NUTRIENT STOCKS, NUTRIENT CYCLING, AND SOIL CHANGES IN COCOA ECOSYSTEMS: A REVIEW

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It is generally assumed that agricultural systems with perennial crops are more sustainable than systems with annual crops. Soil erosion is negligible and perennial crops have more closed nutrient cycling. Moreover, inorganic fertilizers are used more commonly in cash crops such as perennial crops so that soil fertility decline and nutrient mining are less likely to occur. In the past decades, considerable research has been devoted to the quantification of nutrient stocks and nutrient cycling in agro-ecosystems. This article reviews the main stocks and flows of nutrients in cocoa ecosystems for several cocoa-growing regions in the tropics. Most of the nitrogen is found in the topsoils, and less than 10% of the total N stock is in the cocoa and shade trees. Nitrogen in the annual litter fall is about 20 to 45% of the total N in the vegetation and 2 to 3% of the total N in the soil. The accumulation of potassium is low in cocoa ecosystems, and in most systems the total amount in the biomass is equivalent to the available P content in the topsoil. Phosphorus in the annual litter fall is about 10 to 30% of the total P in the vegetation and 10 to 40% of the available P in the soil. Potassium is a major nutrient in mature cocoa. Stocks of exchangeable K in the topsoil

Advances in Agronomy, Volume 86

0065-2113/05 $35.00

vary from 100 to 550 kg ha^{-1}, and high K levels in the soil correspond to high K levels in the vegetation and litter. Partial nutrient balances were calculated that compares the losses, addition, and transfer of N, P, and K. The nutrient balance is negative in the absence of inorganic fertilizers, especially for K. Rainwash and litter fall are key components in the cycling of nutrients of cocoa ecosystems. The amount of nutrients transferred by rainwash is less than 8 kg ha^{-1} for N and P but varies from 38 to more than 100 kg ha^{-1} $year^{-1}$ for K. Most soils under cocoa had a lower fertility when compared to primary forest, although soil chemical properties seem to settle at equilibrium levels. This review shows that large amounts of nutrients in cocoa ecosystems are transferred each year and that such nutrient cycling is essential for maintaining cocoa production.

I. INTRODUCTION

Nutrient cycling is a relatively new concept in ecological research that has made considerable progress since the seminal work of Nye and Greenland (1960) on nutrients flows and pools in shifting cultivation systems. It has been used in many areas of ecological research, and in the last decade the developments have been especially large in research on agroforestry systems (Sanchez, 1995) and in the quantification of stocks and flows in nutrient balance studies of smallholder agriculture. It is often mentioned that the quantification of nutrient flows and stocks is an important step in the development of sustainable land use systems, especially on low-fertility soils of the humid tropics (Schroth *et al.*, 2001; Smaling *et al.*, 1999). Nonetheless, the number of studies on nutrient cycling and balances on perennial plantation crops is limited, despite the importance of plantation cropping for the economies of many developing countries (Hartemink, 2003). For example, it was not until the early 1980s that a N balance was available for coffee and cocoa, as available data for N cycling in coffee and cocoa plantations were scarce (Robertson, 1982).

Cocoa—food of the gods (*Theobroma cacao* L.)—is a major cash crop in many tropical countries. Cocoa is produced within 10 °N and 10 °S of the equator where the climate is suitable for growing cocoa trees (Fig. 1). West Africa has been the center of cocoa cultivation for many decades, as two-thirds of the world's cocoa is produced in West Africa. However, in 1900 Africa's share of the total world cocoa production was a mere 17% (Duguma *et al.*, 2001). Currently, the main producers are the Ivory Coast, Ghana, and Indonesia. The Ivory Coast is the largest cocoa producer with a 95% increase in output over the 1980s and it now holds more than 40% of the world market. In Ghana, cocoa export accounts for about 60% of the country's

Figure 1 Main cocoa-producing countries in the world (map from the International Cocoa Organization).

foreign earnings, whereas in Indonesia, the revenue of cocoa is over \$600 million per year. Yields in 2001 were about 540 kg ha^{-1} in the Ivory Coast and 280 kg ha^{-1} in Ghana and Nigeria. A considerable part of the cocoa in the world is produced by smallholders, and the International Cocoa Organization (ICCO) estimates that approximately 14 million people are directly involved in cocoa production.

The most significant contribution to the rise in global output is expected from Africa where production is forecast to rise by close to 9%, followed by the Americas, whereas production in the Asia and Oceania region is likely to remain static. Africa remains the main cocoa-producing region, accounting for 69% of world cocoa production in 2002 and 2003, followed by Asia and Oceania (18%) and the Americas (13%) according to ICCO (2003). Compared to other agricultural activities, cocoa has been a leading subsector in the economic growth and development of several West African countries (Duguma *et al*., 2001).

The first systematic research on nutrient cycling in cocoa was started in Cameroon by Boyer in the early 1970s (Boyer, 1973). In Malaysia, where the area under cocoa rapidly expanded in the 1980s, data related to cocoa growth and nutrition were insufficiently available and studies were undertaken to formulate more precise and efficient fertilizer programs to reduce manuring costs (Ling, 1986; Thong and Ng, 1978). In the 1980s several studies were conducted in South America. Aranguren and co-workers (1982a) conducted nutrient cycling research in Venezuela and assessed the role of cocoa and shade tree litter in the N cycle of a cocoa plantation. A series of experiments on nutrient cycling in cocoa ecosystems was conducted at the CATIE research station, Turrialba, Costa Rica (Alpizar *et al*., 1986; Beer *et al*., 1990; Fassbender *et al*., 1988, 1991; Heuveldop *et al*., 1988) and although the research was somewhat hampered by the size of the experimental plots (Somarriba *et al*., 2001), it yielded much insight in the nutrient cycling pattern of shaded cocoa. Overall, research on nutrient cycling in cocoa ecosystems was undertaken to increase understanding of the systems and served for a more accurate assessment of inorganic fertilizer requirements.

This article reviews the results of research on nutrient cycling in cocoa ecosystems, including data on soil changes under permanent cocoa cultivation. The objectives are to calculate and compare nutrient stocks of cocoa ecosystems and to compose nutrient balances for some of the world's cocoa growing areas. Hereto, the cocoa ecosystem is divided into two pools (soil and vegetation) and one flow (litter fall). This review is restricted to pools and flows of N, P, and K. Although Ca and Mg are quantitatively important as well, they are not included due to insufficient data for comparison.

