			H^+			K			Mg		
	RS1	DS2	RS2	RS1	DS2	RS2	RS1	DS2	RS2	RS1	DS2	RS2	RS1	DS2	RS2	RS1	DS2	RS2	RS1	DS2	RS2	RS1	DS2	RS2
	Rainfall ($\mu g\ L^{-1}$)																							
Rainfall	1.9b	1.0	1.9b	2804b	5850b	2804b	119	552	119b	272b	1897b	272b	1.2b	1.1	1.2	4.9b	0.3	4.9abc	161b	1685	161b	49	283	49b
Sanhueza et al. (1992)[a]		–			–			–			–			–			–			–			–	
Galy-Lacaux and Modi (1998)[b]		–			–			184–1790			249–1118			–			2.1–7.6			98–657			35–183	
Forti and Neal (1992)[c]		–			–			< 50–1500			140–4500			–			2.0–100			20–1330			< 20–250	
	Throughfall ($\mu g\ L^{-1}$)																							
CE	7.7ab	9.3	17a	4028b	8079ab	3793b	301	706	251b	770ab	2401	553ab	2.4a	3.0	2.0	6.0b	1.0abc	8.0ab	285b	1339	372b	109	304	114b
PI	24a	13	17a	6495a	15244a	6661a	402	658	194b	965a	2144	434ab	2.9a	3.2	1.9	16a	2.0ab	21a	570b	2591	493b	217	333	79b
DP	8.8ab	9.9	6.0b	2825b	6435b	3187b	467	1669	224b	587ab	4633	513ab	2.0ab	2.2	1.5	3.7b	2.3a	7.8ab	418b	1186	383b	196	373	86b
PP	7.9ab	1.2	4.9b	3634b	6906b	3192b	491	1283	208b	679ab	5267	523ab	2.2ab	2.3	1.5	2.1b	1.0abc	3.6b	564b	937	401b	170	336	84b
CC	8.8ab	0.0	7.1b	3966b	5720b	3650b	555	1129	636a	1002a	2264	1129a	2.6a	1.2	1.9	1.3b	0.6bc	1.4b	1596a	1488	1798a	211	285	219a
Forti and Neal (1992)[a]		–			–			60–5600			370–2880			–			–			260–12500			80–8300	
Lilienfein and Wilcke (2001)[b]		–			–			581			826			2.4			–			2110			199	
	Stemflow ($\mu g\ L^{-1}$)																							
CE	97	448	113	10895	16017	10570	469	525	275	653	2602	514	5.1	6.0	3.0	11	12	9.4	900	3372	767	280	570	169
PI	63	152	88	17825	21134	23201	539	288	371	437	2982	580	17	6.1	15	58	60	85	762	2708	812	160	202	140

Table 3. Continued

	Al			TOC			Ca			Cl^-			Cu			H^+			K			Mg		
	RS1	DS2	RS2	RS1	DS2	RS2	RS1	DS2	RS2	RS1	DS2	RS2	RS1	DS2	RS2	RS1	DS2	RS2	RS1	DS2	RS2	RS1	DS2	RS2
	Rainfall ($\mu g\ L^{-1}$)																							
Rainfall	0.53b	0.54	0.53	125	649	125b	108b	417	108b	266c	1305	266b	260b	532c	260c	85	0.0	85	6.9	9.5	6.9			
Sanhueza et al. (1992)[a]		–			42–98			28–70			–			–			64–192[e]			–				
Galy-Lacaux and Modi (1998)[b]		–			181–267			125–172			–			152–1162			234–480[e]			–				
Forti and Neal (1992)[c]		–			50–860			5.0			170–850			210–1810			370–1240[e]			–				
	Throughfall ($\mu g\ L^{-1}$)																							
CE	2.6b	4.6	5.7	96	621	175ab	174b	473	232b	515bc	1821	573b	475ab	993ab	367bc	84	510	104	56	40	14			
PI	6.1a	5.5	4.3	263	727	200ab	319ab	928	352ab	1189a	2125	929ab	738ab	1166a	539a	164	176	157	64	53	10.2			
DP	1.1b	11	1.9	168	1246	194ab	290b	986	242b	717abc	2540	833b	872a	823abc	329bc	203	207	108	14	137	11			
PP	1.8b	8.5	1.6	437	623	162ab	309b	983	310b	997ab	1915	522b	695ab	614b	335bc	237	71	109	18	26	9.2			
CC	2.8ab	0.0	1.7	242	626	298a	638a	703	674a	1348a	1744	1734a	506ab	572b	417b	272	0	345	14	9.2	9.8			
Forti and Neal (1992)[c]		–			62–2240			–			–			240–18300			150–830			–				
Lilienfein and Wilcke (2001)[d]		1.3			–			–			1550			493			376			9.3				
	Stemflow ($\mu g\ L^{-1}$)																							
CE	9.1	47	7.7	129	343	135	93	187	161	591	1595	657	638	266	499	100	109	102	9.7	8.1	6.9			
PI	5.5	27	7.4	134	496	251	172	267	190	1350	2350	1460	801	388	596	167	127	173	11	9.7	6.7			

[a]Range of Venezuelan savanna sites. [b]Range of African savanna sites. [c]Range of tropical rain forests. [d]Volume-weighted mean concentration in throughfall under corn canopy during the rainy season in the Brazilian Cerrado. [e]Data refer to SO_4–S

On 28 October 1998, the pH ranged 3.5–6.7 in the 20 throughfall collectors of CE1 and 4.5–6.2 in those of PI1. On 31 March 1999, the ranges were 4.8–6.6 in CE1 and 4.7–5.6 in PI1.

Element concentrations

The P concentrations in all samples were below the detection limit of our method of 0.2 mg L^{-1}. Although the small (or no) evaporation of water intercepted by the DP canopy indicated a small effect of the plants on the water volume that reached the soil, we observed considerable differences in the chemical composition of rainfall at 1 m and throughfall at 0.3 m above the soil surface (Table 3). Thus, the chemical composition of the water collected at 0.3 above the soil surface in DP in the first rainy season was not representative of the quality of the rainfall above the canopy. Therefore, we used the VWM element concentrations of the second rainy season measured above the DP canopy for the calculation of the rainfall deposition in the first rainy season. The VWM concentrations of most elements were higher in the dry than in the rainy season except for Al, Cu, H^+, Mn, and S. The increase in VWM concentrations in the dry season compared with the rainy season was element-specific.

