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REGULAR ARTICLE

Litterfall and litter nutrient dynamics under cocoa ecosystems in lowland humid Ghana

Evans K. Dawoe · Marney E. Isaac · James Quashie-Sam

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Abstract There have been few studies quantifying litterfall, standing litterstock and gross litter decomposition following forest conversion to plantation crops such as cocoa. Additionally, an assessment of changing processes occurring in forest floor litter systems with plantation age is lacking. We investigated litterfall production, standing litter changes and litter decomposition along a chronosequence of shaded cocoa farm fields (secondary forest, 3, 15 and 30-year-old) in the moist semi-deciduous forest belt in the Ashanti Region of Ghana in West Africa over 24 months. Mean annual litterfall production differed significantly among study sites and ranged from 5.0 to 10.4 Mg DM ha^{-1}. Similarly, standing litter differed significantly between land-use /plot ages. The results showed significant differences in quality between litter from forest and litter from cocoa plantations. Litterfall from forests had higher concentrations of nitrogen and lower concentration of soluble polyphenols and lignin compared to litter from cocoa systems. Monthly decomposition coefficients (k) estimated as $k = (\mathrm{A} - (\mathrm{L}_1 - \mathrm{L}_0))/((\mathrm{L}_1 + \mathrm{L}_0)/2)$, where A is litterfall production during the month, L_0 is the standing litterstock at the beginning of the month and L_1 is the standing litterstock at the end of the month. Annual decomposition coefficients (k_L) were similar in cocoa systems (0.221–0.227) but higher under secondary forests (0.354). Correlations between litter quality parameters and the decomposition coefficient showed nitrogen and lignin concentrations as well as ratios that include nitrogen are the best predictors of decomposition for the litters studied. Our results confirm the hypothesis that decomposition decreases following forest conversion to shaded cocoa systems because of litter quality changes and that decomposition rates correlate to litter quality differences between forest and cocoa ecosystems. The study also showed that standing litter pools and litterfall production in recently converted cocoa plantations are low compared to secondary forests or mature cocoa systems. Management strategies involving the introduction of upper canopy species during plantation development with corresponding replacement of tree mortality with diverse fast growing species will provide high quality and quantity litter resources.

Keywords Cocoa · Litterfall production · Standing litterstocks · Decomposition coefficient · Litter quality

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E. K. Dawoe (✉) · J. Quashie-Sam
Faculty of Renewable Natural Resources,
Kwame Nkrumah University of Science and Technology,
Kumasi, Ghana
e-mail: elkdawoe@daad-alumni.de
e-mail: elkdawoe@yahoo.com

M. E. Isaac
Department of Physical and Environmental Sciences
and Department of Social Sciences, International
Development Studies, University of Toronto
at Scarborough,
Toronto, Canada

Introduction

Litterfall and litter decomposition and subsequent nutrient release represent major biological pathways for element transfer from vegetation to soils, and play an important role in regulating nutrient cycling, and in maintaining soil fertility in forest and agro-ecosystems (Yang et al. 2003). Forest litter acts as an input-output system of nutrients and the rates at which forest litter falls contribute to the regulation of nutrient cycling, fertility sustenance and primary productivity in forest and tree-based ecosystems (Berg 2000; Ranger et al. 2003). In Ghana, cocoa has re-emerged as an important export and cash crop. For the majority of farmers, fertility of soils under cocoa plantations is maintained through the recycling of nutrients through leaf fall and decomposition of leaf litter (ISSER 2004; Appiah et al. 2006). The decomposition process is influenced by a number of factors. These comprise: (1) microclimate, mainly temperature and humidity, (2) litter quality, (3) soil nutrient content and (4) the qualitative and quantitative compositions of decomposer communities (Anderson and Swift 1983). These factors interact to determine decomposition rates.

Despite many studies carried out on litterfall and decomposition dynamics, in both tropical and temperate forests and agroforests (Berg 2000; Ranger et al. 2003; Martius et al. 2004; Isaac et al. 2005), few attempts have been made to assess ecological processes on forest floor litter systems under cocoa. To date, no study has assessed litter dynamic parameters under cocoa systems along a chronosequence with forest systems as a reference. Thus, it is vital to understand the nutrient dynamics of litter in these ecosystems (Schroth 2003; Appiah et al. 2006) to advise small farmers who depend on natural nutrient recycling for fertility sustenance.

