Agriculture, Ecosystems and Environment, 32 (1990) 143–154
Elsevier Science Publishers B.V., Amsterdam

Nutrient cycling in the cacao ecosystem: rain and throughfall as nutrient sources for the soil and the cacao tree

J. de Oliveira Leite[1] and Raul René Valle[2]
Divisions of Geoscience[1] and Botany[2], Cacao Research Center, CEPEC/CEPLAC, km 22 da Rodovia, Ilhéus-Itabuna, CP 7, Itabuna, Bahia 45.600 (Brazil)

(Accepted for publication 3 October 1989)

ABSTRACT

Leite, J. de O. and Valle, R.R., 1990. Nutrient cycling in the cacao ecosystem: rain and throughfall as nutrient sources for the soil and the cacao tree. *Agric. Ecosystems Environ.*, 32: 143–154.

Rainwater and throughfall water were evaluated nutrient sources for a cacao (*Theobroma cacao* L.) ecosystem in Ilhéus, Bahia, Brazil. Rainwater was collected for 35 months in an open area. Throughfall was collected on shaded and unshaded cacao plots. The shade trees were *Erythrina* and some species of *Ficus*. In evaluating the results, the agricultural year was subdivided into winter (April–September) and summer (October–March). It was found that the concentrations of N, P, K, Ca and Mg, in both rainwater and throughfall varied between and for periods within years. The nutrient concentrations in the throughfall also varied with the presence or absence of shade trees in the cacao plantation. The rainwater contributions of N, Ca, Mg, K, and P reached averages of 43, 21, 9, 9 and nearly 1 kg ha^{-1} $year^{-1}$, respectively. The averages of annual throughfall recycling to the soil in the unshaded and shaded plots, respectively, were 141 and 47 kg K ha^{-1}, 28.4 and 21 kg Ca ha^{-1}, 21 and 12.2 kg Mg ha^{-1}, and 13 and 8 kg P ha^{-1}. The throughfall K and P appears to be rapidly absorbed by the cacao roots, whilst most of the Mg, Ca, and N are retained in the soil. The throughfall and leaf fall constitute the most important nutrient recycling processes in the cacao ecosystem, which appears to be self-sufficient in terms of its nutrient requirements.

INTRODUCTION

The paper by De Saussure in 1984, is one of the first published sources of information on the chemical composition of rain percolated through the tree canopy (Tukey, 1970), which Boyer (1973) defined as throughfall. However only since the 1950s have studies been conducted to evaluate the significance of chemical recycling of nutrients in the throughfall to the nutrition of temperate climate forests (Tamm, 1951; Stemlid, 1958 cited by Voigt, 1960). In an African cacao ecosystem, Boyer (1973) found that the throughfall represented an important source of nutrients, with recycling of Ca, Mg, and K to the soil in the order of 38, 33 and 113 kg ha^{-1} $year^{-1}$ respectively. However,

0167-8809/90/$03.50

Boyer did not indicate if shade conditions of the ecosystem modified the elements recycling. In Bahia, Brazil, on a cacao plantation shaded with swamp immortelle (*Erythrina fusca*) the quantities found for these elements in throughfall were 18, 12 and 21 kg ha^{-1} $year^{-1}$, respectively, based on data taken between July 1981 and June 1983 (Santana and Cabala Rosand, 1984).

The objective of this research was to quantify nutrient recycling to the soil in throughfall, the effects of shading by associated trees and to assess how significant recycling of nutrients in throughfall might be in cacao tree nutrition.

MATERIALS AND METHODS

The study was conducted at the Experimental Station of the Cacao Research Center (CEPEC), located in Ilhéus, Bahia, Brazil. The cacao trees were planted on a Typic Tropudalf soil of high fertility (Da Silva et al., 1976) with an average slope of 24% and covered with a continuous litter layer. The litter biomass ranges from 9 to 14 t ha^{-1} and is formed from plant residues and fine roots of cacao and shaded trees (Leite, 1987). The litter and the surface horizons constitute the most important reservoir of soil nutrients for in these layers grow most of the cacao and shade tree roots, 85% of the cacao root system is distributed in the top 30 cm depth (Zevallos, 1970). However, the fertility of the soil beneath extends to the B_1 horizon down to an average depth of 45 cm (J. de O. Leite and A.A.O. de Melo, unpublished data) which will be the maximum depth considered in this study. The distribution of the coarse and fine sand, silt, and clay components in the soil is as follows: 4.5, 17.5, 45.5, and 32.0% in the top soil (0–6.5 cm); 2.7, 121.0, 36.2, and 50.0% in the B_1 horizon (6.5–45 cm). The bulk density of the top soil is 1.04 and that of the B_1 horizons is 1.06 (Da Silva and Melo, 1970).