Most element concentrations in throughfall of all systems were higher than in rainfall during dry and rainy seasons. In all systems, the VWM element concentrations in throughfall were higher during the dry season than during the rainy season except for Al, H^+, Na and in CC also K. Among the systems, highest VWM concentrations of Al, TOC, H^+, and partly also of Cu and Mn were found in the throughfall of PI and highest Ca, K, Mg, NH_4^+, NO_3^-, TN, and S concentrations were found in the throughfall of CC. While in CE, PI, and the pastures element concentrations in throughfall were higher during periods with little rain (not shown), the element concentrations in throughfall of CC increased during the rainy season as the crops grew. This effect was particularly pronounced for K (Figure 3). In all systems, the TON concentration increased in throughfall compared with rainfall in both the rainy and dry seasons (Figure 4). Although this was true for each individual system and for all three monitored seasons with few exceptions, only the difference between the mean TON concentration in PI throughfall and in rainfall during the first rainy season was significant. This was because of the large variation in TON concentrations of throughfall among the replicates of the individual ecosystems as indicated by the large error bars in Figure 4.

The differences in selected element concentrations between the mean of the first 5 collectors and the mean of all 20 collectors in CE1 and PI1 on 28 October 1998 and 31 March 1999 were larger than those in throughfall volumes (Table 2).

The VWM concentrations of Al, TOC, Cu, H^+, K, and TON were higher in stemflow than in throughfall of CE and PI during the dry and rainy seasons, those of NO_3-N, Zn, and partly also of NH_4-N were lower. The VWM concentrations of Ca in stemflow were higher than in throughfall during the rainy season and lower during the dry season. The VWM concentrations of the remaining elements did not show consistent differences between stemflow and throughfall. For most elements, the VWM concentrations in stemflow of PI were higher than in stemflow of CE

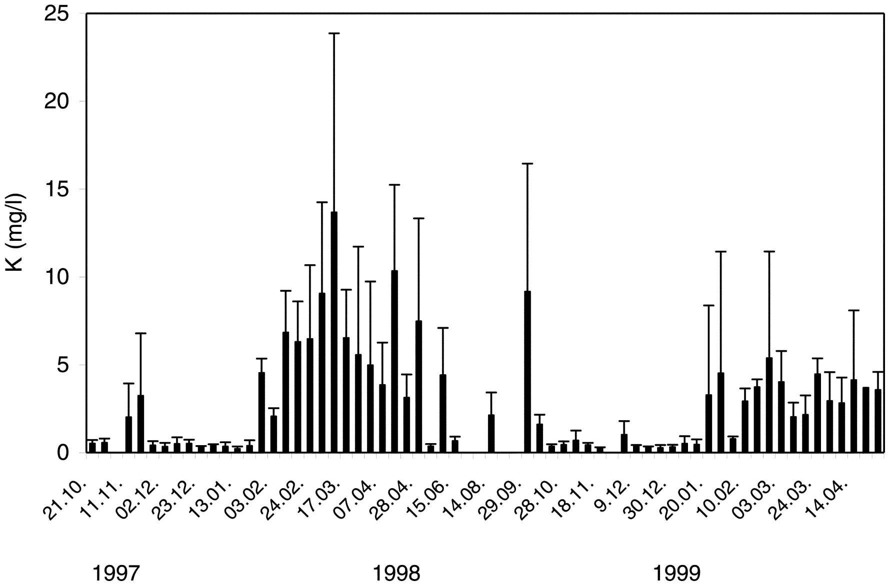


Figure 3. Course of the K concentration in throughfall of continuous cropping with soybean between 21 October 1997 and 28 April 1999. Error bars represent standard deviations of three replicate plots.

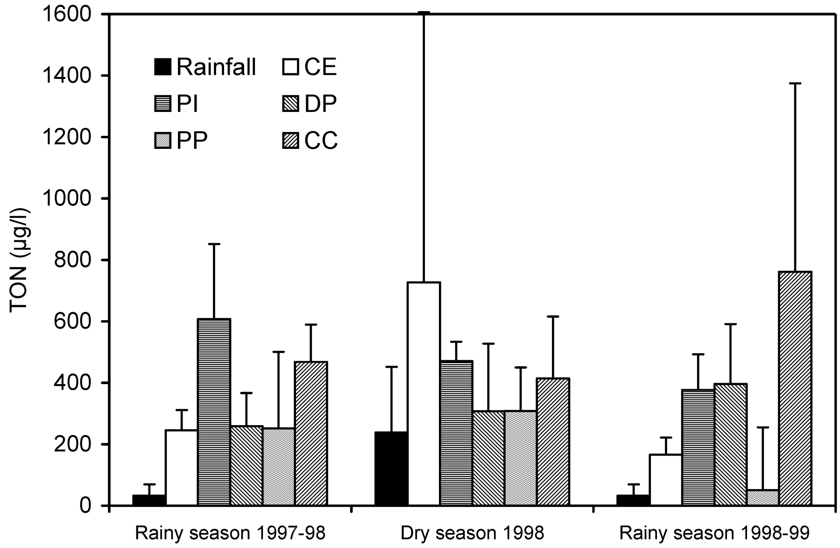


Figure 4. Mean total organic N (TON, filtered < 4–7 μm) concentrations in rainfall and in throughfall of Cerrado (CE), *Pinus* (PI), degraded (PP) and productive pasture (PP), and continuous cropping (CC) during two rainy and one dry seasons. Error bars represent standard deviations of three replicate plots.

during the dry and rainy seasons. However, those of Al, Mg, and Mn were consistently higher in stemflow of CE.

Element fluxes

Although only about 10% of the annual rainfall occurred during the dry season, the element deposition during this period accounted for about one third of the annual nutrient input by rainfall deposition (Table 4). The throughfall deposition of Al, TOC, H^+, and Mn was highest in the forested systems (PI, CE), that of the major plant nutrients Ca, K, Mg, N, and S was highest in the fertilized systems (CC, PP). The stemflow deposition accounted for 0.4% (Zn) to 7.2% (Al) of the total deposition to the soil (throughfall + stemflow) in CE and for 0.4% (NO_3-N) to 4.3% (Cu) in PI.