The present study was carried out to comparatively measure litterfall production, standing litterstock, gross litter decomposition and nutrient cycling in forest and shaded-cocoa systems as the plantations age. The aim of the work presented here is to investigate litter dynamics and to understand decomposition and nutrient cycling patterns following forest conversion to cocoa cultivation in humid semi-deciduous forests of Ghana, West Africa. The specific objectives were to (a) measure the production and accumulation of litter in forest and cocoa ecosystems, and (b) compare litter decomposition under forest and cocoa ecosystems using the litter turnover method. We hypothesized that: i) litter pools (stand litter-stocks) and litterfall production in recently converted cocoa plantations will be low compared to forests or mature cocoa systems, ii) decomposition rates will correlate to litter quality in cocoa ecosystems and iii) forest litter decomposition rates will be more rapid due to specific litter dominance of higher quality.

Materials and methods

Site description

The study was conducted from January 2006 to December 2007 on small-holder farms in the Ashanti Region of Ghana, West Africa, located between longitudes 1^0 40′ and 2^0 23′ W and latitude 6^0 75′ N. The region falls within the wet semi-equatorial rain-forest climate zone with average monthly temperatures ranging between 27°C (August) and 31°C (March). Rainfall ranges from 1,300 mm–1,850 mm yr^{-1} with a double maximum characteristic, with May/June and September/October as peaks separated by a dry spell from late November to early March. The predominant vegetation in the district is the semi-deciduous forest type with some of the trees in the upper and middle layers shedding their leaves in the dry season. The cocoa agroforestry systems in the district are mostly mixed stands of cocoa and with variable proportions of naturally generated upper canopy shade trees such as *Terminalia superba* Engl. & Diels, *Triplochiton scleroxylon* K. Schum., *Alstonia boonei* de Wild and *Ceiba pentandra* (L.) Gaertn. Fruit trees may be planted, e.g., orange *Citrus sinensis* (L.) Osbeck, Avocado (*Persea americana*) and mango (*Mangifera indica* L.), for shade, food and other purposes. The soils of the study area are developed from weathered phyllites and are classified as Ferric Lixisols or Leptosols/Regosols (FAO/UNESCO/WRB 1990). They are deep, moderately well drained and brashy with a silty-loam humus texture in the 0–20 cm soil layer, which gives it a high moisture retention capacity. The fertility status of soils on the site is generally low to medium with near-neutral to acid conditions (Table 1).

The study followed a completely randomized design with four plot ages: a secondary forest referred to as forest land-use, 3, 15 and 30-year-old shaded-

Table 1 Stand characteristics and means (±SE) for selected soil physical and chemical properties of the study sites

Parameters	Land-use			
	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 30 years
Mean DBH (cm)				
Cocoa canopy	–	3.36	10.6	12.4
Upper story canopy	23.1	24.2	38.5	51.3
Stand density (trees ha^{-1})				
Cocoa canopy	–	1,500	1,100	900
Upper storey canopy	900	16	35	26
Soil (0–20 cm depth)				
Bulk density (gm cm^{-3})	1.1 (±0.04) ^{a}	1.3 (±0.10) ^{a}	1.2 (±0.10) ^{a}	1.2 (±0.03) ^{a}
Clay (%)	14 (±1.4) ^{a}	11 (±1.1) ^{a}	16 (±2.9) ^{a}	18 (±2.5) ^{a}
Silt (%)	65 (±2.3) ^{a}	62 (±1.1) ^{a}	64 (±2.1) ^{a}	59 (±2.0) ^{a}
Sand (%)	20 (±1.8) ^{a}	26 (±3.9) ^{a}	19 (±2.7) ^{a}	22 (±1.6) ^{a}
Textural class	Silty loam	Silty loam	Silty loam	Silty loam
pH	5.7 (±0.1) ^{a}	5.8 (±0.4) ^{a}	5.7 (±0.2) ^{a}	5.7 (±0.1) ^{a}
CEC (cmol kg^{-1})	98 (±0.8) ^{a}	97 (±1.8) ^{a}	83 (±14.9) ^{a}	96 (±1.9) ^{a}
BS (%)	10.1 (±1.6) ^{a}	10.9 (3.2) ^{a}	12.5 (±0.8) ^{a}	13.5 (±1.1) ^{a}
Organic C (%)	2.0 (±0.17) ^{a}	1.4 (±0.18) ^{a}	1.7 (±0.35) ^{a}	1.7 (±0.33) ^{a}
Total N (%)	0.19 (±0.11) ^{a}	0.14 (±0.03) ^{b}	0.14 (±0.02) ^{b}	0.13 (±0.02) ^{b}
C:N Ratio	10.7	10.1	11.8	12.8
Available P (mg kg^{-1})	2.0 (±0.91)^{a}	1.8 (±0.39) ^{a}	1.5 (±0.77) ^{a}	0.9 (±0.17) ^{b}
Exchangeable K (cmol kg^{-1})	0.35 (±0.06) ^{a}	0.44 (±0.16) ^{a}	0.36 (±0.04) ^{a}	0.48 (±0.11) ^{a}
Exchangeable Ca (cmol kg^{-1})	7.1 (±0.89)^{a}	6.6 (±1.72)^{a}	7.4 (±0.74)^{a}	7.7 (±0.92)^{a}