The climate is a Koeppen's Af type with an annual rainfall of 1862 mm, 86% relative humidity and winter and summer average temperatures of 22.2 and 24.3°C, respectively (Climatology Division, CEPEC. Personal communication).

Each month, from April 1984 to December 1986, chemical determinations of N, P, K, Ca, Mg in: (1) rainwater collected in a Whilh-Lambert type rainfall collector located 1.60 m above the soil surface in an open area 40 m from the cacao plantation; (2) throughfall water collected in a cacao plot with 10% shade; (3) throughfall water collected in the same plantation but in a plot with 36% shade by swamp immortelle and 15% shade by *Ficus* spp. In both plots, eight Whilh–Lambert rainfall collectors per plot were located in line along the hillslope direction. They were spaced 15 m apart and placed 0.50 m above the ground. The distance between the lines of collectors was 90 m.

Every month, the collectors were cleaned with distilled water to prevent the growth of moss on the funnel of the collector. Also, to avoid the deposition of small leaves, fragments of stems, flowers and insects, all the collectors placed in the cacao plots were covered with a cone made of a plastic fine screen with the vortex upwards.

Every month, all the rainwater and half of the throughfall collected during the first 15 days of the month by the eight collectors in each plot were treated with chloroform and stored in a freezer. At the end of each month, rain and throughfall waters in volumes equal to those collected in the first 15-day period were mixed, filtered, and sent for analysis.

Aliquots of the three types of water samples were used for determining total nitrogen by the Kjeldahl method (using H_2SO_4, a mixture of 10 g of $CuSO_4$, 100 g of Na_2SO_4 and 1 g of H_3BO_3 and indicator). The available P was determined colorimetrically, exchangeable K by flame photometry, and exchangeable Ca and Mg, by atomic absorption spectrophotometry by the methods described by Santana et al. (1976).

The rainfall interception by the vegetation, cacao and shade tree canopies was in order of 13% (J. de O. Leite unpublished data) and 2% by the trunk (Miranda, 1985).

In evaluating the results, the agricultural year, beginning in April, was subdivided into winter (April–September) and summer (October–March), as suggested by Leite (1985) for the cacao agroecosystem.

RESULTS AND DISCUSSION

Relationships between N, P, K, Ca, and Mg in the rainwater and throughfall

In general, quantities of solutes in the rainwater varied from year to year and between seasons within the year (Table 1). Highest concentrations were found for N and lowest for P with solute concentrations in the following order: $N > Ca > Mg > P$. The rainwater concentrations of N, P, and Mg tended to be higher in winter than in summer. Potassium concentration values, however, showed a reverse trend.

The concentrations of P, Ca, and Mg were higher in the throughfall than in the rainwater in both shaded and unshaded plots. The chemical element concentrations in the throughfall, besides the annual and intra-annual variations, varied also with the shade (structure) conditions of the plantation. In the latter, the throughfall nutrient concentrations were $K > Ca > Mg > N > P$. In winter, the concentrations of P, K, Mg, and Ca in the unshaded plot throughfall were 9, 27, 2, and 3 times higher, respectively, than the concentrations in the rainwater. In the summer season the ratios were 17, 14, 3 and 3 times higher, respectively.

In the shaded plot, the ratios of the same elements from throughfall and those from rainwater were 6, 13, 1.5, and 1.4 respectively, in winter, while in summer the proportions, in the same order, were 10, 4, 3, and 3 (Table 1).

