MATERIALS AND METHODS

Litterfall production

Ten litter traps 1 m x 1 m, 50 cm high above the ground were installed at 20 subplots on each plot. Litter was collected monthly intervals from the traps for one year (March 2005 – February 2006). The litter was taken to the laboratory and dried to a constant dry weight at 80ºC before being categorized into leaf, woody (small branches and bark), and reproductive parts. The components were weighed separately and total litterfall was obtained by weighing the total dry weight.

Soil surface litter (SSL)

Soil surface litter was taken from each plot by using 50 cm x 50 cm quadrangle. Soil surface litter samples were taken four times in a year. At each collecting time, twenty-five of SSL samples were collected randomly in each plot. The SSL was taken to the laboratory and dried to a constant dry weight at 80ºC.

Leaf-litter decomposition

The decomposition was evaluated by using the litter bag technique. The litter bags (10 cm x 20 cm) were constructed from nylonet (1 mm^2 opening screen). Five grams of dried fallen intact leaves was placed in each bags. The bags were pinned to the ground under the trees. One litter bag from each plot was harvested each month during three months incubation, twice in 12 months. First period and second period were done from March to June 2005 and September to December 2005 respectively. After three months incubation in each period, the collected litter bags were taken to the laboratory, and dried to a constant dry weight at 80° C to determine the percentage of the mass remaining. Nitrogen and organic carbon content in initial leaf-litter and mass remaining of leaf-litter were determined by the Kjeldahl for nitrogen content, whereas organic carbon content with the Walkley and Black method.

The mass loss over time was fitted with a simple exponential curve. The decay-rate coefficient, *k,* for the rate of decomposition as outlined in Olson (1963).

$$\ln (X_t/X_O) = -kt$$

where X_t is the amount of leaf-litter after time, t, t is the time (month), X_O is the original mass leaf-litter, and k is the decay rate coefficient.

The total amount of nutrient released in relation to total amount of litter produced at each study site was calculated from the amount of litter decomposed from time t_O to t and nutrient content associated with decomposed litter at t_O and t time, as follows (Kamaljit et al. 2006) :

$Y_O = X_O$ x initial nutrient concentration

where, Y_O is amount of nutrients at time t_O in litter, X_O is amount of litter at time t_O. At time t, amount of remaining litter = X_t.

Thus the nutrient content at time t in the remaining litter (Y_t):

$Y_t = X_t$ x nutrient content at t

The amount of nutrient released during t_O to t time = $Y_O - Y_t$

Fine roots biomass (living fine root)

Root samples were taken four times in 1 year (March, June, September, and December 2005) with a soil corer (3.5 cm in diameter) from surface mineral soil down to 15 cm soil depth. The soil from core method was used to extract volume-based fine roots samples (< 2 mm in diameter). It was done in each study site with 25 replications at each time sampling, yielding 4 plots x 4 time sampling x 25 replications = 400 samples. The soil samples were soaked in water and cleaned from soil residues using a sieve with a mesh size of 2 mm. Large root fractions (> 2 mm in diameter) were extracted by hand. Only live fine root of trees (roots < 2 mm in diameter) were considered for analysis. The fine root samples were sorted under stereomicroscope for live fine roots (biomass) and dead, tree and non-tree roots, and diameter. Fine roots biomass was dried to a constant dry weight at 70° C to determine dry weight.

Periodic curve fitting

Periodic curve fitting can be applied for periodic data when the observations are equally spaced a complete cycle (daily, weekly, or yearly cycles). Technically, periodic curve referred to as harmonics (Little and Hills 1977). In this study, periodic curve fitting would be applied for data of monthly litterfall and climates (precipitation, temperature, air humidity, and wind speed).

Fitting a periodic curve we need two P values called PU_i ($\sum U_iY$) and PV ($\sum V_iY$) where:

Y is monthly litterfall and monthly climates,

U_i is cosCX, V_i is sinCX (X is month, which January was called month 0, February month number 1, etc., C = 1/12 x 360º).