II. CLIMATIC AND SOIL CONDITIONS OF STUDY AREAS

Nutrient stocks and balances could be calculated from experimental data from Malaysia, Venezuela, Costa Rica, Brazil, and Cameroon. A brief description of the environmental conditions of the areas where the studies were conducted is given. The experimental site in Malaysia was located in a flat to undulating area with deep red, highly weathered soils derived from granite. The soils were classified as Oxisols and Ultisols. Average annual rainfall is about 1850 mm with a dry spell of 6 to 8 weeks. The cocoa was of the upper Amazon hybrid type and was planted with a density of 1074 plants ha^{-1}. The cocoa was 8 to 10 years when the nutrient studies were made. Yield levels were high at about 1400 kg ha^{-1} (dry beans), and shade trees are *Gliricidia maculata*.

The soils of the study site in Venezuela were well drained and located in a flat area at sea level. They are of recent alluvial origin and are classified as Psammentic Entisol (Psamment). The soil reaction is slightly alkaline (pH 7.4), and organic C levels are below 1.5% in the topsoil. Mean annual rainfall is 740 mm, and average temperatures are around 25 °C. Cocoa was planted at a density of 947 plants ha^{-1} and was about 30 years when the nutrient studies were conducted. The cocoa is of the Criollo type and yields are 640 kg ha^{-1} (dry beans).

The soils under cocoa in Costa Rica are poorly drained and the soil reactions are extremely acid (pH-H_2O 3.8). The soils are derived from fluvial-lacustrine deposits and are classified as Typic Dystropepts. Average annual rainfall is 2648 mm, and mean temperatures are 22 °C. Cocoa was 10 years old and planted at a density of 1111 plants ha^{-1}. Annual yield levels were around 650 kg ha^{-1}. Shade trees planted at 278 ha^{-1} were *Cordia alliodora* and *Erythrina poeppigiana*.

The soils of the study site in Brazil were classified Alfisols and have a high fertility. Total annual rainfall is 1862 mm, and the average temperature is about 23 °C. There is no information available on the cocoa but shade trees were *Erythrina fusca* and *Ficus* spp. at a density of 278 ha^{-1}.

Not much data are available for the experimental site in Cameroon. The site was formerly a tropical rain forest and the soils were red and clay-like. Total annual rainfall is 1700 mm. The cocoa was planted under natural shade with a population of about 1000 plants ha^{-1}. Table I summarizes the environmental growing conditions and information on the cocoa and shade trees of the study areas.

III. NUTRIENT STOCKS

Nutrient stocks of cocoa ecosystems comprise above and belowground biomass and the nutrients in the soil. Stock size depends on the amount of biomass and fertility status of the soils. The aboveground biomass is subdivided into the biomass of the cocoa and the shade tree. The total biomass of cocoa ecosystems is variable, and in Malaysia, 7.5-year-old cocoa had a biomass of about 60 tons dry matter (DM) ha^{-1} (Thong and Ng, 1978), whereas a 10-year-old cocoa plantation in Costa Rica had 8.5 to 11 tons DM ha^{-1} (Alpizar *et al*., 1986). Shade trees in Costa Rica accumulated about 23 to 35 tons DM ha^{-1}. Biomass includes roots, as they are an important component of primary production in perennial cropping systems and consist of about 25 to 43% of the aboveground biomass (Young, 1997). Research at CATIE (Costa Rica) showed that the fine root biomass of cocoa shaded with *Erythrina poeppigiana* or *Cordia alliodora* was around 1 ton ha^{-1}, but higher values were found at the end of the rainy season (Munoz and Beer, 2001).

In most papers on cocoa ecosystems, soil nutrient stocks were given in kg ha^{-1} and these stocks were calculated from soil chemical analysis: total N, available P, and exchangeable K. These nutrients were generally given as % (N), mg kg^{-1} (P), and mmol$_c$ kg^{-1} (K) and were multiplied with the soil bulk density values to obtain nutrient stocks in kg ha^{-1}. Nutrient stocks

Table I
Summary of Soil, Climate, Cocoa, and Shade Tree of Cocoa Ecosystems

	Soil		Climate			Cocoa			Shade		
Country	Type[a]	Diagnostic property	Annual rainfall (mm)	Dry periods	Mean annual temperature (°C)	Age (years)	Trees (ha^{-1})	Yield (kg ha^{-1})	Species	Trees (ha^{-1})	Reference
Malaysia	Oxisol, Ultisol	Poor fertility	1850	6–8 weeks	21	8–10	1074	1400	*Gliricidia maculata*	268	Ling (1986)
Venezuela	Entisol	Very sandy	740	3 months	25	30	947	636	Mixture	566	Aranguren *et al.* (1982a)
Costa Rica	Inceptisol	Poorly drained	2648	1 month	22	10	1111	ca. 700	*Cordia/ Erythrina*	278	Alpizar *et al.* (1986)
Brazil	n.d.[b]	High fertility	1862	n.d.	23	n.d.	n.d.	n.d.	*Erythrina fusca*	278	de Oliveira Leite and Valle (1990)
Cameroon	n.d.	n.d.	1700	n.d.	n.d.	30	1000	700	Natural	n.d.	Boyer (1973)

[a]USDA soil taxonomy classification.
[b]No data.

have been restricted to the upper 30 cm, as most feeding roots of cocoa are concentrated to that depth. The root system of a cocoa tree consists of a thick tap root and a mat of lateral roots that lies in the top 20 cm of the soil; these lateral roots are the main channel for moisture and nutrients (Wood and Lass, 1985). De Oliveira Leite and Valle (1990) found that 85% of the roots are concentrated in the first 30 cm of the column, and Thong and Ng (1978) also found that cocoa is a surface-root feeder with most lateral roots found in the surface soil layer (0–30 cm). Also, de Geus (1973) mentioned that 80% of the roots are found within 15 cm of the soil surface. In most soils in the tropics the major part of the nutrients are also found in the top 25 cm.

Nitrogen accumulation in the above- and belowground biomass of cocoa ranges from 100 to over 400 kg ha^{-1}. This variation is explained by the age of planting, difference in cultivar, and environmental conditions. In Costa Rica and Brazil, more than twice the amount of N was present in the shade tree than in the cocoa, and it is not uncommon that shade trees contain more N than the cocoa (Stephenson and Raison, 1987). Total N contents in the shade tree does not vary much and is around 260 kg N ha^{-1}. As total biomass of the shade trees differs between the cocoa ecosystems, nutrient content per unit biomass largely varies.

Most of the N is found in the topsoils and less than 10% in the cocoa and shade trees. The total N content in the upper 30 cm varies from about 4800 to 18,750 kg ha^{-1}. The N content of the soils in Costa Rica with a leguminous shade tree (*Erythrina poeppigiana*) is about 1000 kg ha^{-1} higher compared to soils under a nonleguminous shade tree (*Cordia alliodora*). As the age of the plantation is 10 years, average yearly N fixation could be 100 kg ha^{-1}, which is very high. It has been reported that *Erythrina* may fix about 60 kg ha^{-1} per year (Young, 1997). The extremely acid soil reactions (pH 3.8) with high Al concentrations favoring P fixation (Giller, 2001) seem to have little adverse effects on nodulation (Alpizar *et al*., 1986).