Generally, significant correlations were found between Mg and Ca in both

TABLE 1

Concentrations of N, P, K, Ca and Mg, and quantities of these elements in the rainwater and in the throughfall of the cacao ecosystem from April 1984 to December 1986

Year	Element	Winter			Summer			Annual		
		Rain-water	Throughfall		Rain-water	Throughfall		Rain-water	Throughfall	
			Unshaded cacao	Shaded cacao		Unshaded cacao	Shaded cacao		Unshaded cacao	Shaded cacao
Mean concentration per period (mg l^{-1})										
1984	N	1.83^{a}	1.92^{a}	0.47^{a}	4.78^{a}	4.08^{a}	5.72^{a}			
	P	0.08^{a}	0.54^{b}	1.87^{a}	0.40^{a}	1.07^{a}	0.83^{a}			
	K	0.25^{a}	6.95^{b}	1.88^{a}	0.80^{a}	10.92^{b}	2.53^{ab}			
	Ca	1.37^{a}	2.93^{b}	1.53^{a}	0.70^{a}	2.00^{a}	2.53^{a}			
	Mg	0.46^{a}	1.66^{b}	0.63^{a}	0.48^{a}	1.38^{b}	1.19^{b}			
1985	N	1.63^{a}	1.17^{a}	0.93^{a}	1.26^{a}	0.70^{b}	1.18^{a}			
	P	0.05^{a}	0.55^{b}	0.36^{b}	0.05^{a}	1.06^{b}	0.45^{a}			
	K	0.40^{a}	7.73^{b}	3.96^{ab}	0.39^{a}	9.83^{b}	3.74^{a}			
	Ca	0.70^{a}	1.90^{b}	1.63^{ab}	1.32^{a}	3.52^{a}	3.00^{a}			
	Mg	0.57^{a}	1.80^{b}	1.09^{ab}	0.46^{a}	2.04^{b}	1.56^{b}			
1986	N	1.40^{a}	0.93^{a}	1.28^{a}	1.40^{a}	0.93^{a}	1.40^{a}			
	P	0.07^{a}	0.76^{b}	0.94^{b}	0.06^{a}	0.53^{b}	0.91^{c}			
	K	0.26a	5.79^{b}	8.12^{b}	0.65^{a}	4.68^{b}	7.67^{c}			
	Ca	1.93^{a}	3.73^{a}	4.00^{a}	1.60^{a}	3.13^{a}	3.27^{a}			
	Mg	0.63^{a}	2.19^{b}	2.33^{b}	1.17^{a}	3.93^{b}	3.16^{ab}			
Quantity per period (kg ha^{-1})										
1984	N	25.89	27.13	5.41	41.41	36.18	52.78	67.30	63.31	58.10
	P	1.12	7.73	2.76	0.36	9.96	7.51	1.48	17.69	10.27
	K	3.21	100.85	26.23	7.31	98.83	21.14	10.52	199.68	47.37
	Ca	20.23	40.59	22.02	6.46	17.60	22.28	26.69	58.19	44.30
	Mg	6.77	23.23	8.80	4.46	11.78	10.37	11.23	35.01	19.17
1985	N	14.61	10.49	9.22	12.18	6.57	11.24	26.79	17.06	20.46
	P	0.18	4.38	2.67	0.69	7.65	3.58	0.89	12.03	6.25
	K	2.71	59.67	26.87	5.12	72.23	29.49	7.83	131.90	56.36
	Ca	4.95	17.20	11.99	9.74	25.96	23.18	14.69	43.16	35.17
	Mg	3.58	14.51	7.16	3.87	14.77	13.75	7.45	29.28	20.91
1986	N	7.00	5.00	6.65	5.33[1]	3.26[1]	5.33[1]	12.33	8.26	11.98
	P	0.57	4.03	5.21	0.20	1.92	3.47	0.77	5.92	8.68
	K	1.30	32.89	36.96	1.73	16.70	29.40	3.03	49.59	66.00
	Ca	13.27	24.73	22.10	5.00	11.62	12.22	18.27	36.35	34.32
	Mg	4.20	11.64	11.57	3.78	15.36	13.30	7.98	27.00	24.87
Annual mean obtained from the means of the quantities per period (kg ha^{-1})										
1984–1986	N	15.83	14.21	7.09	26.80	21.38	32.01	42.63	35.59	39.10
	P	0.62	5.38	3.55	0.53	8.81	5.55	1.15	14.19	9.10
	K	2.41	64.47	30.21	6.22	85.53	25.32	8.63	150.00	55.53
	Ca	12.82	27.51	18.70	8.10	21.78	22.73	20.92	49.29	41.43
	Mg	4.85	16.46	9.18	4.17	13.28	12.06	9.02	29.74	21.18