Periodic curve need PU_1, PV_1 for first degree curve and PU_2, PV_2 for second degree curve. The equation of first degree curve is

$$\hat{Y}_1 = a_0 + a_1 \cos CX + b_1 \sin CX$$

Where $a_0 = \sum Y/n$

$a_1 = 2\ PU_1/n$

$b_1 = 2\ PV_1/n$

The second degree equation is

$$\hat{Y}_2 = a_0 + a_1 \cos CX + b_1 \sin CX + a_2 \cos 2CX + b_2 \sin 2CX$$

Where $a_2 = 2\ PU_2/n$

$b_2 = 2\ PV_2/n$

Periodic curve consists of month (X-axis) and deviation of mean (Y-axis). The deviation of mean is deviation of the second degree values from each parameter.

Data analysis

Data on litterfall production, and fine roots biomass, leaf-litter decomposition and C and N release were analyzed using general linear models (GLMs). All post hoc tests were carried out using Tukey-tests. The standard level of significance was $p < 0.05$. All analyses were done using SPSS 13.0 software. To investigate relationship between parameters were analyzed using regression and Pearson's correlation analysis.

RESULTS

Litterfall production

Monthly litterfall production among study sites is depicted in Figure 4.1. Total annual litterfall varied significantly among land-use types ($p < 0.05$, Tukey-test). The greatest litterfall was recorded under the NF, that was 1367.4 g m^{-2} y^{-1} and the lowest litterfall was 497.7 g m^{-2} y^{-1} under CF2 (Figure 4.2).

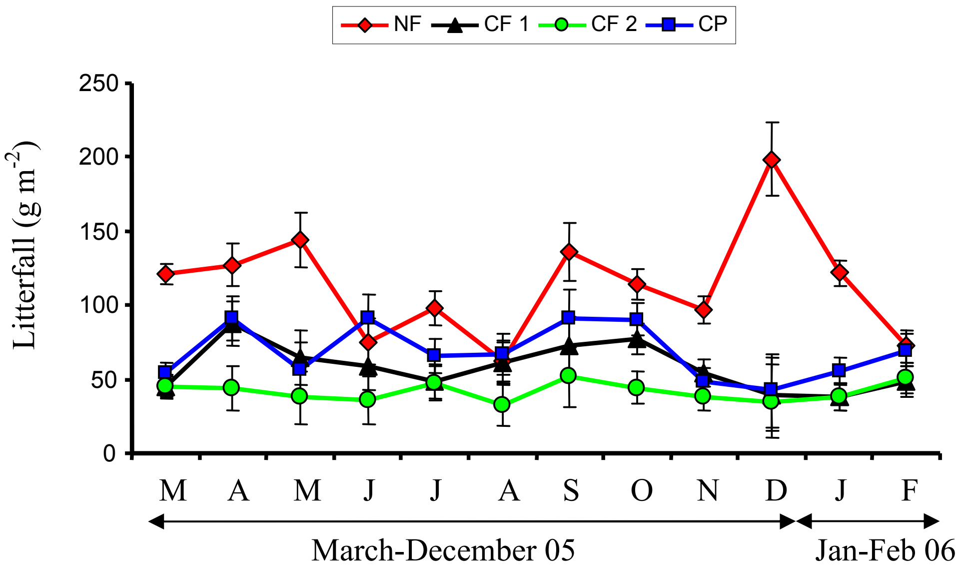


Figure 4.1. Monthly litterfall (g m^{-2} $month^{-1}$) in the natural forest (NF) and the cacao agroforestry systems (CF1, CF2, and CP) from March 2005 to February 2006. Bars represent mean ± SE.