Mean values in the same row followed by the same superscript for the different land-uses are not significantly different at $P<0.05$ according to Tukey's HSD test. Numbers in parentheses are standard errors of the means

cocoa plantations as treatments. Three replicate sites each measuring approximately 35 m×35 m plots were randomly established in each of selected treatments. The treatments represented three distinct phases: specifically the planting and developing (3-year), productive (15-year) and maturity (30-year) phases in the development of a cocoa plantation after forest conversion. The forest treatment represents the period before forest conversion. All replicates were similar with respect to soil type across the chronosequence. The distance between replicate sites varied from 0.5 to 9.0 km, i.e., replicates were widely scattered over the respective forests. The minimum distance between sites and forest edges was 1.2 km. Details of stand characteristics and selected properties of the surface soil are described in Table 1.

Litterfall sampling

Litterfall was collected monthly by pooling together fortnightly samples using 0.25 m^2 litter traps (Anderson and Ingram 1998). Litter traps consisted of 50 cm× 50 cm wooden-framed open boxes, 30 cm high with 1 mm nylon screen mesh base. Each trap was raised on four preservative-treated wooden stands 10 cm above the forest floor to prevent decay. Four litter traps were established in each plot at three replicates for four land-use chronosequence ages giving a total of 48 litter traps or 12 litter traps per chronosequence age. To improve representativeness of plot means, the litter traps were distributed randomly within the experimental plots and their positions changed from time to time (Schroth 2003) throughout the study period. The collected litter was manually separated into different fractions; leaves, twigs and branches and floral parts (flowers and seeds), and oven-dried at 65°C for 4 days for dry weight determination. Monthly values of litterfall production for each land-use were summed up to obtain the annual litterfall at each site. Every 4 months litterfall material from each treatment plot was returned to the laboratory for nutrient analysis.

Standing litter sampling

Standing litter (Mg DM ha^{-1}) was determined monthly using 20 cm×20 cm quadrats. Steps were taken to ensure that no area of the forest/cocoa floor was sampled twice by tagging all previously sampled points with colored polythene strips. The material from one sampling event every 4 months (for 24 months) was manually cleaned from adhering soil particles and returned to the laboratory for nutrient analysis.

Litter decomposition coefficients

The accumulation of litter depends on the litterfall production and the litter decomposition. The decomposition coefficient k can be estimated from two parameters, the annual litterfall production and the accumulated litter on the forest floor. We calculated the monthly decomposition coefficient (k) for each land-use as $k = (A - (L_1 - L_0))/((L_1 + L_0)/2)$, (formula simplified after Olson 1963) where A is litterfall production during the month, L_0 is the standing litterstock at the beginning of the month and L_1 is the standing litterstock at the end of the month (Bernhard-Reversat 1993). Monthly values of k for each land-use for 12 months were summed up to obtain the annual decomposition coefficient (k_L) at each site.