[1]The data of this column refer only to half of the summer (October–December of 1986).
Means with the same superscript within each line are not significantly different at $P<0.05$ by Duncan's test.

the rainwater and throughfall collected in the unshaded and shaded plots with exception of the 1985 data for the shaded plot. In the unshaded plot, correlations between Mg and K, Mg and P, and K and P were observed during the three-year experimental period, whereas, in the shaded plot none were found. Independently of shade conditions, more significant correlations were found in winter than in summer.

Based on the significant correlations, the ratios between the average concentrations of Mg and K, Mg and Ca, Mg and P, and P and K in rainwater and in both throughfalls were calculated (Table 2). In rainwater, the ratio between the average concentration of Mg and Ca was approximately 3, whereas in both throughfalls it was about 2. In the unshaded cacao plot the proportions between the concentrations of Mg and Ca, Mg and K, Mg and P, and P and K were 1:2, 1:4, 1:0.3 and 1:0.1, respectively.

Rainwater inputs and throughfall nutrient recycling to the soil

Inputs in the rainwater to the soil were greatest for N and Ca, with an annual mean of 43 and 21 kg ha^{-1} respectively (Table 1). In general, higher quantities of these elements were input to soil during the summer. The rainwater contributions of Mg and K were small, both approximately 9 kg ha^{-1} $year^{-1}$, and those of P about 1 kg ha^{-1} $year^{-1}$.

The source of nitrogen is probably atmospheric and originates, mainly, from lightning during rainstorms. The possibility of inputs derived from factories is remote as factories are few and are located downwind about 20 km from the study area. Most of the other elements in rainwater originate, probably, from dust. The lower quantity of elements in the rainwater in the winters of 1985 and 1986 compared to those of the winter of 1984 were due to the lower precipitation in those years. The total precipitation in the winters of 1984, 1985 and 1986 was 1375, 879 and 538 mm, respectively, and 364, 1066 and 737 mm, respectively, in the summer.

Results showed that K was the element with the highest concentration in the throughfall of both shaded and unshaded cacao plots. Under the unshaded plot the quantity estimated was 150 kg ha^{-1} $year^{-1}$ compared with the shaded plot where it was, approximately, 56 kg ha^{-1} $year^{-1}$. The amount of N, Ca and Mg varied from 20 to 50 kg ha^{-1} $year^{-1}$. Phosphorus was the element in the lowest concentration in the throughfalls of both types of cacao ecosystems (Table 1).

Subtracting the average quantity of the elements in rainwater from the average in the throughfalls, the net amount recycled to the soil in throughfall is obtained. The amounts of N in the throughfall and rainwater were similar, so there was no leaching of N from the canopy. However, the net throughfall in the unshaded cacao was, approximately 13, 141, 28 and 21 kg ha^{-1} $year^{-1}$ for P, K, Ca and Mg, respectively, whilst for those same elements in the shaded

TABLE 2

Ratio of mean concentration of Mg to Ca, Mg to K, Mg to P, and of K to P in rainwater and throughfall

Year	Mg:Ca			Mg:K			Mg:P			K:P		
	Rainwater	Throughfall		Rainwater	Throughfall		Rainwater	Throughfall		Rainwater	Throughfall	
		Unshaded cacao	Shaded cacao		Unshaded cacao	Shaded cacao		Unshaded cacao	Shaded cacao		Unshaded cacao	Shaded cacao
Winter												
1984	3.0	1.8	2.4	*	4.2	3.0	*	0.3	*	*	0.1	1.0
1985	1.2	1.1	*	*	4.3	*	*	0.3	*	*	0.1	0.1
1986	3.1	1.7	1.7	*	2.6	*	0.1	0.3	0.4	*	0.1	*
Summer												
1984	*	*	*	*	*	*	0.8	*	*	*	0.1	*
1985	*	1.7	*	*	*	2.4	–	0.5	0.3	0.1	–	0.1
1986	*	*	*	*	*	*	*	*	*	*	–	*