To assess the importance of atmospheric inputs for plant nutrition, we estimated the contributions of dry deposition and plant canopy leaching to the total soil input of plant nutrients with the model of Ulrich (1983) using Na as tracer. We have shown in a previous paper that Cl^- was not a nonreactive tracer in the ecosystems of the study region (Lilienfein and Wilcke 2001). Mean dry deposition, estimated with the help of the Na deposition ratios individually for each of the one dry and two rainy seasons and summed up, was highest in PI (Ca, K, Mg, Mn, N_{tot}) or DP (Cu, S, and Zn, Table 5). Total deposition (rainfall + dry deposition) accounted for 104% of the K and 164% of the Ca mean annual application with fertilizers in PP. In CC, the proportion of the total deposition of the mean annual fertilizer input ranged between 0.3% (Mn) and 12% (Ca).

The element deposition with coarse particles that were retained in the filters, represented < 2% of the Ca, Cu, Mg, and Mn and up to 6% of the K input by rainfall + dry deposition in all systems.

Mean canopy leaching was highest in CC except for Cu, Mn, and Zn where highest canopy leaching occurred in CE (Figure 5). In the forested systems (CE, PI), mean annual canopy leaching was negative for the base metals Ca (PI only), K, and Mg and for S. In the pastures, this was the case for Cu and in DP also for S and Zn. During the vegetation period, between 28 and 50% of the applied K and Ca were leached from the canopy in PP and between 8.7 and 17% of the applied, K, Ca, Mg, and S in CC.

Discussion

Water input

The mean annual rainfall in the first monitored year was lower than the mean of 1550 mm yr^{-1} between 1981 and 1990 in Uberlândia, in the second year it was higher (Rosa et al. 1991). The reason for lower annual rainfall in the first year was probably the El Niño effect in 1997.

The throughfall of PI accounted for similar percentages of the rainfall as reported for tropical lowland forests of 77–93% (Bruijnzeel 1990). The higher percentage of the rainfall that reaches the soil in CE was attributable to the low canopy density.

Table 4. Rainfall (RF) and throughfall deposition in Cerrado (CE), *Pinus* (PI), degraded (PP) and productive pasture (PP), and continuous cropping (CC) during two rainy (RS) and one dry seasons (DS) and in the literature. Different letters indicate significant differences among the ecosystems according to Tukey's HSD test ($p < 0.05$).

Element	Rainfall/ Ecosystem	RS 1997/98 ($kg\ ha^{-1}$)	DS 1998	RS 1998/99	Year 2 1998–99	Lima (1985)[a] ($kg\ ha^{-1}\ yr^{-1}$)	Galy-Lacaux & Modi 1998[b]	Filoso et al. (1999)[c]	Lara et al. (2001)[d]
Al	RF	0.025b	0.001	0.031c	0.033c				
	CE	0.123ab	0.022	0.25a	0.27a				
	PI	0.27a	0.020	0.22ab	0.24ab				
	DP	0.12ab	0.017	0.10abc	0.12abc				
	PP	0.099ab	0.001	0.088bc	0.089bc				
	CC	0.110ab	0.000	0.1abc1	0.11abc				
TOC	RF	38	9.2	46b	55b				
	CE	57	13	53b	66b				
	PI	77	20	85a	105a				
	DP	38	11	53b	64b				
	PP	46	11	56b	67b				
	CC	49	8.7	57b	65b				
Ca	RF	1.6	0.86	1.9b	2.8b	17	3.1	2.5	0.82–1.7
	CE	4.1	1.1	3.4b	4.5b	23		5.5	
	PI	4.6	0.84	2.4b	3.3b	22			
	DP	6.4	3.0	3.7b	6.7b				
	PP	6.2	1.9	3.7b	5.6b				
	CC	6.8	1.8	9.8a	12a				
Cl^-	RF	3.7b	3.0	4.4	7.4		1.3	1.6	2.1–2.9
	CE	10ab	3.8	7.5	11			5.4	
	PI	11ab	2.8	5.4	8.3				

Table 4. Continued

Element	Rainfall/ Ecosystem	RS 1997/98	DS 1998	RS 1998/99	Year 2 1998–99	Lima (1985)[a]	Galy-Lacaux & Modi 1998[b]	Filoso et al. (1999)[c]	Lara et al. (2001)[d]
		($kg\ ha^{-1}$)				($kg\ ha^{-1}\ yr^{-1}$)			
Cl^-	DP	8.0ab	8.2	8.4	17				
	PP	8.5ab	6.8	9.3	16				
	CC	12a	3.5	18	21				
Cu	RF	0.015b	0.002	0.020	0.022				
	CE	0.033a	0.005	0.028	0.033				
	PI	0.035a	0.004	0.024	0.028				
	DP	0.028ab	0.004	0.025	0.029				
	PP	0.027ab	0.003	0.028	0.030				
	CC	0.032a	0.002	0.030	0.032				
H	RF	0.066b	0.000c	0.081ab	0.081		0.010	0.21	0.34–0.44
	CE	0.083ab	0.002abc	0.110ab	0.111			0.05	
	PI	0.186a	0.003ab	0.263a	0.266				
	DP	0.050b	0.004a	0.144ab	0.148				
	PP	0.025b	0.001abc	0.066ab	0.068				
	CC	0.016b	0.001bc	0.021b	0.022				
K	RF	2.2b	2.7	2.6b	5.3b	9.8	0.90	0.73	0.90–1.3
	CE	4.0b	2.1	5.3b	7.4b	78		28	
	PI	6.7b	3.4	6.2b	9.6b	28			
	DP	5.7b	2.1	6.2b	8.2b				
	PP	7.2b	1.3	7.0b	8.3b				
	CC	19a	2.2	28a	30a				
Mg	RF	0.66	0.45	0.79b	1.2b	5.2	0.34	0.37	0.17–0.32
	CE	1.5	0.47	1.5b	2.0b	12		2.7	