Chemical analysis

Composite samples of litterfall and standing litter samples from each land-use were analyzed for C and major nutrients (N, P, K, Ca and Mg) in triplicate. All samples were oven-dried (65°C, 48 h) and ground to pass through 0.5 mm mesh. Carbon (C) in litterfall was determined by wet oxidation method (Walkley and Black 1934), total N using the standard micro-digestion method (Kjeldahl) with colorimetric determination by spectrophotometer. Calcium (Ca), Mg and K were analyzed by atomic absorption spectrophotometry. Available P was determined using the Bray and Kurtz (1945) method. Lignin (L) content of 1 g ground dried (60°C) litterfall material was determined by alcohol extraction after acid digestion (72% H_2SO_4) and correction for ash following the acid detergent fibre method of Van Soest (1963). Total soluble polyphenols (PP) was determined according to Anderson and Ingram (1998) after extracting with 20 ml methanol.

Data processing and analysis

Analysis of variance (ANOVA) was used to test for significant effects of land-use on total litterfall, stand litterstocks and decomposition coefficients using STATISTIX 6.0 statistical software. Multiple comparisons were determined with the Tukeys HSD test at a significance level of 0.05. Regressions and correlations were also employed to establish trends and relationships between measured parameters.

Results

Litterfall production

Monthly patterns of litterfall production were similar among the treatments (plot ages) with peaks during the dry period and dips during the rainy period (Fig. 1). Differences in total annual litterfall production along the chronosequence were significant (F= 20.41; P<0.001) between land-use types (Table 2). Annual litterfall production was higher in forest and older cocoa (15 and 30-year-old treatments) compared to the 3-year-old system.

Litterfall composition

In the case of litter fractions, there were significant differences in leaf litter (F=12.34; P<0.001), twigs and small branches (F=9.8; P<0.001) and floral/ reproductive parts (F=27.21; P<0.001) between the land-use ages. Leaves always represented the largest fraction in both forest and cocoa systems (Table 2). Three-year-old land-use produced the least litter for all the litter fractions. For each land-use, mean seasonal litterfall production differed significantly: Forest (F= 6.48; P=0.0291), 3 years (F=5.64; P=0.0390), 15 years (F=13.77; P=0.004) and 30 years (F=8.5; P=0.0154) between the rainy and dry periods.

Litter decomposition coefficient

Monthly decomposition coefficients among land-uses ranged from 0.022–0.685 $month^{-1}$ (Fig. 1). The average annual decomposition coefficients differed significantly (F=12.67; P=0.003) between land-uses with coefficients in the cocoa systems being significantly lower than in the older cocoa or forest systems (Table 3).