$P < 0.05$; * without correlation.

cacao it was 8, 47, 21 and 12 kg ha^{-1} $year^{-1}$. Therefore, the recycling from the canopy was generally K > Ca > Mg > P. This relationship is similar to that found by Eaton et al. (1973), Henderson et al. (1977) and Lockaby (1986). However, in these cacao ecosystems studied, the quantities of Mg and P recycled in the throughfall were 5 and 12 times higher respectively, than those obtained by Eaton et al. (1973) and Henderson et al. (1977) in a forest ecosystem, and more than 2 and 3 times higher than the values obtained by Lockaby (1986) in a cottonwood plantation.

The chemical elements in the net throughfall, especially K, are leached from the foliage (Epstein, 1975); i.e. K is well known to be easily leached (Rodriguez, 1965; Kline and Tukey, 1969; both cited by Tukey, 1969). Only N in throughfall is derived totally from the atmosphere since statistical differences were not found between the concentration of this element in the rainwater and in both throughfalls.

Variation and interaction of elements in throughfall and their significance to cacao production

A high degree of variation was found in the chemical element concentrations in both rainwater and throughfalls (Table 3). Variation in the latter may be associated with different growth phases of the cacao and related to

TABLE 3

Coefficient of variation of N, P, K, Ca and Mg in the rainwater and in throughfall in the winter and summer from April 1984 to December 1986

Year	Element	Rainwater	Throughfall		Rainwater	Throughfall	
			Unshaded cacao	Shaded cacao		Unshaded cacao	Shaded cacao
1984	N	89.27	74.18	17.46	58.10	46.53	91.50
	P	143.52	42.90	36.28	50.00	107.77	92.45
	K	68.22	40.50	24.18	146.14	107.76	64.36
	Ca	56.62	51.14	39.28	93.46	50.59	94.95
	Mg	34.67	25.63	33.34	72.46	53.43	44.29
1985	N	69.99	72.66	77.46	24.84	0.00	34.23
	P	138.45	28.41	63.26	87.65	49.55	35.10
	K	60.18	52.63	110.48	70.71	49.04	42.69
	Ca	109.54	30.33	57.65	117.17	54.88	57.93
	Mg	103.81	44.60	69.92	73.02	48.06	17.81
1986	N	44.72	38.73	41.06	0.00	43.30	0.00
	P	128.54	80.03	45.01	140:10	29.31	15.34
	K	181.66	63.16	49.83	124.90	22.02	24.03
	Ca	106.04	81.86	46.37	69.59	25.80	21.50
	Mg	101.99	52.47	37.68	63.21	34.07	41.60

seasonally varying plant demands for specific nutrients. For example, the normal fruit development for the mid crop, and flowering and fruit bearing for the main crop, occur from May to August and from November to March, respectively. In addition, the first leaf and shoot flushing occur from February to March and the second one from September to October. Lockaby (1986), studying the throughfall in a cottonwood plantation, found an association between the nutrient concentration in young leaves and the metabolic activity of the plant. However, the quality and quantity of chemical elements in the throughfall can be affected by leaf age, development stage, vigor and plant reserves, intensity and duration of rainfall, and other factors like air temperature (Tukey, 1970).

It is possible, therefore, that the relations in the unshaded cacao, are due to the physiological processes related to crop formation. Hardy et al. (1935), found highly significant positive correlations between cacao yield and the total quantity of K, and the relationship K/P in the foliage. The reason for these relationships is that K is one of the principal elements in the fruit (Fassbender et al., 1985).

Magnesium, Ca and P, among other ions, interact and are absorbed by the plants in direct relation to root absorption and plant translocation characteristics, and their chemical equivalence (Usherwood, 1982). Usherwood (1982) has shown that K interacts with P for greater productivity.