The accumulation of P is low in cocoa ecosystems. In most systems the total amount in the biomass is equivalent to the available P content of the soil. The content of phosphorus in the cocoa is about 55 kg ha^{-1} for Malaysia and around 12 kg ha^{-1} for Costa Rica and Brazil. The P stocks in the cocoa of Cameroon is extremely low but concerns the aboveground biomass only. The P content of the shade trees is typically around 25 kg ha^{-1}. Cocoa and shade trees in Costa Rica contain more P under nonleguminous shade trees, possibly as *Rhizobium* sp. is high P demanding, which restricts uptake by the vegetation. The P content in the litter varies from 7 to 14 kg ha^{-1}. In Brazil and Costa Rica, the same amount of P is found in the cocoa biomass as in the annual litter fall, but for Malaysia, about 8 times more P is found in the cocoa biomass than in the annual litter fall.

Potassium is a major nutrient in mature cocoa. Stocks of exchangeable K in the topsoil vary from 100 to 550 kg ha^{-1}. The K content of mature cocoa in Malaysia is over 600 kg ha^{-1} whereas in other studies the K contents of soils under cocoa were found to be only 10 to 15% of these values. High K levels in the soil correspond to high K levels in the vegetation and annual litter fall (Table II).

IV. NUTRIENT CYCLING

For nutrient cycling in cocoa ecosystems, a simple balance is used that was first presented by Boyer (1973) and later adjusted by Wessel (1985) and Ling (1986). The cocoa ecosystem is divided into a soil and vegetation pool (Fig. 2). Nutrients can be removed or added from the soil and vegetation pool or transferred between the soil and the vegetation pool. Pathways for nutrient losses include nutrient removal by the yield and leaching, and soil erosion. Denitrification under cocoa is small, as the crop is mostly grown on well-drained soils.

A. NUTRIENT REMOVAL: YIELD

Removal of nutrients from cocoa ecosystems includes yield (beans and husks), immobilization in stem and branches, and leaching of nutrients below the rooting zone. Most nutrients in cocoa ecosystems are lost by the harvest of beans and husks. Table III shows the nutrients removed in a crop with a yield of 1000 kg dry beans per ha. If data of Venezuela are disregarded, about 20 kg N, 4 kg P, and 10 kg K are removed with 1000 kg dry beans. When the husks are also removed, the amount is increased to about 35 kg N, 6 kg P, and 60 kg per 1000 kg beans, which indicates that K removal by the husks is high. Nutrient removal in beans shows little variation, whereas large differences can be noticed for husks. According to Wessel (1985), this is caused by the fact that husks are affected more strongly by the environment and the type of fruits than beans. Nutrients immobilized in the stem and branches of cocoa and shade trees are also considered lost for the system as they are excluded from nutrient cycling. Immobilization of nutrients is particularly important for young cocoa, but is unimportant for mature cocoa (Wessel, 1985).

B. NUTRIENT REMOVAL: LEACHING

Leaching is an important pathway for nutrient losses in soils of the humid tropics (Buresh and Tian, 1997; Grimme and Juo, 1985; Sollins, 1989). Despite the differences in crop phenology and soil management, very few

Table II
Nutrient Stocks of the Soil and Vegetation (kg ha^{-1}) Pool and in the Litterfall (kg ha^{-1} year^{-1}) of Cocoa Ecosystems

	Country	Soil (0–30 cm)	Vegetation: Cocoa	Vegetation: Shade tree	Vegetation: Total	Litterfall cocoa	Shade tree	Total	Calculated from
Nitrogen	Malaysia	6699	423	245	668	84	48	132	Ling (1986)
	Malaysia	n.d.[a]	438	n.d.	n.d.	n.d.	n.d.	n.d.	Thong and Ng (1978)
	Venezuela	18750	302	n.d.	n.d.	115	205	320	Aranguren *et al.* (1986)
	Costa Rica[b]	5327	110	260	370	n.d.	n.d.	115	Alpizar *et al.* (1986); Heuveldop *et al.* (1988)
	Costa Rica[c]	6370	109	249	388	n.d.	n.d.	175	Alpizar *et al.* (1986); Heuveldop *et al.* (1988)
	Brazil	4805	103	263	366	n.d.	n.d.	128	De Oliveira Leite and Valle (1990)
	Cameroon	4782	39[d]	n.d.	n.d.	52	n.d.	n.d.	Boyer (1973)
	Mean ± 1 SD[e]	7789 ± 5429	248 ± 161	254 ± 9	448 ± 147	84 ± 32	127 ± 111	174 ± 85	
Phosphorus	Malaysia	59	57	20	77	5	2	7	Ling (1986)
	Malaysia	n.d.	48	n.d.	n.d.	n.d.	n.d.	n.d.	Thong and Ng (1978)
	Costa Rica[b]	n.d.	14	32	46	n.d.	n.d.	14	Heuveldop *et al.* (1988)
	Costa Rica[c]	n.d.	10	29	39	n.d.	n.d.	9	Heuveldop *et al.* (1988)
	Brazil	30	12	26	38	n.d.	n.d.	12	De Oliveira Leite and Valle (1990)
	Cameroon	79	1[d]	n.d.	n.d.	4	n.d.	n.d.	Boyer (1973)
	Mean ± 1 SD	56 ± 25	28 ± 22	27 ± 5	50 ± 18	5 ± 1	n.d.	11 ± 3	
Potassium	Malaysia	557	607	140	747	91	33	124	Ling (1986)
	Malaysia	n.d.	633	n.d.	n.d.	n.d.	n.d.	n.d.	Thong and Ng (1978)
	Costa Rica[b]	385	105	258	363	n.d.	n.d.	66	Alpizar *et al.* (1986); Heuveldop *et al.* (1988)
	Costa Rica[c]	475	52	252	304	n.d.	n.d.	54	Alpizar *et al.* (1986); Heuveldop *et al.* (1988)
	Brazil	113	67	237	304	n.d.	n.d.	25	De Oliveira Leite and Valle (1990)
	Cameroon	103	51[d]	n.d.	n.d.	38	n.d.	n.d.	Boyer (1973)
	Mean	327 ± 209	253 ± 285	222 ± 55	430 ± 213	65 ± 37	n.d.	67 ± 42	

[a]No data.
[b]Cocoa with *Cordia alliodora* as shade tree.
[c]Cocoa with *Erythrina poeppigiana* as shade tree.
[d]Excluding roots; figure not included for the calculations of mean and CV%.
[e]Standard deviation.