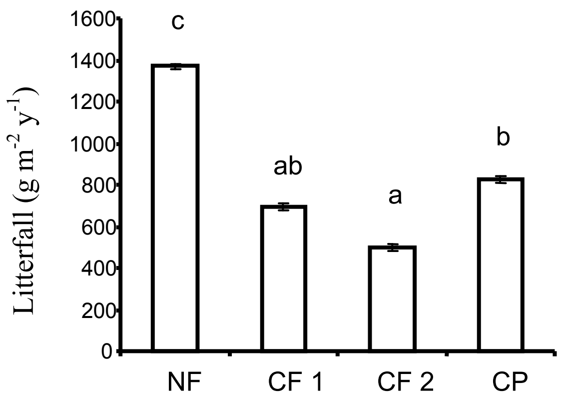


Figure 4.2. Annual litterfall in the natural forest (NF) and cacao agroforestry systems (CF1, CF2, and CP). Data represent mean ± SE. Different letters indicate significantly different (Tukey-test, $p < 0.05$).

Contribution of various litter components such as leaf-litter, woody-litter and reproductive parts to the total litterfall of all study sites are given in Table 4.1. The composition order of litter as followed the leaves > stems > fruits. Leaf-litter was the predominant litter component averaged from 76.5 to 83.5%. The high contribution of leaf-litter (95.8%) to the total litterfall was recorded under the NF and CF2 systems. The lowest leaf-litter component (89%) was recorded in the cacao agroforestry system CP. Leaf-litter under NF was higher than those under cacao agroforestry systems ($p < 0.05$) similar pattern was also exhibited by stem-litter. But, fruit-litter of NF was not different ($p > 0.05$) from those under cacao agroforestry systems.

Table 4.1. Contribution and ranged (minimum – maximum) of litter components (%) (March 2005 to February 2006) in the natural forest (NF) and the cacao agroforestry systems (CF1, CF2, and CP).

Land-use types	Leaf		Stem		Fruit	
	Min.-max. (%)	**Mean (g m^{-2}) ± 1 SE**	**Min.-max. (%)**	**Mean (g m^{-2}) ± 1 SE**	**Min.-max. (%)**	**Mean (g m^{-2}) ± 1 SE**
NF	**72.0 – 95.8**	**190.4±4.3^{b}**	**2.6 – 36.3**	**64.5±3.2^{b}**	**0.7 – 16.1**	**7.0±2.8^{a}**
CF1	**72.3 – 91.8**	**100.3±4.3^{a}**	**2.9 – 19.3**	**12.9±3.2^{a}**	**0.3 – 22.9**	**14.9±2.8^{a}**
CF2	**41.9 – 95.8**	**75.6±4.3^{a}**	**2.6 – 41.9**	**11.5±3.2^{a}**	**0.7 – 16.1**	**3.0±2.8^{a}**
CP	**46.3 – 89.0**	**121.1±4.3^{a}**	**9.7 – 28.6**	**25.9±3.2^{a}**	**0.0 – 43.8**	**11.0±2.8^{a}**

Values followed by different superscript(s) in the same column indicate significant difference. Significance of Tukey-test given at $p < 0.05$. Values are mean ± SE.

Annual litterfall production was influenced by basal area, canopy cover, and tree density were shown in the Figure 4.3 A, B and, C respectively. Litterfall generally tended to increase with increasing basal area, canopy cover, and tree density.