Recycling of throughfall nutrient elements

The elements recycled in throughfall can be subject to various processes. One is direct reabsorption by the cacao and shade trees. Most of the nutrients can be directly absorbed in the ionic form by the roots (Tukey, 1970; Foster and Morrison, 1976; Herrera et al., 1978). Another is biological immobilization by the micro- and mesoflora in the litter and the A_{11} horizon. This horizon is chemically richer than the horizons below (Table 4). This third process may be the fixation by the soil mineral reservoir (Tukey, 1969). The fourth route may be the transport in subsurface lateral leaching and/or deep drainage. Depending upon the cacao ecosystem structure (shaded or unshaded), the plant nutrient absorption intensity, microbial activity, or the soil adsorption capacity, the nutrients can be lost in the drainage waters.

With K, it is probable that the direct absorption by the cacao roots may be the main route. This is so because soil K retention is low and losses by leaching are only 17 kg ha^{-1} year^{-1} (Leite, 1985). The total of 150 kg ha^{-1} year^{-1} of K, transported by the throughfall in the unshaded cacao plot is high in comparison with the soil reserves of 179 kg ha^{-1} year^{-1} contained in the litter, the A_{11} horizon, and the mineral soil to 45 cm depth. This depth is the main rooting depth where 85% of the cacao root system is found (Zevallos, 1970). Thus dividing the quantity of a given nutrient in the soil rooting depth

TABLE 4

Quantity of K, Mg, Ca, P and N in the plant reservoir (cacao and shade trees), in the soil reservoir, in other nutrient sources including rainwater and net throughfall, and in the losses by interflow water and by export of cacao beans in the ecosystem

Chemical element	Plant reservoir[1]		Soil reservoir					Other nutrient sources					Nutrient losses	
	Cacao	Swamp immortelle	Unshaded cacao		Shaded cacao		A_2/B_1 horizon[3] (6.5–45 cm)	Rainwater	Net throughfall[4]		Leaf-fall[5]	Cacao husk[6]	Interflow[7]	Export[6]
			Litter[2]	Top soil[2]	Litter[2]	Top soil[2]			Unshaded cacao	Shaded cacao				
K ($kg\ ha^{-1}$)	66.8	237.1	22.9	60.3	24.6	54.2	95.5	8.6	141.4	46.9	25.9	33.4	17.0	12.4
Mg ($kg\ ha^{-1}$)	-	-	80.5	512.6	50.9	379.9	3466.0	9.0	20.7	12.2	52.7	2.7	18.2	3.1
Ca ($kg\ ha^{-1}$)	-	-	384.4	2389.9	305.5	2094.3	3658.2	20.0	28.4	20.5	161.6	4.3	85.8	1.0
P ($kg\ ha^{-1}$)	12.1	26.3	11.5	6.0	11.9	19.8	16.4	1.1	13.0	8.0	13.4	1.3	0.9	4.6
N ($kg\ ha^{-1}$)	102.8	262.5	118.5	2051.2	128.3	1833.0	4868.5	42.6	−12.9	−3.5	112.0	13.2	22.1	22.0

[1]Fassbender et al. (1985); [2]Leite (1987); [3]J. de O. Leite and A.A.O. Melo (unpublished data); [4]this study; [5]Santana and Cabala Rosand (1984), average related to two periods, obtained in cacao under swamp immortelle shade; [6]means of values obtained by Hardy (1961), Kannapathy (1976), Santana and Cabala Rosand (1982) and Alpizar et al. (1983) cited by Fassbender et al. (1985). [7]Leite (1985b).

by the quantity contained in the throughfall, the residence index, *RI*, for that nutrient is obtained. In the unshaded cacao plot, the *RI* of K was calculated, therefore, as 1.2. This *RI* was lower than the *RIs* for P, Mg, Ca and N which were 2.4, 137, 131 and 237, respectively. The *RI* calculated for K, P, Mg, Ca, and N in the shaded cacao plot were 3.1, 5.3, 184, 146 and 174. These *RIs* indicate that the storage soil capacity for K and P are low, whereas those for Mg, Ca and N are high. Measurements of the K and P concentrations in river waters of a watershed grown with cacao (Leite, 1985), with fertile soils rich in primary minerals similar to the soils in this study, suggest that the quantities of these elements lost by soil leaching are low in comparison with their concentration in the throughfall.