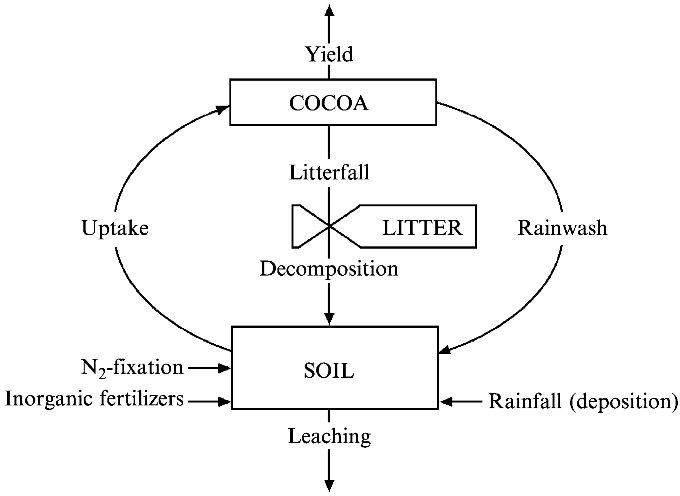

Figure 2 Simplified nutrient cycling diagram for cocoa ecosystems.

studies have compared leaching losses under perennial and annual crops in the tropics (Seyfried and Rao, 1991). A leaching experiment was conducted at CATIE with two contrasting cropping systems: (i) a mixed perennial cropping system composed of *Cordia alliodora* (a timber species), cocoa, and plantain and (ii) an annual monocropping system with maize (Seyfried and Rao, 1991). Losses of Ca, Mg, and K were significantly greater by 2 to 15 times in the maize system, and NO_3 losses from the maize plots were 56 kg ha^{-1} compared to 1 kg NO_3 ha^{-1} in the mixed perennial plots. The difference was explained by the much larger nutrient retention and uptake capabilities of the perennial crops (Seyfried and Rao, 1991). Research conducted in West Africa also concluded that leaching losses under annual crops are likely higher than under oil palm (Omoti *et al.*, 1983), whereas Imbach *et al.* (1989) concluded that leaching losses in cocoa ecosystems are much lower than under annual crops. These studies provide evidence for the "safety net" theory of tree crops whereby nutrients leached to a deeper soil horizon can be taken up by tree roots at great depths (Sanchez, 1995; van Noordwijk, 1989).

In the cocoa-growing regions of south Bahia, Brazil, a lysimeter study was conducted on a 30- to 40-year-old cocoa plantation with Tropudalfs as the dominant soil orders (Santana and Cabala-Rosand, 1982). Leaching losses in unfertilized and fertilized plots (40 kg N, 40 kg P, and 50 kg K ha^{-1}) were compared. The amount of NH_4-N and NO_3-N losses was proportional to the amount of rainfall. Less N was leached from the fertilized plots than from the unfertilized plots. This was possibly because the

Table III
Nutrients (kg) Removed by 1000 kg Dry Cocoa Beans

	Beans			Husks			Total			
	N	P	K	N	P	K	N	P	K	Calculated from
Malaysia	20.4	3.6	10.5	10.6	1.3	43.3	31.0	4.9	53.8	Thong and Ng (1978)
Venezuela	39.3	n.d.[a]	n.d.	31.4	n.d.	n.d.	70.7	n.d.	n.d.	Aranguren *et al.* (1982a)
Costa Rica[b]	19.3	4.6	10.9	11.5	1.8	34.5	30.8	6.4	45.4	Heuveldop *et al.* (1988)
Costa Rica[c]	21.3	4.2	10.5	14.8	1.8	27.2	36.1	6.0	37.7	Heuveldop *et al.* (1988)
Brazil	22.0	n.d.	n.d.	12.0	n.d.	n.d.	34.0	n.d.	n.d.	Santana *et al.* (1982)
Cameroon	19.2	4.4	10.6	15.0	1.9	62.0	34.2	6.3	72.6	Boyer (1973)
Nigeria	22.8	4.0	8.4	17.0	2.3	77.2	39.8	6.3	85.6	Wessel (1985)
Nigeria	22.9	3.9	8.5	15.4	1.8	68.4	38.3	5.7	76.9	Wessel (1985)
Ivory Coast	22.1	3.0	7.5	13.2	1.8	43.0	35.3	4.8	50.5	Snoeck and Jadin (1992)
Trinidad	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	44.0	3.5	53.1	van Dierendonck (1959)
Trinidad	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	26.6	4.5	37.4	van Dierendonck (1959)

[a]No data.
[b]Cocoa with *Cordia alliodora* as shade tree.
[c]Cocoa with *Erythrina poeppigiana* as shade tree.

Table IV
Annual Leaching Losses (kg ha^{-1} ± 1 SD), Inorganic Fertilizer Inputs (kg ha^{-1}), and Soil Nutrient Reserves (kg ha^{-1} for 0–45 cm) Under Cocoa with Different Shade Trees at Turrialba, Costa Rica[a]

	Cocoa with *Erythrina poeppigiana* as shade tree	Cocoa with *Cordia alliodora* as shade tree	Inorganic fertilizer inputs	Soil nutrient reserves[b]
N	5.3 ± 0.2	5.2 ± 0.3	120	8800
P	0.5 ± 0.1	0.5 ± 0.1	29	3400
K	1.5 ± 0.1	1.2 ± 0.1	33	650

[a]Modified from Imbach *et al.* (1989) and Alpizar *et al.* (1986).
[b]Averaged and rounded data from soils under cocoa with *E. poeppigiana* or *C. alliodora* as shade tree.

application of P and K increased the development of cocoa roots, thus increasing nutrient-absorbing surfaces and decreasing the amounts of N available for leaching. No data were given in kg ha^{-1} or as a percentage of applied nutrients, but it was concluded that N leaching losses were small and do not seriously affect N availability to the cocoa (Santana and Cabala-Rosand, 1982). Another study with cocoa on Alfisols in Bahia showed mean annual losses of 22 kg N, 0.9 kg P, and 17 kg K ha^{-1} (de Oliveira Leite, 1985). These are fairly high losses, particularly when it is considered that the cocoa was unfertilized. At the cocoa experiment at CATIE, inorganic fertilizer input was 120 kg N, 29 kg P, and 33 kg K ha^{-1} year^{-1}. Leaching losses were calculated from nutrient concentrations in lysimeter capsules at 1 m depth and the volume of percolated water (Table IV). Losses of N, P, and K were very small and seem to have no management significance when compared to inorganic fertilizer inputs or to the total soil reserves on the experimental site. Reports from cocoa on Psamments in the lowlands of Venezuela showed that leaching losses under traditional shaded cocoa were low, although leaching may be large when inorganic fertilizers are applied in such light-textured soils (Aranguren *et al.*, 1982b).