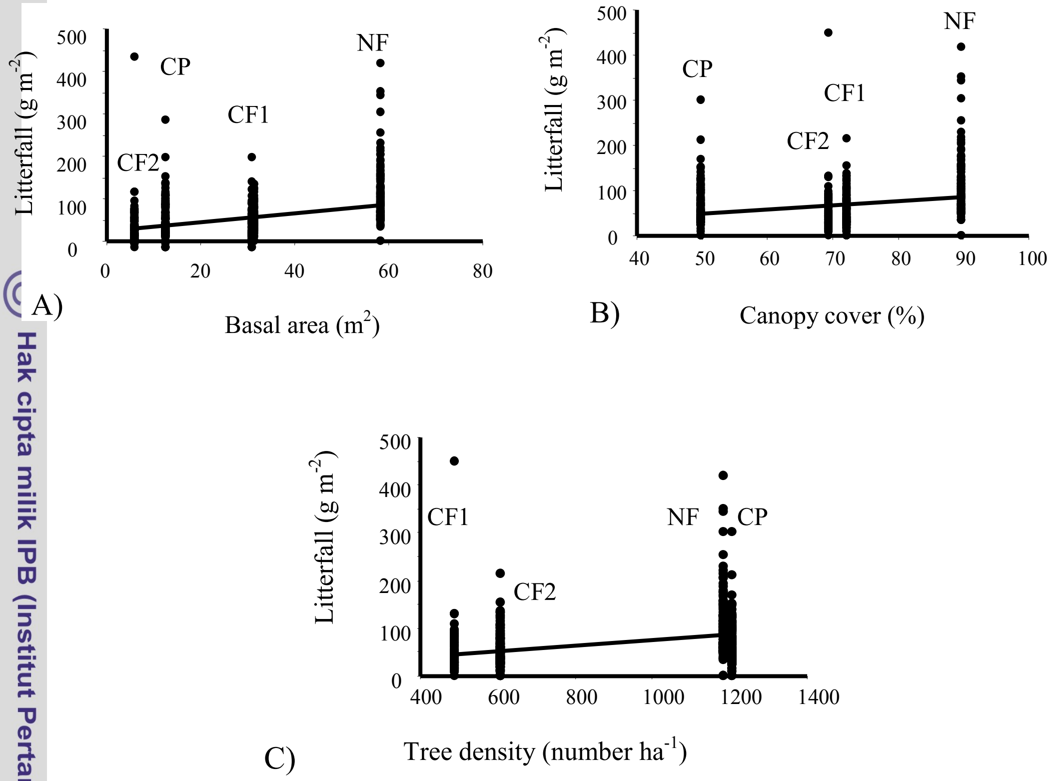


Figure 4.3. Litterfall (g m^{-2}) in the natural forest (NF) and cacao agroforestry systems (CF1, CF2, and CP) in relation to A) basal area, B) canopy cover, and C) tree density.

Periodic curve of the monthly litterfall and several recorded climatic factors (temperature, precipitation, air humidity, and wind speed) are shown in Figure 4.4. When the periodic curves in a period of 12 months of monthly litterfall, and recorded climate factors (temperature, precipitation, air humidity, and wind speed) were superimposed, the following analyses may be made: (1) the climatic factors (temperature, precipitation, air humidity, and wind speed) modified each other producing a peculiar impacts on the litterfall, (2) during a year period may be differentiated into a period of high air humidity (January to July) and a period of low air humidity (July to November), (3) the dry period was characterized by cold and dry air with high wind speed and low rainfall, (4) the wet period was warm humid air with low wind speed and high rainfall, (5) high litterfall production occurred during low air humidity, high wind speed and high temperature, (6) cacao agroforestry system modified the time of maximum litterfall production. Another lower peak of litter which occurred even during wet period maybe due to the leaf age.