Table 4. Continued

Element	Rainfall/ Ecosystem	RS 1997/98 (kg ha^{-1})	DS 1998	RS 1998/99	Year 2 1998–99	Lima (1985)[a] (kg ha^{-1} yr^{-1})	Galy-Lacaux & Modi 1998[b]	Filoso et al. (1999)[c]	Lara et al. (2001)[d]
Mg	PI	2.5	0.43	0.99b	1.4b	6.8			
	DP	2.7	0.66	1.4b	2.1b				
	PP	2.2	0.51	1.5b	2.0b				
	CC	2.5	0.44	3.4a	3.8a				
Mn	RF	0.007b	0.001	0.009	0.009b				
	CE	0.036ab	0.008	0.079	0.087a				
	PI	0.069a	0.007	0.054	0.061ab				
	DP	0.015b	0.019	0.034	0.052ab				
	PP	0.022b	0.010	0.029	0.039ab				
	CC	0.035ab	0.000	0.027	0.027ab				
NH_4-N	RF	1.7	1.0	2.0b	3.1		0.88	0.64	1.1–3.1
	CE	1.3	0.98	2.4b	3.4			0.51	
	PI	3.0	0.9	2.5ab	3.4				
	DP	2.3	2.2	3.2ab	5.3				
	PP	5.6	0.9	2.9ab	3.8				
	CC	3.0	0.96	4.6a	5.6				
NO_3-N	RF	1.5b	0.66	1.8b	2.4b		0.84	0.78	2.1–4.1
	CE	2.3b	0.73	3.1b	3.9b			0.62	
	PI	3.6b	1.1	4.3b	5.5b				
	DP	3.9b	1.7	4.1b	5.8b				
	PP	3.8b	1.4	5.4b	6.8b				
	CC	7.8a	1.1	10a	12a				
TN	RF	3.6c	2.1	4.3b	6.4b	7.3		8.3	

Table 4. Continued

Element	Rainfall/ Ecosystem	RS 1997/98 (kg ha^{-1})	DS 1998	RS 1998/99	Year 2 1998–99	Lima (1985)[a] (kg ha^{-1} yr^{-1})	Galy-Lacaux & Modi 1998[b]	Filoso et al. (1999)[c]	Lara et al. (2001)[d]
TN	CE	7.0bc	2.9	7.9b	11b	7.0		35	
	PI	14ab	2.7	12b	14b	4.8			
	DP	9.6abc	4.4	14b	18ab				
	PP	13ab	2.7	9.4b	12b				
	CC	17a	2.7	27a	29a				
Na	RF	3.5	0.84	4.2b	5.1b	36	0.85	2.4	0.64–1.1
	CE	6.4	1.6	5.0ab	6.6ab	26		3.8	
	PI	8.7	1.5	6.8a	8.3a	37			
	DP	12	1.4	5.5ab	6.9ab				
	PP	8.8	1.0	5.9ab	6.9ab				
	CC	6.2	0.88	6.4ab	7.3ab				
S	RF	1.2	0.00	1.3	1.3		0.67[e]	1.0[e]	2.1–4.1[e]
	CE	1.1	0.79	1.4	2.2			1.7[e]	
	PI	1.9	0.25	2.0	2.2				
	DP	2.8	0.35	1.9	2.3				
	PP	3.0	0.08	1.9	2.0				
	CC	3.4	0.00	5.4	5.4				
Zn	RF	0.064	0.015	0.12	0.13				
	CE	0.79	0.063	0.19	0.25				
	PI	0.72	0.070	0.13	0.20				
	DP	0.18	0.230	0.19	0.42				
	PP	0.23	0.035	0.16	0.20				
	CC	0.17	0.015	0.15	0.17				

[a]Rainfall and throughfall in a Cerradão and a *Pinus caribaea* plantation near São Paulo. [b]Rainfall (wet only) in Banizoumbou (semiarid savanna of the Sahel, Niger). [c]Rainfall and throughfall in a seasonally flooded Amazon rain forest. [d]Rainfall (wet only) at four stations in the Piracicaba valley, state of São Paulo, Brazil. [e]Data refer to SO_4-S only.

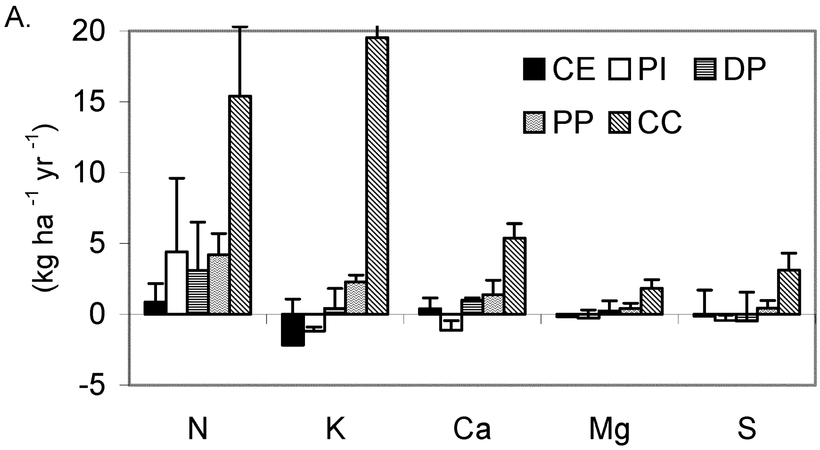
Table 5. Mean annual element input by rainfall deposition, dry deposition, and fertilizer application between October 1997 and April 1999 (one dry and two rainy seasons) in Cerrado (CE), *Pinus* (PI), degraded (PP) and productive pasture (PP), and continuous cropping (CC). Different letters indicate significant differences among the ecosystems according to Tukey's HSD test ($p < 0.05$).

Element	Ecosystem	Rainfall deposition	Dry deposition	Fertilizer	Total
		($kg\ ha^{-1}\ yr^{-1}$)			
Al	CE	0.029	0.014		0.043
	PI	0.026	0.024		0.050
	DP	0.028	0.033		0.062
	PP	0.026	0.023		0.049
	CC	0.029	0.017		0.045
TOC	CE	50	27		77
	PI	52	45		97
	DP	52	57		109
	PP	53	37		89
	CC	54	26		80
Ca	CE	2.7	1.7		4.5b
	PI	3.0	2.5		5.5b
	DP	2.6	2.9		5.4b
	PP	2.9	1.7	2.8	7.4b
	CC	2.9	1.1	33	37a
Cl	CE	7.1	4.7		12 b
	PI	7.7	6.1		14b
	DP	7.0	7.0		14b
	PP	7.7	3.8	7.5	19b
	CC	7.7	2.6	106	116a
Cu	CE	0.016	0.008		0.024
	PI	0.015	0.013		0.027
	DP	0.019	0.019		0.039
	PP	0.018	0.013		0.031
	CC	0.021	0.012		0.032
H +	CE	0.084	0.041		0.125
	PI	0.103	0.097		0.200
	DP	0.074	0.105		0.180
	PP	0.093	0.082		0.175
	CC	0.084	0.052		0.136
K	CE	5.2	3.7		8.9b
	PI	6.3	4.7		11b
	DP	5.2	5.1		10b
	PP	6.2	2.4	8.3	17 b
	CC	6.0	1.6	117	125a