C. Nutrient Removal: Soil Erosion

In perennial crop systems, soil erosion can be considerable with inappropriate land-clearing methods and with insufficient soil cover immediately after forest clearance (Lal, 1979, 1986). Most annual crops provide adequate cover within 30 to 45 days after planting and pastures within 2 to 6 months, but tree crops may require 2 to 5 years to close their canopy (Sanchez *et al.*, 1985). Erosion is greater during the initial stages of tree establishment than when the tree canopy is fully developed and a much-used solution to the problem of soil exposure during plantation establishment is to use a managed cover crop (Sanchez *et al*., 1985). Erosion losses are thought to be low except in cocoa grown on steep slopes without shade and when the cocoa is young (Roskoski *et al*., 1982). Under monocropping cocoa in Malaysia, soil erosion losses were 11 mg ha^{-1} $year^{-1}$, but losses were very low when cover crops such as *Indigofera spicata* were planted (Hashim *et al*., 1995). When the cocoa was intercropped with banana and clean weeding with herbicide was practiced, soil losses up to 70 mg soil ha^{-1} $year^{-1}$ were measured, which are high losses based on a general rating of tolerable soil erosion losses (Hudson, 1986). Overall, soil erosion is negligible in mature cocoa and losses of nutrients with soil erosion are insignificant.

D. Addition of Nutrients

Nutrients are added to cocoa ecosystems by inorganic fertilizers, atmospheric deposition, and symbiotic and asymbiotic N fixation. Weathering of parent material resulting in a release of P and K is not considered an input to the ecosystem. Inorganic fertilizers add directly to the soil pool, although a significant portion may be lost through volatilization or leaching directly after application. Nutrients supplied by rainfall (i.e., wet and dry deposition) vary from 5 to 12 kg N ha^{-1}, 0.2 to 3.0 kg P ha^{-1}, and 2.5 to 12 kg K ha^{-1} in the study areas (Table VII). Nitrogen in the rainfall in Venezuela (11 kg ha^{-1}) and Cameroon (12 kg ha^{-1}) is particularly high. Sanchez (1976) mentioned that about 4 to 8 kg N ha^{-1} must be considered as a low and high estimate of annual contribution by rain and dust in tropical areas. Fixation of N by leguminous shade trees may be a considerable source of N for the cocoa as was shown in the total N content of the soils under cocoa with and without a leguminous shade tree (Table II).

E. Transfer of Nutrients

In cocoa ecosystems, nutrients are transferred through litter, rainwash, and fine-root turnover. Litter fall is subdivided into the litter from the cocoa and shade tree and includes branches, twigs, leaves, fruits, and flowers. In many parts of the world, cocoa is produced under natural or planted shade trees. Shade trees compete for growth resources but may also ameliorate adverse climate conditions; reduce soil erosion, pests, and diseases; and increase nutrient use efficiency in cocoa (Beer *et al*., 1998; Johns, 1999).

Table V
Annual Litterfall of Cocoa Ecosystems in kg DM ha^{-1}

Country	Age cocoa (years)	Annual litter fall: Cocoa	Shade tree	Total	Reference
Malaysia	8–10	5460	2660	8120	Ling (1986)
Venezuela	30	7630	13,571	21,201	Aranguren *et al.* (1982a)
Costa Rica[a]	10	n.d.[b]	n.d.	7071	Heuveldop *et al.* (1988)
Costa Rica[c]	10	n.d.	n.d.	8906	Heuveldop *et al.* (1988)
Brazil	n.d.	n.d.	n.d.	9000–14,000	De Oliveira Leite and Valle (1990)
Cameroon	30	5092	3408	8500	Boyer (1973)
Ghana	n.d.	n.d.	n.d.	5000	Wessel (1985)

[a]Cocoa with *Cordia alliodora* as shade tree.
[b]No data.
[c]Cocoa with *Erythrina poeppigiana* as shade tree.

Generally, cocoa yield increases dramatically when high levels of inputs are made, but under low levels of inputs, cocoa yields are substantially higher with shade trees (Wood and Lass, 1985).

Litter fall ranges from 5 to more than 21 tons DM ha^{-1} year^{-1} (Table V). The average annual litter fall of cocoa and the shade tree is 10 tons ha^{-1}, which resembles the litter production of other plantation crops under shade trees, such as coffee with *Inga* spp. (Young, 1997). High litter fall in the cocoa of Venezuela may be due to the low rainfall of the experimental site (Table I). Maximum leaf fall coincides with low rainfall or drought (Ling, 1986), and leaf fall is further related to shade (cocoa under light-shaded conditions defoliates more rapidly than under light shade) and the age of planting (the older the plant, the more leaf fall), according to Wood and Lass (1985). Climate has more influence on the amount of litter fall than the age of the cocoa, and it seems that shade trees drop their leaves under dry conditions.

Large amounts of nutrients are returned to the soil with the litter fall. Nutrient concentrations in the leaf fall are lower than in the fresh leaves as nutrients are resorbed before the leaves fall. The amount of nutrients annually transferred depends on the amount of litter fall and the nutrient concentration. The N concentration varies from 11 to 20 g kg^{-1} with a mean of all data of 15 g kg^{-1} (Table VI). Phosphorus is only present in very low concentration, typically around 0.1%, and the concentration of K shows large variation. The high values of K in the cocoa litter in Malaysia and

Table VI
Nutrient Concentration (g kg^{-1}) in Cocoa and Shade Tree Litterfall

	Nutrient concentration (g kg^{-1})			
Country	N	P	K	Calculated from
Malaysia	16.3	0.8	15.3	Ling (1986)
Venezuela	15.1	n.d.	n.d.	Aranguren *et al.* (1982a)
Costa Rica[a]	16.3	2.0	9.3	Alpizar *et al.* (1986); Heuveldop *et al.* (1988)
Costa Rica[b]	19.6	1.0	6.1	Alpizar *et al.* (1986); Heuveldop *et al.* (1988)
Brazil	11.2	1.0	2.1	De Oliveira Leite and Valle (1990)
Cameroon	11.1	1.2	11.7	Boyer (1973)
Mean ± 1 SD[c]	14.9 ± 3.3	1.2 ± 0.5	8.9 ± 5.1	

[a]Cocoa with *Cordia alliodora* as shade tree.
[b]Cocoa with *Erythrina poeppigiana* as shade tree.
[c]Standard deviation.

Cameroon may be due to a high K content in the soil and the luxury consumption of K by the cocoa and shade tree. Apparently less K is resorbed before the leaves fall.

The NP ratio varies from 21 for Malaysia to 9 for Cameroon. Decomposition is most rapid if the ratio is around 10, which is the case for the litter in Cameroon, Brazil, and in Costa Rica under leguminous shade. With decomposition, N and P concentrations tend to increase, but K concentrations decline rapidly, as K is mobile and leached rapidly from the litter (Giller, 2001). Nitrogen in the annual litter fall is about 20 to 45% of the total N in the vegetation and 2 to 3% of the total N in the soil. Phosphorus in the annual litter fall is about 10 to 30% of the total P in the vegetation and 10 to 40% of the available P in the soil. About 10 to 20% of the exchangeable K in the soil is yearly transferred by the litter fall, and K in the litter is about 15% of the total K in the biomass.