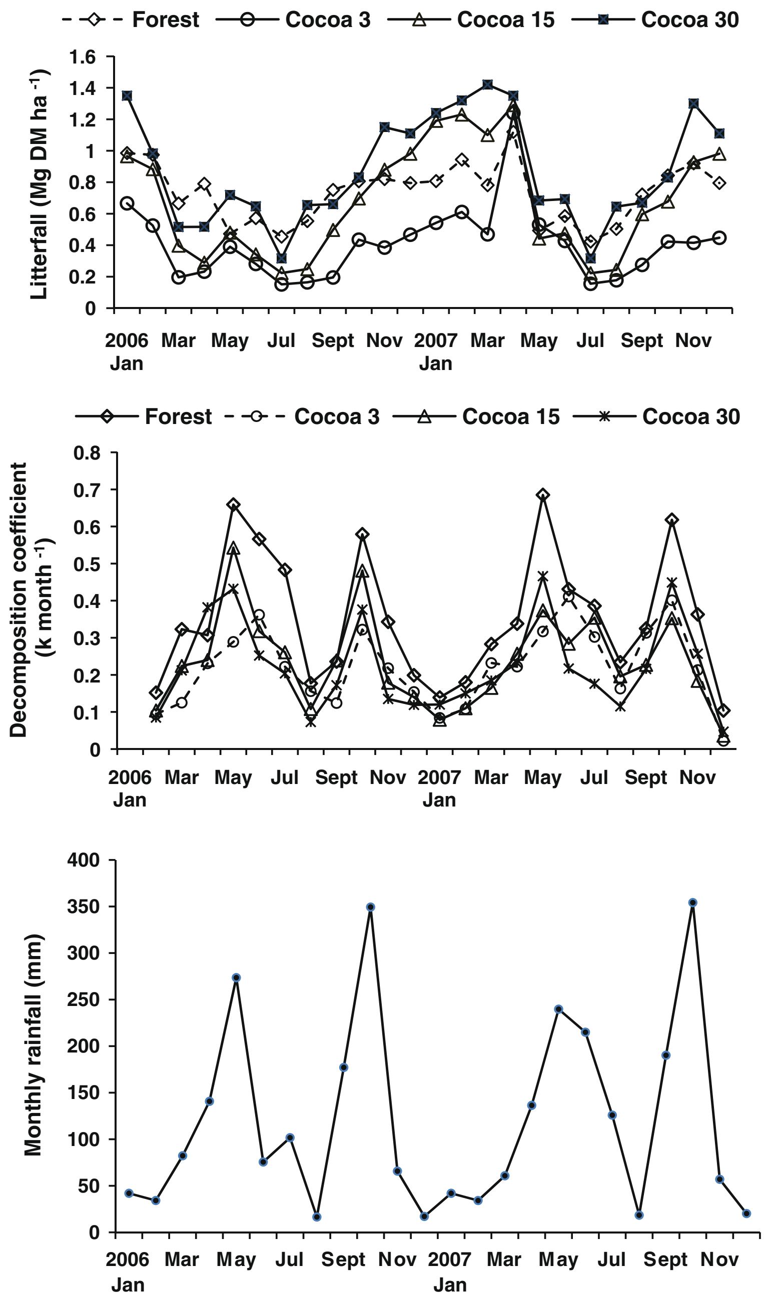

Fig. 1 Monthly litterfall production (Mg DM ha^{-1}), decomposition coefficients (k month^{-1}) and rainfall (mm) for the study sites

Standing litter and bio-elements sequestered

The standing litter varied with the age of the system and significant differences (F=8.78; P<0.001) were observed, with a trend toward a lower amount in the younger (3-year-old plots) than in the forest and older plantations (Table 3). Quantities of nutrients held in surface litter are given in Table 4. Carbon (C) accumulation ranged from 1.3 to 2.4 Mg C ha^{-1} for 3 and 30-year-old cocoa plots respectively. Elemental nutrients sequestered in surface litter ranked in the order Ca > N > Mg > K > P in forest, 3 and 15-year-old cocoa land-use, and in the order Ca > N > K > Mg > P in 30-year-old cocoa land-uses. It is likely

Table 2 Quantity (Mg DM $ha^{-1}yr^{-1}$ ± SEM) and composition (%, in parenthesis) of litterfall in forest and cocoa land-use systems

Land-use	Leaf	Twigs and small branches	Reproductive parts	TOTAL
Forest	6.9±0.32[a]	0.9±0.12[a]	1.0±0.09[a]	8.8±0.36 [a]
	(78.4)	(10.2)	(11.4)	(100)
Cocoa 3 years	4.6±0.37[b]	0.06±0.005[b]	0.3±0.03[b]	5.0±0.39[b]
	(92.0)	(1.2)	(6.0)	(100)
Cocoa 15 years	6.7±0.53[a]	0.7±0.11[a]	0.8±0.07[c]	8.2±0.61[a]
	(81.7)	(8.5)	(9.8)	(100)
Cocoa 30 years	8.4±0.46[a]	1.0±0.16[a]	1.0±0.09[a]	10.4±0.58[a]
	(80.5)	(9.0)	(10.5)	(100)

Mean values in the same column with the same superscript for the different land-uses are not significantly different at $P<0.05$ level according to Tukey's HSD test

that nutrient sequestered might be slightly overestimated as no correction was made for mineral soil particles that may be adhering to surface litter.