Table 5. Continued

Element	Ecosystem	Rainfall deposition	Dry deposition	Fertilizer	Total
		(kg ha^{-1} yr^{-1})			
Mg	CE	1.4	0.80		2.2
	PI	1.4	1.1		2.4
	DP	1.3	1.3		2.6
	PP	1.3	0.67		2.0
	CC	1.2	0.44	21	23
Mn	CE	0.009	0.004		0.013
	PI	0.011	0.009		0.020
	DP	0.009	0.011		0.020
	PP	0.011	0.007		0.018
	CC	0.010	0.005	4.6	4.6
TN	CE	5.8	3.7		9.5
	PI	6.1	4.8		11
	DP	6.0	6.1		12
	PP	6.3	3.2		9.6
	CC	6.7	2.4		9.1
Na	CE	4.7	2.5		7.3
	PI	5.0	4.3		9.2
	DP	4.8	5.4		10
	PP	4.9	3.5		8.3
	CC	4.8	2.4		7.2
S	CE	1.5	0.68		2.2
	PI	1.3	1.3		2.6
	DP	1.2	1.6		2.8
	PP	1.1	0.95		2.0
	CC	0.77	0.49	18	19
Zn	CE	0.096	0.048		0.144
	PI	0.104	0.088		0.192
	DP	0.106	0.105		0.211
	PP	0.112	0.075		0.188
	CC	0.120	0.059	3.2	3.4

The interception loss of the studied CE was lower than reported for the ecologically similar semideciduous forest in the Venezuelan savanna of 12–19% (San Jose and Montes 1992) which may be explained by the smaller tree stature in our study. Interception losses of the soybean canopy in CC were similar to those in PI. This was unexpected as the interception losses from adjacent corn canopies were close to zero (Lilienfein and Wilcke 2001). The reason for low throughfall under soybean may be that part of the rainfall reached the soil as stemflow that was not measured. Under the corn canopy, stemflow accounted for 25–30% of the rainfall (Lil-



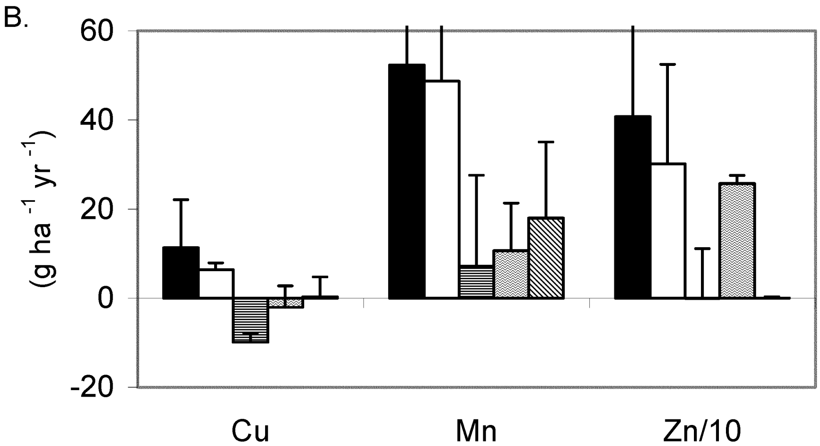


Figure 5. Mean annual canopy leaching or uptake of (negative values) A.) macronutrients and B.) micronutrients in Cerrado (CE), *Pinus* (PI), degraded (PP) and productive pasture (PP), and continuous cropping (CC) during two rainy and one dry seasons. Error bars represent standard deviations of three replicate plots.

ienfein and Wilcke 2001). However, the soybean canopy was denser and rougher than the corn canopy and the soybean plants are not similarly prone to stemflow as the corn plants with their water collecting leaves and smooth and tall stems. The throughfall under the grass canopy of PP was only measured when the grass was > 0.3 m tall. During this time, apparent evaporation losses of intercepted water were as high as those in CE. This was particularly true in the first monitored year when 8–16% of the rainfall was lost by evaporation from the grass canopy or reached the soil as (unmeasured) stemflow while in the second – wetter – year only 0–4.6% of the rainfall was not collected in the througfall collectors. The low evaporation losses of intercepted water in DP are attributable to the open canopy that did not completely cover the soil.

The small difference in mean throughfall between 5 and 20 collectors in CE1 and PI1 indicate that the mean of the 5 collectors was sufficiently close to the true mean. As this was true for the end members of canopy homogeneity of the studied ecosystems with CE having the most heterogeneous and PI the most homogeneous canopy we assume that in all other systems the mean throughfall was also estimated with a standard error < 10% of the mean.

Stemflow in CE and PI only contributed little to the total soil water input. Similarly low stemflow was observed by San Jose and Montes (1992) in the Venezuelan Llanos. Stemflow in tropical lowland forests frequently comprises 1–2% of the rainfall (Bruijnzeel 1990).

Chemical composition of solutions

pH

The VWM pH of the rainfall was similar to the 4.0–5.7 reported for lowland rainforests in the Amazon basin by Forti and Neal (1992) who attributed the lower pH than expected in equilibrium with atmospheric CO_2 (5.7) mainly to organic acids such as formic and acetic acid. Galy-Lacaux and Modi (1998) reported a pH range of 5.1–5.7 for several savanna sites in Africa. The VWM pH of 6.5 during the dry season indicates that basic materials such as ashes of vegetation fires reached our study sites. In contrast to our findings, Andreae et al. (1990) and Williams et al. (1997) observed lower VWM pH in rain water of the Amazon basin during the dry season than during the rainy season that was explained by a concentration effect and by biomass burning. The effect of biomass burning on the pH of rain water may depend on the distance to the fire. At nearer distance the ashes will be deposited resulting in increased pH and at larger distance the gaseous and therefore further distributed mineral acid-forming SO_2 and NO_x will cause a decreased pH.