Losses of P and K in an ecosystem of the Amazon forest through river waters, were estimated to be 0.008 and 1.4 kg ha^{-1} $year^{-1}$, respectively. The K rainwater input was 2.1 kg ha^{-1} $year^{-1}$ and that by the net throughfall was 22.1 kg ha^{-1} $year^{-1}$. In the case of P, the rainwater input was estimated in 0.104 and in the throughfall was 0.266 kg ha^{-1} $year^{-1}$ (Schubart et al., 1984). Therefore, these results strongly indicate that most of the K cycled from the canopy carried in the throughfall is directly absorbed by the cacao and/or shade tree roots. In the shaded plot, however, the recycling processes are smaller, because the quantity of K in the total throughfall is nearly three times lower than that of the unshaded plot.

The results also suggest that the throughfall P is absorbed directly by the plants because the subsurface leaching losses, the P concentration in river waters, and the *RI* of P are small. It is inferred that the total throughfall together with elements recycled in leaf fall constitute the most important sources of K and P in the nutrition of the cacao ecosystem. For N, Ca, Mg, these sources make a smaller contribution. The average biomass of the litter layer for unshaded and shaded cacao ecosystems is 9–11 ton ha^{-1} $year^{-1}$ (Leite, 1987), with leaf fall being the most important litter source of nutrients. Stems and branches of cacao and shade trees, weeds and macro- and microfauna and flora contribute less. Fruit husks could constitute an important nutrient source, especially for K and N (Table 4), but this source cannot be considered in the ecosystem budget due to the common practice of farmers of not returning these to the plantation soil after harvesting the crop. The results, however, indicate that nutrient losses in the ecosystem due to this source are offset by the aerial inputs, mainly K and P, and by the natural soil reserves. Therefore, in shaded or unshaded cacao ecosystems, the element cycling appears efficient in nutritional terms, suggesting that farmers could reduce the use of K fertilizers and still maintain good commercial yields in the area studied.

CONCLUSIONS

(1) The concentrations of N, P, K, Ca and Mg in the rainwater and in the throughfall varied between and within years. The nutrient concentrations in

the throughfall also varied with the structure (shaded or unshaded) of the cacao plantation.

(2) The interactions that occurred in the winter period between Mg and Ca in the rainwater, between Mg and Ca, and K and P in the throughfall, of both cacao plots, suggest an association between these combinations and the structure of the cacao plantation.

(3) The greater rain contributions to the soil reservoir are N and Ca which can reach an average of 43 and 21 kg ha^{-1} $year^{-1}$, respectively. The contributions of Mg and K are lower, 9 kg ha^{-1} $year^{-1}$, and those of P near 1 kg ha^{-1} $year^{-1}$.

(4) The net throughfall is richer in the unshaded than in the shaded cacao plot. The average annual recyclings obtained in this study, for the unshaded and shaded cacao plots, respectively, were 141 and 47 kg K ha^{-1}, 28.4 and 21 kg Ca ha^{-1}, 21 and 12.2 kg Mg ha^{-1}, and 13 and 8 kg P ha^{-1}.

(5) The direct absorption by the cacao roots of the K and P in the throughfall appears to be the principal route to these elements. Most of the Mg, Ca and N in the throughfall are retained in the soil.

(6) The throughfall and leaf fall constitute the most important nutrient sources for the soil in the cacao ecosystem.

(7) In general terms, more knowledge about the throughfall nutrient interactions, as well as a relationship of these interactions with the season of the year, would be an important ecological instrument for the diagnosis of cacao nutritional deficiencies, especially K.

(8) The data suggest that the cacao agroecosystem, in the soil studied, is self-sufficient in terms of nutrient requirements, especially K.

ACKNOWLEDGMENTS

We would like to thank Valda Maria Freitas Ribeiro and Irenice Ferraz de Oliveira for typing the manuscript; the Geosciences Laboratory for the chemical analysis. We wish to express grateful appreciation to Virgnínia Oliveira Daamceno for her assistance in collecting rain and throughfall waters and preparing the tables. The authors are also indebted to Waldeck Dié Maia, Joseph Robert Iturbe, and Alex-Alan F. de Almeida for many helpful suggestions during the preparation of the manuscript.

REFERENCES

Boyer, J., 1973. Cycles de la matière organique et des éléments minéraux dans une cacaoyère camérounaise. Café Cacao Thé, 17: 13–24.