Litterfall quality

Polyphenol (PP) concentrations were similar in all three cocoa stands but significantly higher ($F=11.15$; $P<0.001$) than in forests (Table 5). Lignin (L) concentration was similar in 3, 25 and 30-year-old plots (14.1–14.6%) but significantly higher ($F=10.22$; $P=0.0013$) compared to the forest plot. Initial leaf litter N concentrations differed significantly between the four land-uses ($F=26.92$; $P<0.001$) (Table 5). While L:N ratios were significantly higher ($F=43.78$; $P<0.001$) in 3 and 15-year-old plots compared to forest and 30-year-old cocoa plots, PP:N and PP+N:N ratios were similar in all cocoa plots though there was a clear trend towards decreasing ratios with increasing stand age. C:N ratios were similar in 3 and 15-year-old plots but significantly higher ($F=30.68$; $P<0.001$) than in both forest and 30-year-old plots. Most of the litter quality parameters were correlated with the decomposition coefficient with significant positive correlations for N and significant negative correlations for C:N, lignin, lignin:N, PP:N and PP+N: N ratios (Table 6).

Discussion

Litterfall production

Litter production is a major process by which carbon and nutrients are transferred from vegetation to soil. Total litterfall production showed a significant increase with time after forest conversion and ranged from 5.0–10.4 Mg DM $ha^{-1}yr^{-1}$ (Table 1). Comparable litterfall rates have been reported by Opakunle (1989), Isaac et al. (2005) and Owusu-Sekyere et al. (2006), in similar moist semi-deciduous and shaded cocoa systems. Vitousek and Sanford (1986) observed above-ground inputs within a tropical forest to be between 8.8 and 10.5 Mg DM $ha^{-1}yr^{-1}$. Hartemink (2005) reviewed the results of research on nutrient

Table 3 Estimated mean standing litterstocks (Mg DM ha^{-1} ± SE), annual decomposition coefficient (k_L $year^{-1}$) and mean residence time (1/k years) in forest and cocoa land-use systems

Parameter	Land-use			
	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 30 years
Standing litter (Mg DM ha^{-1})	4.6[a]	3.6[b]	5.8[a]	5.9[a]
	(± 0.63)	(± 0.31)	(± 0.46)	(±0.42)
Annual decomposition coefficient (k_L yr^{-1})	0.35[a]	0.22[b]	0.24[b]	0.22[b]
	(± 0.07)	(± 0.03)	(± 0.03)	(± 0.02)
Mean residence time (MRT) (1/k years)	2.8	4.6	4.2	4.5

Mean values in the same row followed by the same superscript for the different land-uses are not significantly different at $P<0.05$ according to Tukey's HSD test. Numbers in parentheses are standard errors of the means

Table 4 Estimated quantities of carbon (Mg ha^{-1}) and nutrients (kg ha^{-1}) sequestered in standing litter. Quantities of nutrient accumulated were computed by multiplying mean nutrient concentrations by mean standing litterstocks

Land-uses	Stocks					
	C	N	P	K	Ca	Mg
Forest	1.85	60.2	4.6	18.0	81.4	30.8
Cocoa 3 years	1.26	37.8	2.9	7.9	56.2	17.6
Cocoa 15 years	2.25	60.3	5.2	16.8	87.0	30.2
Cocoa 30 years	2.39	64.9	6.5	31.3	96.8	27.1

cycling in cocoa ecosystems and found that litterfall production ranged from 5 Mg DM ha^{-1}yr^{-1} in Ghana to more than 21 Mg DM ha^{-1}yr^{-1} in Venezuela. Compared to our soils, these non-amended soils of Venezuela are reputed to be more fertile but with lower annual rainfall resulting in higher litterfall rates. In our study biomass inputs via litterfall had reached natural forest levels by 15 years after forest conversion suggesting a sustained level of nutrient inputs at this stage.

Seasonality of litterfall production

Litterfall may be affected by physical factors such as the mechanic action of wind and rain or physiological responses of the plants to environment changes (ICP Forests 2004; Santiago and Mulkey 2005). We found a seasonal pattern of litterfall production, which increased in the dry season, indicating that the physiological response to drought/reduced humidity plays a major role in this process. These factors together with lower night temperatures which prevail during the dry seasons are known to stimulate abscisic acid synthesis in plant foliage which, in turn, stimulates leaf senescence (Yang et al. 2003). Most litterfall studies in tropical forests have demonstrated a strong seasonality of leaf litterfall, with the dry season being the peak of litterfall (Wieder and Wright 1995; Lawrence and Foster 2002). Seasonal pattern of litterfall largely depended on the factors responsible for leaf senescence and abscission (Lian and Zhang 1998). This pattern of litterfall in our study, consistent with patterns in vegetation forms under seasonal climates, is different from those found in vegetation forms under climates without dry seasons, such as the Atlantic rain forest, where the production peak occurs in the rainy season, indicating an effect of mechanical factors (Moraes et al. 1999).