In agreement with our results, Lima (1985) reported a decrease in pH from 6.0 in rainfall to 5.9 in the throughfall of a cerradão, a particularly dense cerrado, and to 5.8 in throughfall of a *Pinus caribaea* plantation in the Brazilian state of São Paulo. The lower pH in throughfall than in rainfall of PI is common for coniferous forests and can be explained by leaching of organic acids from the leaves (Parker 1983). The throughfall in PI introduces more H^+ to the soil than the throughfall in CE. Although the pH of the throughfall in PI was higher than the mean pH (KCl) of the topsoil (0–15 cm: 4.0) the higher H^+ input than in CE (pH [KCl] of the 0–15 cm mineral soil layer: 4.2) together with the acid litter contribute to the enhanced soil acidification observed by Lilienfein et al. (2000a). The increased pH in throughfall of the two fertilized systems PP and CC may be attributed to the buffering of H^+ by leaching of base metals from the vegetation canopy. The buffering increases with increasing stature of the soybean plants as indicated by the increasing K concentrations in throughfall (Figure 3) probably because of the increasing interception by the growing canopy area. While this implies nutrient losses from the plant tissue, the less acid pH of throughfall than of the topsoil (pH [KCl] of the 0–15 cm layer: 4.8 in PP and 4.9 in CC) may increase the pH of the topsoil solution which would be particularly important for the P availability of these P-limited soils (Goedert 1983). Furthermore, the nutrients are recycled in a readily plant-available form. In DP the throughfall had a slighly lower pH than the rainfall. However, throughfall pH was still higher than the pH (KCl) of the topsoil (0–15 cm: 4.3) in DP. Thus, similar to PP and CC, throughfall in DP may increase the pH of the topsoil solution with the same implications concerning P availability.

There was a considerable variation in pH among the 20 collectors of CE1 that was higher than in PI1 as shown by the range of the values. This was probably the result of the heterogeneous canopy structure in CE. The significantly lower pH of the stemflow than of the throughfall in PI and CE is commonly observed. It is caused by the release of organic acids from the bark that contains low base metal concentrations and may therefore not buffer H^+ (Parker 1983). As a result of the small quantitative importance of stemflow, the stemflow does not significantly contribute to soil acidification.

Element concentrations

The VWM concentrations of Ca and S in rainfall were within the range of VWM concentrations at other savanna sites while those of Cl^-, K, Mg, NH_4-N and NO_3-N were higher (Table 3, Sanhueza et al. 1992; Galy-Lacaux & Modi 1998). The VWM concentrations of Ca, Cl^-, Na, and S in rainfall were in the lower half of the range of concentrations reported for tropical rain forests by Forti and Neal (1992), those of K, Mg, and NH_4-N covered the whole range. Thus, element concentrations in rainfall of savanna regions seem to be lower than in tropical rain forests. Relatively high concentrations of nutrients that are included in fertilizers at our study sites compared with other savanna regions may be the result of the intensive agricultural use in our study region.

Higher element concentrations in rainfall in the dry than in the rainy season have also been observed by Andreae et al. (1990) and Forti and Moreira-Nordemann (1991) in central Amazonia. These authors reported dry/wet season concentration ratios of 1.4–6 for Ca, Cl^-, H^+, K, Mg, NH_4, NO_3, Na, and SO_4. In the same region, Williams et al. (1997) observed a dry/wet season concentration ratio of 6.1 for K, while those of K, Ca, Mg, Na, NO_3, Cl^-, TOC, and S varied only little around 1 (0.6–1.7). Higher element concentrations in rainfall during the dry than during the rainy season may partly be explained by a concentration effect. However, the different dry/wet season concentrations of different elements indicate that there were additional reasons for higher dry season concentrations because the concentration effect should be similar for all elements. Thus, there were additional sources particularly for the base metals, N species, and Cl^- in the dry season. These sources probably include vegetation fires during the dry season and emissions of the widespread charcoal production.

Before discussing the element concentrations in throughfall, the accuracy of the throughfall measurements should be assessed. This was done by analyzing the throughfall samples from all rain collectors individually on two dates. The concentrations of TN, K, and Cu were highly variable among the 20 throughfall samples from two dates in CE1 and PI1. Under the more homogeneous *Pinus* canopy this variation was smaller than under CE. The accuracy of our estimate of the mean element concentrations in throughfall expressed as percentage of the standard error of the mean was < 23% when measured with five collectors and < 10% when measured with 20 collectors. In CE this error was < 64% for 5 collectors and < 45% for 20 collectors. Thus, under the heterogeneous CE canopy even 20 throughfall collectors were not enough to determine the concentrations of all elements within an error margin of 10–20% while in PI this was already reached with 5 samplers although in both ecosystems the water input was measured with an error < 10% with only 5 collectors.

The VWM concentrations of Ca, K, Mg, Na, and S in throughfall of CE and PI were at the lower end of the range of concentrations in tropical forests (Forti and Neal 1992). Those of Cl^- and NH_4-N were similar (Table 3). The VWM concentrations of all elements under the soybean canopy of CC were similar to those under corn in the same region (Lilienfein and Wilcke 2001). Partly elevated element concentrations in throughfall of CC are attributable to leaching of the plant stubbles that remained on the fields because of the used no-tillage system. The highest concentrations of Al and partly also of Cu and Mn in the throughfall of PI during the rainy seasons were the result of the low pH and the high TOC concentrations. The highest concentrations of all major plant nutrients in the throughfall of CC during the rainy seasons may be explained by leaching of plant nutrients from leaves that contain higher concentrations of these elements because of fertilizing. The leaching probably also included N as indicated by higher TON concentrations in throughfall of all systems than in rainfall. The assumption that leaching of the leaves contributed significantly to the increased nutrient concentrations in CC is supported by the finding that the K concentration in throughfall increased during the vegetation period as shown in Figure 3 because K is known to be most easily leached from plant tissue (Tukey 1970). This large contribution of plant leaching to the element concentrations in throughfall resulted in similar element concentrations during the rainy and dry seasons.

The increased Al, Cu, and K concentrations in stemflow of PI and CE may be attributed to the lower pH and higher TOC concentrations in stemflow than in throughfall. The decrease in the concentrations of inorganic N and of Zn in stemflow of CE and PI compared with throughfall indicates that inorganic N and Zn were taken up by the stems or immobilized by microorganisms residing on the stems. In contrast, TN concentrations increased from throughfall to stemflow except during the dry season in CE indicating that organic N was leached from the stems or from organisms residing on the stems.

Element fluxes

Rainfall and throughfall deposition vary much among tropical forests (Proctor 1987; Filoso et al. 1999). In a cerradão and an adjacent *Pinus caribaea* plantation in the southern part of the Cerrado, Lima (1985) reported one order of magnitude higher rainfall and throughfall deposition of base metals and NH_4^+ than in our study (Table 4). In our study region, the deposition of base metals (K, Na, Ca, and Mg) and Cl^- was higher than in the more densely populated and more industrialized Piracicaba valley of the state of São Paulo while that of H^+ and N was lower possibly reflecting the predominance of agricultural emissions (including fertilizers) and probably also biomass burning in our study area and of industrial emission in the Piracicaba valley (Lara et al. 2001). Relatively large agricultural emissions may also explain the higher annual deposition rates of all elements except Ca in our study region than at several African savanna sites (Galy-Lacaux and Modi 1998).