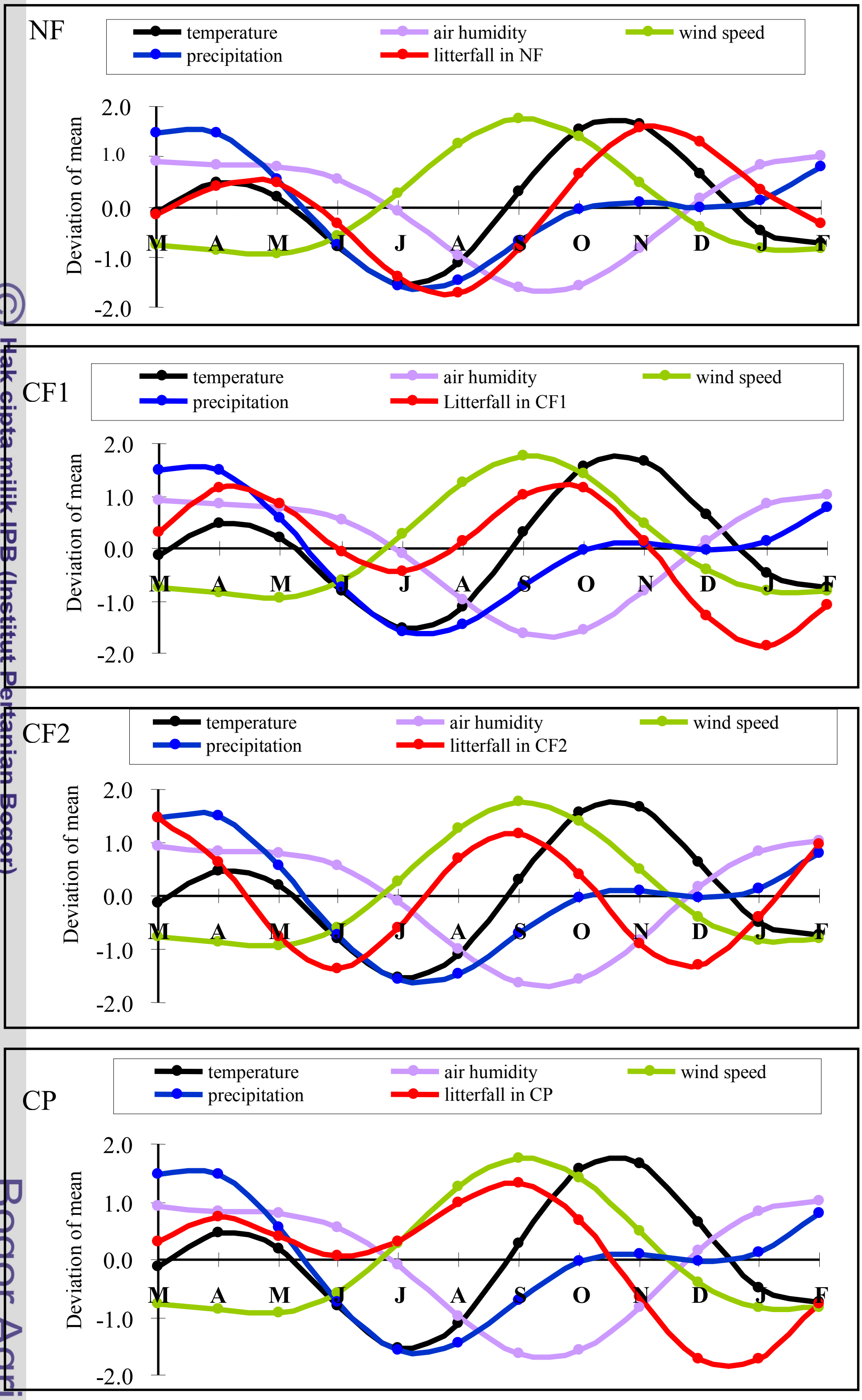


Figure 4.4. Periodic curve of monthly litterfall and several recorded climatic factors (temperature, precipitation, air humidity, and wind speed) in the natural forest (NF) and cacao agroforestry systems (CF1, CF2, and CP).

Figure 4.5 shows that annual soil surface litter (SSL) was significantly different among land use types (p < 0.05). Natural forest had the highest SSL (1858.02 g m^{-2}). Among these cacao agroforestry, that under CP had the highest SSL (907.28 g m^{-2}). Soil surface litter under CF1 and CF2 were 764.26 and 907.28 g m^{-2} respectively.