Standing litter and carbon/bio-elements sequestered

The standing litterstocks on the forest floor are a dynamic component of C and nutrient cycling in the forest ecosystem. Average standing litterstocks were lowest in the 3-year-old plots compared to the forest and older cocoa plots. Correlations between standing littersocks and decomposition coefficients were not significant. Higher standing litter in forests and older cocoa systems are due to high litterfall in these systems. It appears that a combination of factors such as litter quality, litterfall production, stand age leading to a relatively long-term accumulation of litter in forest and 15 and 30-year-old cocoa systems compared with the short-term accumulation of litter in 3-year-old plots interact to affect litter layer build up (Yang et al. 2003). The rapid increase of standing litterstock between 3 and 15 years at least could partly

Table 5 Mean chemical composition of senesced leaf litter from forest and cocoa land-use systems

Composition	Forest	Cocoa 3 years	Cocoa 15 years	Cocoa 30 years
Lignin (mg g^{-1} DM)	112±9.4^{b}	141±1.1^{a}	146±0.05^{a}	143±0.3^{a}
Polyphenol (mg g^{-1}DM)	18±1.5^{b}	27.1±1.0^{a}	27.7±1.8^{a}	33.9±2.9^{a}
C (mg g^{-1} DM)	433±7.2^{a}	426±13.1^{a}	428±18.2^{a}	436±24.0^{a}
N (mg g^{-1} DM)	17±0.6^{a}	10±0.2^{b}	10±0.4^{b}	15±0.8^{a}
Polyphenol:N Ratio	1.1±0.08^{b}	2.9±0.04^{a}	2.8±0.23^{a}	2.4±0.40^{a}
P+N:N Ratio	2.1±0.08^{b}	3.9±0.06^{a}	3.8±0.23^{a}	3.4±0.40^{a}
C:N Ratio	25.6±1.10^{b}	45.0±0.71^{a}	42.9±1.50^{a}	31.6±2.70^{b}
Lignin:N Ratio	6.6±0.6^{b}	14.9±0.2^{a}	14.7±0.6^{a}	9.9±0.9^{b}

Mean values for the different land-uses with the same superscript are not significantly different at $P<0.05$ level using Tukey's HSD test $N=6$

Table 6 Correlations between the decay coefficient (k_L year^{-1}) and parameters of litter quality in the forest and shaded-cocoa stands

Parameters of litter quality	*R*	*P*
Polyphenol	−0.67	0.320
Lignin	−0.89	0.023
Nitrogen	0.98	0.018
C:N Ratio	−0.82	0.012
Polyphenol:N Ratio	−0.11	0.001
Lignin:N Ratio	−0.97	0.003
Polyphenol+N:N Ratio	−0.60	0.048

be due to litter quality changes leading to lower decomposition rates in cocoa systems. The high standing litter in forest and older cocoa systems imply that the forest floor is an important pool for carbon and bio-elements in forest and cocoa ecosystems. Thus ecosystemic services such as carbon sequestration in litterfall, protection of soil against erosion and organic matter and nutrient conservation are expected to be maintained following forest conversion to cocoa plantations.