The more than proportional element input during the dry season contributes to high element concentrations in soil solution at the beginning of the rainy season because during the dry season little leaching occurs (Lilienfein et al. 2000a, 2000b, 2000c). In the forest and pasture systems, these nutrients may be readily used for plant nutrition while in the cropping systems they may be quickly leached to greater soil depth. Fast leaching rates have been shown particularly for no-till cropping systems in the study region (Lilienfein et al. 2000b). Thus, at least in the perennial systems deposition during the dry season contributes to plant nutrition.

The high VWM concentrations of Al and Mn in throughfall of PI and CE and of the plant nutrients in throughfall of PP and CC explain the high throughfall deposition fluxes of these elements. In CE and PI, stemflow contributed little to total deposition because of its small contribution to total water input. However, stemflow concentrates the input of plant nutrients in readily bioavailable form on a small surface area of intensively rooted soil. During the rainy season 1998/1999 up to 156 L (mean: 53 L, n = 28) of water reached the stemfoot area of a tree or shrub in CE, and up to 140 L in PI (mean: 73 L, n = 9). Thus, the contribution of stemflow to plant nutrition is larger than indicated by its contribution to the total soil input.

The interception of atmospheric particles by the plant canopies among the studied systems as indicated by the mean Na deposition ratios between October 1997 and April 1999 varied surprisingly little. The dense grass canopy of PP scavenged similar amounts of particles as the PI canopy; the occurrence of a few trees seemed to be sufficient to result in a similar dry deposition in DP as in PI. The lower dry deposition of CC may partly be explained by the delay in the development of a continuous canopy at the beginning of the rainy season. During the dry season, the systems with trees (DP, PI, and CE) had higher Na deposition ratios than those without trees (PP and CC) because of the higher roughness of the surface and the lack of a continuous canopy in PP and CC.

The contribution of coarse particles that were collected in our rainfall and throughfall collectors to the total nutrient deposition was negligibly small. Furthermore, nutrients bound to coarse particles were only extractable with strong acids and are thus probably not plant-available.

The large proportion of the rainfall + dry deposition of the fertilizer application to PP illustrates that the nutrient input from the atmosphere contributes considerably to the nutrition of the plants in the not or little fertilized systems. As the Cerrado ecosystems are strongly P-limited (Goedert 1983), even possible very small P inputs below the detection limit of our method may contribute to improve P availability for the plant uptake.

The high canopy leaching of the fertilized plants had already been indicated by the pronounced increase in nutrient concentrations in throughfall of CC. Canopy uptake of nutrients indicate that there may be limitations of plant growth by base metals and S in PI and CE and by S, Cu and Zn in the pastures.

Conclusions

Our results demonstrate that the type of agro- or forest ecosystem changes the soil water input by modifying the losses of intercepted rain water from the vegetation canopies compared with CE. In PI and possibly also under soybean (CC), the soil water input is reduced while the pastures only have a small effect on the soil water input compared with CE.

The vegetation canopies change the pH of the rain water. The effect of the CE and DP canopies on the pH of the rain water is small; there is only a decrease in pH during the dry season. The throughfall in PI is more acid than the rainfall indicating that the PI canopy increases the H^+ inputs to the soil compared with the native Cerrado vegetation. The throughfall in the fertilized PP and CC systems is less acid than the rainfall and thus increases the pH of the soil solution which may be particularly important for the P availability. The stemflow is more acid than the throughfall. Although stemflow only contributes < 8% to the total element input to soil, this input is concentrated on a small area where it is readily available for the plants. Thus, stemflow may contribute to plant nutrition.

Dry deposition estimated by a Na-tracer technique, contributes up to 51% of the total element input and is therefore an important nutrient source for the not or little fertilized systems. Dry deposition varies little among the systems. It is only slightly lower in CE and CC than in PP, PI, and DP. Thus, the few trees and shrubs in DP and the dense grass canopy in PP create a surface that is similarly efficient in scavenging dry deposition as the canopy of the *Pinus* trees.

Net canopy uptake of nutrients indicate that there may be limitations of plant growth by base metals and S in PI and CE and by S, Cu and Zn in the pastures.

Net canopy uptake of base metals and S in PI and CE, S, Cu, and Mn in DP, and Cu in PP indicate that plant growth may be limited in part by these nutrients. In CC and particularly PP, leaching of nutrients from the canopy accounts for a considerable part of the fertilizer applications.

Our results demonstrate that PI causes larger water losses and enhanced acid inputs to the soil compared with all other ecosystems. However, the PI and pasture canopies scavenge more nutrients from the atmosphere than CE and CC.

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References

Andreae M.O., Talbot R.W., Berresheim H. and Beecher K.M. 1990. Precipitation chemistry in central Amazonia. J. Geophys. Res. 95: 16987–16999.

Bruijnzeel L.A. 1990. Hydrology of moist tropical forests and effects of conversion: a state of knowledge review. Unesco, Division of Water Sciences, International Hydrological Programme, Paris, France.

Castro E.Ad. and Kauffman J.B. 1998. Ecosystem structure in the Brazilian Cerrado: a vegetation gradient of aboveground biomass, root mass, and consumption by fire. J. Trop. Ecol. 14: 263–283.

Clark K.L., Nadkarni N.M., Schaefer D. and Gholz H.L. 1998. Atmospheric deposition and net retention of ions by the canopy in a tropical montane forest, Monteverde, Costa Rica. J. Trop. Ecol. 14: 27–45.

Eiten G. 1972. The Cerrado vegetation. Bot. Rev. 38: 201–341.

Filoso S., Williams M.R. and Melack J.M. 1999. Composition and deposition of throughfall in a flooded forest archipelago (Negro River, Brazil). Biogeochem. 45: 169–195.

Forti M.C. and Moreira-Nordemann L.M. 1991. Rainwater and throughfall chemistry in a ″Terra firme″ rain forest: central Amazonia. J. Geophys. Res. 96: 7415–7421.

Forti M.C. and Neal C. 1992. Hydrochemical cycles in tropical rainforests: an overview with emphasis on central Amazonia. J. Hydrol. 134: 103–115.