Da Silva, L.F. and Melo, A.A.O., 1970. Levantamento detalhado dos solos do Centro de Pesquisas do Cacau. Bol. Téc. no. 1. CEPLAC (CEPEC), Bahia, Brasil, 89 pp.

Da Silva, L.F., Carvalho Filho, R. and Melo, A.A.O., 1976. Solos da região cacaueira. IICA-CEPLAC, Ilhéus, 176 p.
Eaton, J.S., Likens, G.E. and Borgman, F.H., 1973. Throughfall and stemflow chemistry in a northern hardwood forest. J. Ecol., 61: 495–508.
Epstein, E., 1975. Nutrição mineral das plantas: princípios e perspectivas. Tradução de E. Malavolta. Rio de Janeiro. Livros Técnicos e Científicos, São Paulo Ed. Univ. São Paulo, 34 pp.
Fassbender, H.W., Alpizar, L., Heuveldop, J., Enrique, G. e Folster, H., 1985. Ciclos da matéria orgânica e dos nutrientes em agrossistemas com cacaueiros. In: Reunião Brasileira de Fertilidade de Solos, 16, Ilhéus, Bahia, pp. 231–257.
Foster, N.W. and Morrison, J.K., 1976. Distributing and cycling nutrients in a natural *Pinus banksiana* ecosystem. Ecology, 57: 110–120.
Hardy, F., McDonald, J.A. and Rodriguez, G., 1935. Leaf analysis as means of diagnosing nutrient requirements of tropical orchard crops. J. Agric. Sci., 25: 610–627.
Henderson, G.S., Harris, W.F., Todd, D.E. and Grizzard, T., Jr., 1977. Quantity and chemistry of throughfall as influenced by forest-type and season. J. Ecol., 65: 365–374.
Herrera, R., Jordan, C.F., Linge, H. and Medina, E., 1978. Amazon ecosystems, their structure and functioning with particular emphasis on nutrients. Interciencia, 3: 223–236.
Leite, J. de O., 1985. Relação entre o fósforo, o potássio e o cálcio contidos em quatro componentes do ecossistema cacau na Bahia. Rev. Bras. Ci. do Solo, 9: 95–101.
Leite, J. de O., 1987. Características do manto detrítico e sua relação com a fertilidade da camada superficial do solo em plantações de cacau. Rev. Bras. Ci. do Solo, 11: 45–49.
Lockaby, B.G., 1986. Nutrient transfer associated with precipitation in plantation of eastern cottonwood. For. Ecol. Manage., 17: 17–24.
Miranda, R.A.C., 1985. Observações iniciais da perda de água por interceptação da chuva em'cacaueiro. Rev. Theobrama, 15: 49–55.
Santana, M.B.M. and Cabala Rosand, P., 1984. Reciclagem de nutrientes em plantações de cacau sombreada com eritrina. In. Conf. Int. Pesq. Cacau. 9a. Lomé, pp. 205–210.
Santana, M.B.M., Pereira, G.C. and Morais, F.I., 1976. Métodos de análise de solos, plantas e água utilizados no laboratório do Setor de Fertilidade do CEPEC, Centro de Pesquisas do Cacau, Ilhéus, 33 pp.
Schubart, H.O.R., Franken, W.S. and Luizão, F.J., 1984. Uma floresta sobre solos pobres. Ciência Hoje, 2: 26–32.
Tukey, H.B., Jr., 1969. Implications of allelopathy in agricultural plant science. Bot. Rev., 35: 1–16.
Tukey, H.B., Jr., 1970. Leaching of substances from plants. Annu. Rev. Plant. Physiol., 21: 305–324.
Usherwood, N.R., 1982. Interação do potássio com outros ions. In: T. Yamada, K. Igue, O. Muzilli and N.R. Usherwood (Editors), Potássio na Agricultura Brasileira. Instituto Internacional da Potassa. Piracicaba, pp. 27–247.
Voigt, G.K., 1960. Alterations of composition of the rainwater by trees. Am. Midl. Nat., 63: 321–326.
Zevallos, A.C., 1970. Estudo do sistema radicular do cacaueiro em alguns tipos de solo da região cacaueira do sul da Bahia. Boletim Técnico no. 5, Centro de Pesquisas do Cacau, Bahia, 31 pp.