Large amounts of nutrients are transferred by rainwash (through fall) in cocoa ecosystems. Rainwash is a transfer of nutrients but can also become an addition if the leaves were covered with dust that has been transported from elsewhere (Asner *et al.*, 2001; Parker, 1983). The major part of the nutrients supplied with the rainwash had been taken up from that same soil. The amount of nutrients transferred by rainwash is less than 8 kg ha^{-1} for N and P. For K this varies from 38 to more than 100 kg ha^{-1} per year, which demonstrates the importance of rainwash for the K nutrition of the cocoa.

Few data were available for the nutrient cycling of roots and although an appreciable store of nutrients and roots constitutes a substantial element in nutrient cycling, they are almost invariably turned to the soil (Young, 1997). Munoz and Beer (2001) showed that fine root turnover was close to 1.0 in cocoa shaded with *Erythrina poeppigiana* or *Cordia alliodora* in Costa Rica. Nutrient inputs from fine root turnover were estimated as 23–24 kg N, 2 kg P, and 14–16 kg K per ha year^{-1}. Such amounts equaled about 6–13% of the total nutrient input in the cocoa shaded with *C. alliodora* and 3–6% in the cocoa shaded with *E. poeppigiana* (Munoz and Beer, 2001).

V. NUTRIENT BALANCES

Partial balances were calculated in which losses, additions, and transfer of nutrients were calculated for the cocoa ecosystems in Malaysia, Venezuela, Costa Rica, and Cameroon. In all cocoa ecosystems, it was found that N removed by cocoa beans (yield) is lower than in the litter fall (Table VII). For Cameroon, N in the litter is about twice the amount removed by the yield, whereas for Malaysia, this ratio is nearly 5. If about 6000 kg N ha^{-1} is present in the topsoil, N removed by the yield is, on average, less than 0.5%. Addition of N by wet and dry deposition is fairly high and ranges from one-sixth to almost half of the yearly N removal. The turnover of N is large compared to the additions and losses, particularly when the cocoa is not fertilized. In Costa Rica where fertilizer N is applied at a rate of 120 kg N ha^{-1}, the total transfer is lower than the yearly addition. The beans remove only 16 to 21% of the applied N. Data of Malaysia and Costa Rica suggest that inorganic fertilizer has no effect on the transfer of N with the litter. A major part of the N requirement is supplied with litter decomposition, which may explain the absence of a significant yield response after inorganic fertilizer applications. It is well known that inorganic fertilizers have little or no effect under shaded cocoa (de Geus, 1973; Wessel, 1985).

A large part of the P in a cocoa ecosystem is found in the vegetation and in the litter, whereas the amount of P in the soil is low. Both the quantity and the distribution within the ecosystem differ from those of N and K, which affect the nutrient balance. Phosphorus losses are equal to half of the transfer of P by rainwash and litter. Addition of P in dry and wet deposition, although variable, may contribute substantially to the P requirements, and in Malaysia, more than half of the removal by the yield is supplied by atmospheric deposition. A relatively large amount (6 to 8%) of the available P in the soil is removed by the cocoa beans. The ratio among losses, additions, and transfer is similar under fertilized conditions as under unfertilized conditions. Inorganic P fertilizers at rates of less than 30 kg ha^{-1} change the balance, but P fertilizers seem to have little influence on the P transfer with litter.

Table VII
Partial Nutrient Balance and Transfer (kg ha^{-1} year^{-1}) of Cocoa Ecosystems

		Process	Malaysia	Venezuela	Costa Rica[a]	Costa Rica[b]	Cameroon
Nitrogen	Losses	Yield	29.0	25.0	19.3	25.7	24.0
		Immobilization	4.0	n.d.[c]	n.d.	n.d.	3.5
		Leaching	n.d.	n.d.	5.5	5.5	n.d.
		Total	33.0	25.0	24.8	31.2	27.5
	Additions	Deposition	8.0	11.0	5.0	5.0	12.0
		N_2 fixation	n.d.	n.d.	n.d.	n.d.	n.d.
		N fertilizers	0	n.d.	120.0	120.0	n.d.
		Total	8.0	11.0	125.0	125.0	12.0
	Transfer	Rainwash	8.0	n.d.	n.d.	n.d.	6.3
		Litter fall	132.0	n.d.	115.0	175.0	52.5
		Total	140.0	329.0	115.0	175.0	58.8
Phosphorus	Losses	Yield	5.0	4.0	4.3	n.d.	4.4
		Immobilization	2.0	n.d.	n.d.	n.d.	0.1
		Leaching	n.d.	0.5	0.5	n.d.	n.d.
		Total	7.0	4.5	4.8	n.d.	4.5
	Additions	Deposition	3.0	0.2	0.2	1.0	1.7
		P fertilizers	n.d.	29.0	29.0	n.d.	n.d.
		Total	3.0	29.2	29.2	1.0	1.7
	Transfer	Rainwash	<1.0	n.d.	n.d.	8.0	1.3
		Litter fall	8.0	14.0	9.0	12.0	1.8
		Total	<8.0	14.0	9.0	20.0	5.1
Potassium	Losses	Yield	15.0	28.4	26.9	n.d.	51.0
		Immobilization	8.0	n.d.	n.d.	n.d.	5.0
		Leaching	n.d.	1.5	1.5	n.d.	
		Total	23.0	29.9	28.4	n.d.	56.0
	Additions	Deposition	8.0	2.5	2.5	8.0	12.0
		K fertilizers	n.d.	33.0	33.0	n.d.	n.d.
		Total	8.0	35.5	35.5	8.0	12.0
	Transfer	Rainwash	38.0	n.d.	n.d.	47.0	101.0
		Litter fall	133.0	66.0	54.0	25.0	38.0
		Total	171.0	66.0	54.0	72.0	139.0

[a]Cocoa with *Cordia alliodora* as shade tree.
[b]Cocoa with *Erythrina poeppigiana* as shade tree.
[c]No data.

Potassium is quantitatively the second nutrient in cocoa ecosystems. The K removed by the yield is about 5 to 10% of the total exchangeable K in the soils of Malaysia and Costa Rica, whereas in Cameroon, half of the exchangeable soil K reserve is removed in the cocoa beans. In Costa Rica, about two times more K is present in the litter than removed by the yield; in the other cocoa ecosystems, K in the litter is three to five times larger than the amount removed by the beans. Rainwash and litter fall are the most important K recycling process in a cocoa ecosystems.