Freydier R., Dupré B. and Lacaux J.P. 1998. Precipitation chemistry in intertropical Africa. Atmos. Environ. 32: 749–765.

Galy-Lacaux C. and Modi A.I. 1998. Precipitation chemistry in the Sahelian savanna of Niger, Africa. J. Atmos. Chem. 30: 319–343.

Goedert W.J. 1983. Management of the Cerrado soils in Brazil: a review. J. Soil Sci. 34: 405–428.

Hartung J. and Elpelt B. 1989. Multivariate Statistik. Oldenbourg-Verlag, München, Germany.

Hesterberg R., Blatter A., Fahrni M., Rosset M., Neftel A., Eugster W. et al. 1996. Deposition of nitrogen-containing compounds to an extensively managed grassland in central Switzerland. Environ. Pollut. 91: 21–34.

Kauffman J.B., Cummings D.L. and Ward D.E. 1994. Relationships of fire, biomass, and nutrient dynamics along a vegetation gradient in the Brazilian Cerrado. J. Ecol. 82: 519–531.

Lara L.B.L.S., Artaxo P., Martinelli L.A., Victoria R.L., Camargo P.B., Krusche A. et al. 2001. Chemical composition of rainwater and anthropogenic influences in the Piracicaba river basin, southeast Brazil. Atmos. Environ. 35: 4937–4945.

Likens G.E. and Eaton J.S. 1970. A polyurethane stemflow collector for trees and shrubs. Ecol. 51: 938–939.

Lilienfein J. and Wilcke W. 2001. Nutrient input from the atmosphere into Brazilian savanna Oxisols under corn. Soil Sci. 166: 391–399.

Lilienfein J., Wilcke W., Ayarza M.A., Lima Sd.C., Vilela L. and Zech W. 1999. Annual course of matric potential in differently used savanna Oxisols, Brazil. Soil Sci. Soc. Am. J. 63: 1778–1785.

Lilienfein J., Wilcke W., Ayarza M.A., Vilela L., Lima Sd.C. and Zech W. 2000a. Soil acidification in *Pinus caribaea* forests on Brazilian savanna Oxisols. For. Ecol. Manage. 128: 145–157.

Lilienfein J., Wilcke W., Ayarza M.A., Lima Sd.C., Vilela L. and Zech W. 2000b. Nutrient concentrations in soil solution of Brazilian Oxisols under conventional and no tillage during the beginning rainy season. Austr. J. Soil Res. 38: 851–866.

Lilienfein J., Wilcke W., Vilela L., Lima S.d.C., Thomas R. and Zech W. 2000c. Effect of conventional and no-tillage systems on the chemical composition of soil solid phase and soil solution of Brazilian savanna Oxisols. J. Plant Nutr. Soil Sci. 163: 411–419.

Lilienfein J., Wilcke W., Zimmermann R., Gerstberger P., Araújo G.M. and Zech W. 2001. Nutrient storage in soil and biomass of native Brazilian cerrado. J. Plant Nutr. Soil Sci. 164: 487–495.

Lima Wd.P. 1985. Ação das chuvas no ciclo biogeoquimico de nutrientes em plantações de pinheiros tropicais e em Cerradão. Instituto de Pesquisa e Estudos Florestais da Escola Superior de Agricultura Luiz de Queiroz (IPEF) Piracicaba 30: 13–17.

Lindberg S.E., Lovett G.M., Richter D.D. and Johnson D.W. 1986. Atmospheric deposition and canopy interactions of major ions in a forest. Science 231: 141–145.

Parker G.G. 1983. Throughfall and stemflow in the forest nutrient cycle. Adv. Ecol. Res. 13: 57–133.

Pivello V.R. and Coutinho L.M. 1992. Transfer of macronutrients to the atmosphere during experimental burnings in an open cerrado (Brazilian savanna). J. Trop. Ecol. 8: 487–497.

Proctor J. 1987. Nutrient cycling in primary and old secondary rainforests. Appl. Geogr. 7: 135–152.

Resck D.V.S., Vasconsellos C.A., Vilela L. and Macedo M.C.M. 2000. Impact of conversion of Brazilian Cerrados to cropland and pastureland on soil carbon pool and dynamics. In: Lal R., Kimble J.M. and Stewart B.A. (eds), Global climate change and tropical ecosystems. Adv. Soil Sci. CRC Press, Boca Raton, FL, USA, pp. 169–196.

Ribeiro J.F. and Walter B.M.T. 1998. Fitofisionomias do bioma Cerrado. In: Sano S.M. and Almeida S.P.d. (eds), Cerrado – Ambiente e Flora. Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA). Planaltina-DF, Brazil, pp. 89–166.

Rosa R., Lima S.d.C. and Assunção W.L. 1991. Abordagem preliminar das condições climáticas de Uberlândia (MG). Universidade Federal de Uberlândia, Sociedade e Natureza 3: 91–108.

Rost-Siebert K. 1983. Aluminium-Toxizität und – Toleranz an Keimpflanzen von Fichte (*Picea abies* Karst.) und Buche (*Fagus silvatica* L.). Allg. Forstz. 38: 686–689.

Sanhueza E., Arias M.C., Donoso L., Graterol N., Hermoso M., Marti I. et al. 1992. Chemical composition of acid rains in the Venezuelan savannah region. Tellus 44B: 54–62.

San Jose J.J. and Montes R. 1992. Rainfall partitioning by a semideciduous forest grove in the savannas of the Orinoco Llanos, Venezuela. J. Hydrol. 132: 249–262.

Soil Survey Staff 1998. Keys to soil taxonomy. USDA-NRCS-NSSC, Lincoln, NE, USA.

Tukey H.B. Jr 1970. The leaching of substances from plants. Annu. Rev. Plant Physiol. 31: 305–324.

Ulrich B. 1983. Interactions of forest canopies with atmospheric constituents: SO_2, alkali and earth alkali cations and chloride. In: Ulrich B. and Pankrath J. (eds), Effects of Accumulation of Air Pollutants in Forest Ecosystems. D. Reidel Publishing, Dordrecht, The Netherlands, pp. 33–45.

Williams M.R., Fisher T.R. and Melack J.M. 1997. Chemical composition and deposition of rain in the central Amazon, Brazil. Atmos. Environ. 31: 207–217.

Zeien H. and Brümmer G.W. 1989. Chemische Extraktion zur Bestimmung von Schwermetallbindungsformen in Böden. Mitteilgn. Dtsch. Bodenkundl. Gesellsch. 59: 505–510.