Decomposition coefficient and litter quality

The patterns of litterfall production and standing litter accumulation resulted in monthly decomposition coefficients *k* exhibiting similar temporal patterns across the chronosequence (Fig. 1). As would be expected, monthly coefficients were highest in the rainy seasons i.e., between the months of April to November with peaks in May and October. The lower rates were recorded during the dry periods in August and between December and March (Fig. 1). Decomposition coefficients tended to decrease from forest to cocoa systems, i.e., forest had significantly higher mean annual decomposition coefficient than the cocoa systems. Many researchers have developed predictors or indices of decomposition and nutrient release (Mtambanengwe and Kirchmann 1995; Mafongoya et al. 1997). These indices which include ratios of carbon to nitrogen (C:N), polyphenol to nitrogen (PP:N), lignin to nitrogen (L:N), and polyphenol plus lignin to nitrogen (PP+L:N) ratios are all apparently valid, however other factors such as site conditions may also be important moderating factors (Anderson and Swift 1983; Mafongoya et al. 1998). In our study, the significantly lower rates of decomposition in cocoa compared to forest systems suggest the possible effect of litter quality dominating the decomposition processes in these land-use systems. Observed trends in decomposition can be linked to increases in litter lignin and polyphenols because of the predominance of cocoa leaves in leaf litterfall (Table 5). Though this study did not differentiate between leaves from cocoa and upper canopy trees, earlier studies by Isaac (2003) confirmed that cocoa leaves constitute the dominant litter (about 60%) in litterfall production under similar cocoa systems in the western region of Ghana. Non-significant differences in C:N and L:N ratios in forest and 30-year-old cocoa systems were expected to have resulted in similar decomposition coefficients in the two systems. These coefficients however differed significantly. This suggests that the decomposition process is very complex with multiple concurrent factors. For instance, the general effect of the occurrence of more adapted soil biota and local decomposers in forest compared to anthropogenic sites (Anderson and Swift 1983; Martius et al. 2004; Goma-Tchimbakala and Bernhard-Reversat 2006) is expected to influence decomposition. We indicate that concentrations of N and lignin in leaf litter, C:N ratio, lignin to N and polyphenol plus lignin to N ratios correlated significantly with decomposition coefficients. Additionally, lignin and PP were significantly correlated to N. It may be assumed that among the quality parameters assessed, lignin and N are the main factors controlling decomposition in these systems.

Relationships with soil chemical characteristics

Soil physico-chemical properties are known to influence the decomposition of leaf litter on forest floors (Ananthakrishnan 1996). An overview of soil and other site characteristics registered during the study period is given in Table 1. For several of these properties: (bulk density, SOC, pH, exchangeable K and exchangeable Ca, base saturation and CEC), no differences were found between forest and the different ages of cocoa system. Total N % and available P declined significantly (0–20 cm soil depth) along the chronosequence. Phosphorus (P) decline at 30 years can be attributed to continuous extraction by cocoa and fixation as organo-mineral complexes. Application of phosphatic fertilizers may be required in old cocoa systems to maintain yields.

The nutrient concentrations of litterfall depend on the availability in the soil and/or the uptake capacity of the plants. However except for N, litter nutrition had no effect on subsequent litter decomposition rates as elemental nutrient concentrations in litterfall was not significantly correlated with decomposition coefficients ($P>0.05$). Thus in this study, soil physico-chemical properties which remained relatively stable did not influence litter nutrient concentrations or decomposition rates.

Conclusions

As hypothesized, rate of litterfall production and stand litter increased along the chronosequence, and forest and mature (15 and 30-year-old) cocoa systems exhibited higher annual litterfall production and standing litter pools compared to the 3-year-old cocoa systems. These changes may suppress nutrient cycles in cocoa sites but may also facilitate the slow release of nitrogen during litter decomposition. In this study, the decomposition rates of different litter types did not vary significantly between aged cocoa systems, however, rates of decomposition for all litter types were considerably more rapid in the forest sites than in the cocoa systems. The variation in annual decomposition coefficient (k_L) values between forest and cocoa systems may be a reflection of structural, thus litter quality, differences. This illustrates the importance of litter attributes over other biological or physical factors in determining the rate of decomposition in cocoa ecosystems. These findings confirm our hypotheses that forest conversion to cocoa land-use results in a reduction in decomposition rates due to litter quality changes.

Management strategies involving the introduction of upper canopy species during plantation development with corresponding replacement of tree mortality with diverse fast growing species will provide high quality and quantity litter resources. Furthermore, the trends in litter decomposition found in this study suggest the need for future research on in-situ mineralization and nutrient uptake studies as well as an assessment of changes in local microbial decomposer community following forest clearing. This will allow for a complete model and comprehensive understanding of nutrient cycling within these low external input agroforestry systems.

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