VI. SOIL CHANGES UNDER COCOA

Tree crops such as cocoa remain in the same field for many years and require an initial high investment. Long-term returns of such investments can only be expected if production is sustained, which requires, among others, that the soil remains in good condition. However, permanent cropping will affect the soil conditions and in order to sustain productivity, it is needed to investigate the long-term changes brought about by the crop and management practices (Hartemink, 2003). The previous section reviewed nutrient stocks and nutrient balances. Although there was a considerable difference between systems and between the three major nutrients, it was shown that the total amount of nutrients in cocoa ecosystems is large and that a considerable part is removed and transferred each year. The effects of cocoa growing on the soils are reviewed here, and several studies have focused on the effects of cocoa on soil organic C, as in many soils of the tropics, maintenance of soil organic C is the key to sustainable crop production (Greenland, 1994; Woomer *et al.*, 1994).

Beer *et al.* (1990) measured soil organic C in cocoa ecosystems on a Typic Humitropept at CATIE, Turrialba (Costa Rica). When the cocoa was shaded with *Erythrina poeppigiana* topsoil (0–15 cm), organic C levels increased from 28 to 32 g kg^{-1} in 9 years. Levels in the 15- to 30-cm soil horizon changed from 23 to 25 g C kg^{-1} over the same period. Similar changes were noted in the top- and subsoil when the cocoa was shaded with *Cordia alliodora* (Beer *et al.*, 1990). None of the changes were statistically significant, which indicates that cocoa ecosystems were able to maintain soil organic C contents.

Several studies have been conducted in Nigeria, which is the fourth largest cocoa producer in the world. Near Ibadan, Ekanade *et al.* (1991) found soil organic C contents under forest of 29 g kg^{-1}, whereas this was 19 g C kg^{-1} under cocoa. Available P was much higher under cocoa than under forest, but exchangeable K was lower. In Oyo State (Nigeria), Adejuwon and Ekanade (1987) found topsoil organic C levels of 26 g kg^{-1} under forest and 19 g C kg^{-1} in the topsoils under cocoa (Table VIII). All major nutrients and the pH were lower under cocoa compared to soils under forest. In another study in the Oyo state of Nigeria, Adejuwon and Ekanade (1988) sampled a large number of soils under forest, and soils that had been under cocoa for 10 to 15 years. Soils were classified as Alfisols, and mean annual rainfall at the sites was about 1300 mm. The soil pH under forest was 6.8, whereas the pH under cocoa had decreased to 5.5. Soil organic C levels were 27 g kg^{-1} under forest but only 13 g C kg^{-1} under cocoa. Also, total N and levels of exchangeable cations were much reduced when the soils under forest were compared to those under cocoa (Adejuwon and Ekanade, 1988).

In southern Nigeria it was found that soil organic C under a secondary forest was about 35 g kg^{-1}; under 10-year-old cocoa, levels were 25 g C kg^{-1} (Ogunkunle and Eghaghara, 1992). Total N and most other soil properties were about the same under cocoa and secondary forest. Ekanade (1988) sampled 60 cocoa plots of ages from 1 to 55 years and collected 30 soil samples under forest on Alfisols in southwestern Nigeria (Table IX). Soil organic C was, on average, 26 g kg^{-1} under forest and 19 g kg^{-1} under cocoa, and the soil reaction was 6.8 under forest and 5.9 under cocoa. All soil chemical properties were significantly lower under cocoa.

Table VIII
Mean Values (Range in Parentheses) of Soil Chemical Properties Under Forest and Cocoa on Alfisols in Nigeria[a]

Sampling depth:	0–15 cm		15–45 cm	
Land use:	Forest	Cocoa	Forest	Cocoa
pH	6.8 (5.4–7.6)	5.9 (4.6–7.4)	4.7 (3.1–6.0)	5.0 (4.0–6.0)
Organic C (g kg^{-1})	26 (13–37)	19 (12–30)	13 (6–23)	12 (6–20)
Available P (mg kg^{-1})	14 (8–23)	12 (6–20)	13 (4–28)	9 (5–16)
CEC ($mmol_c$ kg^{-1})	144 (90–191)	95 (52–174)	78 (31–200)	62 (27–129)
Exchangeable Ca ($mmol_c$ kg^{-1})	90 (54–112)	53 (20–118)	47 (14–113)	41 (15–73)
Exchangeable Mg ($mmol_c$ kg^{-1})	38 (21–53)	20 (14–38)	29 (9–63)	20 (6–47)
Exchangeable K ($mmol_c$ kg^{-1})	7 (4–15)	4 (2–14)	5 (2–8)	3 (2–5)

[a]Modified from Adejuwon and Ekanade (1987).

Table IX
Mean Values of Soil Chemical Properties Under Forest and Cocoa on Alfisols in Nigeria[a]

	Forest ($n = 30$)	Cocoa ($n = 60$)	Difference
pH ($CaCl_2$)	6.8	5.9	$P < 0.01$
Organic C (g kg^{-1})	25.2	18.5	$P < 0.01$
Available P (mg kg^{-1})	16	12	$P < 0.01$
CEC ($mmol_c$ kg^{-1})	196	125	$P < 0.01$
Exchangeable Ca ($mmol_c$ kg^{-1})	122	83	$P < 0.01$
Exchangeable Mg ($mmol_c$ kg^{-1})	57	28	$P < 0.01$
Exchangeable K ($mmol_c$ kg^{-1})	9	4	$P < 0.05$

[a]Modified from Ekanade (1988).

These studies from West Africa provide insight into the differences and changes that may be expected when the natural forest is converted to perennial cropping. The studies consistently show that soil organic C equilibrium data under cocoa settle below those of the soils under natural forest. Carbon storage under cocoa is, however, often higher than in comparable soils under annual cropping (Duguma *et al*., 2001; Kotto-Same *et al*., 1997). Studies have shown that nutrient and metal pollution levels on cocoa farms are generally very low (Okuneye *et al*., 2003) due to the relatively low use of agrochemicals such as inorganic fertilizers.

The soil chemical fertility was significantly lower under cocoa compared to soils under forest, and this is often found under perennial crops (Hartemink, 2003). However, in Cameroon, soil pH, organic C, and exchangeable actions were generally higher in home gardens dominated by cocoa than in secondary forest (Table X). The secondary forest was developed after fields that were used for food crop production were left fallow.

VII. DISCUSSION

Several sources of variation were identified when comparing nutrient stocks and balances in cocoa ecosystems: climatic and soil conditions, cocoa and shade tree (age, cultivar, or species, plant density), and research approach and methods (sampling techniques, analytical methods). Differences in the research approach and methods also resulted in some variations in the studies reviewed here, and despite the temporal and spatial variation, several trends emerged. They are discussed here.

Nitrogen is the main nutrient in cocoa ecosystems and about 90% of the total N is found in the topsoil. More P and K are found in the cocoa and shade tree than in the soil. High K levels in the soil result in high concentrations in the vegetation and litter fall, which is likely affected by the luxury consumption of K by the cocoa. No clear relation was found between N and P concentrations in the soil, vegetation, and annual litter fall.

The calculations on the nutrient stocks have some limitations. Total N is determined by total analysis, whereas P is available (bicarbonate extraction) and K is exchangeable (NH_4-acetate); P and K are therefore a fraction of the total content in the soil. As much of the P and K are locked up in insoluble compounds or in minerals that weather very slowly, data give a fair estimate of the amounts of P and K that are potentially available for crop production. Nitrogen is based on total analysis and thus equals the total amount present in the topsoil. As most cocoa roots are found in the top 30 cm, deep capture of nutrients, which is important in many perennial cropping systems, is not

Table X
Soil Chemical Properties (0–20 cm) in Cocoa-Dominated Home Gardens and Secondary Forest in Southern Cameroon[a]

	pH (H_2O)		Organic C (g kg^{-1})		Exchangeable cations ($mmol_c$ kg^{-1})					
					Ca		Mg		K	
Study site	Cocoa	Forest	Cocoa	Forest	Cocoa	Forest	Cocoa	Forest	Cocoa	Forest
Yaounde	6.9	5.2	26.4	15.0	108	26	21	10	4	1
Mbalmayo	6.8	6.5	24.6	28.8	114	52	20	18	6	2
Ebolowa	6.5	4.8	28.2	19.2	118	30	25	9	14	2

[a]Modified after Duguma *et al*. (2001).

so relevant. The nutrient stocks reported for the topsoil are more or less equal to the amount of nutrients available.

Transfer of nutrients takes place with the litter fall and rainwash, and the rate of litter fall and nutrient concentration determines the amount of nutrients transferred. Rate of litter fall depends on climate (dry spells), age and type of the plantings, and shading density. The nutrient concentration of litter depends on the availability in the soil and/or the uptake capacity of the plants. This review has shown that K is transferred via rainwash in large amounts (up to 100 kg ha^{-1} $year^{-1}$) as K is mobile in the plant, whereas N and P are more fixed in organic compounds. Total transfer via litter fall and rainwash covers the removal with the beans in all nutrient balances. For N the ratio transfer to losses is 2 to 13, whereas for P this ratio is 1 to 3. Although more nutrients are transferred than lost annually, this does not necessarily imply that cocoa ecosystems are self-sufficient in terms of N, P, and K nutrition, as the transfer does not compensate for losses. The size of the total nutrient transfer is, however, important in relation to the sustainability of a cocoa ecosystem, and a large annual transfer of nutrients may indicate that the system is more self-sufficient.

Under unfertilized conditions (Malaysia, Cameroon), yearly losses of N are about two to four times higher than the nutrient addition. For P, losses are about two to three times higher, and about three to five times more K is lost annually when no inorganic fertilizer is applied. Under fertilized conditions (Costa Rica), the balance changes and even at moderate fertilizer applications, annual losses are lower than additions. However, as part of the nutrients applied in inorganic fertilizers are lost after application, the nutrient balance is less positive. Because fertilizer use efficiency differs among nutrients, fertilizer types, time and method of application, soil types, and cropping systems, no standard fraction can be deducted from the application rate. Most cropping systems in the tropical regions have negative nutrient balances (Henao and Baanante, 1999; Pieri, 1989; Smaling, 1993). This is caused by the low use of inorganic fertilizers, which has severe environmental implications, as it results in soil mining and soil fertility depletion (Dudal and Byrnes, 1993). The low use of inorganic fertilizers in the cocoa ecosystems results in a negative nutrient balance, but leaching and erosion losses are much lower than in systems with annual crops. Moreover, cocoa ecosystems have relatively large nutrient stocks of which only a fraction is removed with the bean yield. As such it can be argued that cocoa ecosystems have a much higher degree of resilience than annual cropping systems.

Changes in soil chemical properties were found to be different as soils, climates, and cropping systems differed. Nevertheless, a decline was found in most soil chemical properties and in most soils. Various studies indicated that the original C and N levels under natural forest are not attained again in perennial cropping systems, although levels of P and exchangeable cations, particularly K, may be higher in soils under perennial crops due to the use of inorganic fertilizers. Changes in soil chemical properties reflect the decrease in nutrient stocks of the soil, but it also reflects immobilization of nutrients in the biomass. Therefore, it is more difficult to assess soil fertility decline and its causes in cocoa ecosystems than, for example, in annual cropping systems.

The studies discussed here have shown that leaching losses under cocoa can be considerable, although the losses are consistently smaller than under annual crops (Hartemink, 2003; Seyfried and Rao, 1991). This is related to the fact that tree crops grow the whole year through in the humid tropics, whereas in annual cropping there may be periods when there is no crop or the crop is either too young or old to take up nutrients from the soil solution. The absence of a crop in combination with the onset of the seasonal rainfall inducing the N priming effect (Birch, 1958) may result in leaching losses: no crop, no uptake. Tree crops generally provide a "safety net," but an adequate supply of all nutrients for a dense root mat is essential to reduce nutrient leaching and to enable a deep uptake of leached nutrients (van Noordwijk and Cadisch, 2002).

VIII. CONCLUDING REMARKS

It is generally assumed that perennial crops are a more sustainable form of land use than systems with annual crops. A perennial plant cover protects the soil better against erosion than an annual crop (Jacks and Whyte, 1939; Lal, 1990; Ruthenberg, 1972), although much depends on the soil, site factors (slope, rainfall, etc.), and management practices. Perennials can also provide a "safety net" whereby nutrients leached to a deeper soil horizon are taken up by tree roots at great depths (Sanchez, 1995; van Noordwijk, 1989), and as perennial crops are often cash crops that receive inorganic fertilizers, nutrient depletion is often lower than under annual crops (Hartemink, 2003). Although the data set was limited, this review showed that large amounts of nutrients in cocoa ecosystems are transferred each year. Such nutrient cycling is important for maintaining cocoa production. Although no attempts were made to compare the cocoa ecosystem with annual cropping systems, this review provided evidence that that cocoa ecosystems are more environmentally sound. Nonetheless, little specific research has been carried out on the macroenvironmental service impact, such as biodiversity conservation, C sequestration, and water quality (Somarriba *et al.*, 2001), which are research priority areas in cocoa ecosystems.

ACKNOWLEDGMENTS

I am grateful to Professor Dr. Marius Wessel and Wouter Gerritsma of Wageningen University for their comments on an earlier draft of this paper. Wouter Bomer of ISRIC–World Soil Information is thanked for the drawing of Fig. 1.

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