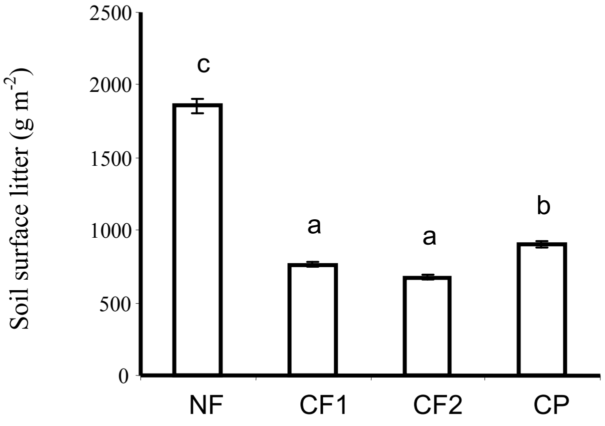
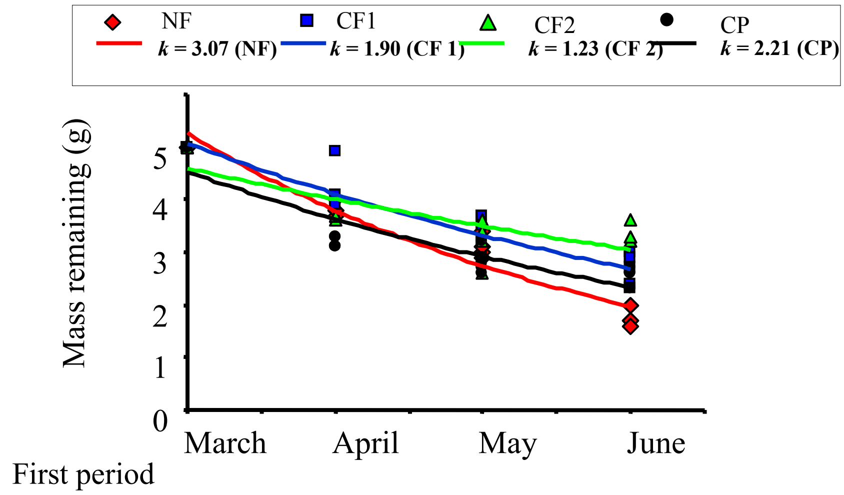


Figure 4.5. Annual soil surface litter in the natural forest (NF) and cacao agroforestry systems (CF1, CF2, and CP). Data represent mean ± SE. Different letters indicate significantly different (Tukey-test, $p < 0.05$).

Leaf-litter decomposition

Leaf-litter decomposition rates depend on litter and land-use types. The relationship of quantity of litter mass remaining and time was determined by an exponential function (Figure 4.6 and Table 4.2). The mass remaining during three months incubation in the first period revealed different pattern among study sites.



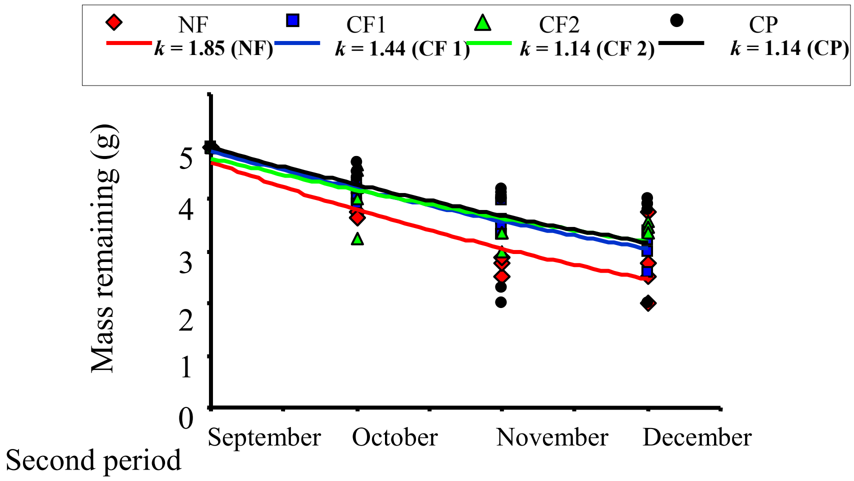


Figure 4.6. Exponential curve of leaf-litter mass remaining (g) in two periods decomposition periods in the natural forest (NF) and cacao agroforestry systems (CF1, CF2, and CP), (A) first period: March to June 2005, (B) second period: September to December 2005.

Table 4.2. Regression and correlation of exponential curve of leaf-litter mass remaining (g) with time of incubation in leaf-litter decomposition at first period (March to June 2005) and second period (September to December 2005).

Land-use types	First period (March to June)					Second period (September to December)				
	Regression			Correlation		Regression			Correlation	
	r^2	*p*	Equation	r (Pearson's)	*p*	r^2	*p*	Equation	r (Pearson's)	*p*
NF	0.92*	2.1×10^{-11}	$y = 280.7.e^{-0.33\,x}$	-0.98**	3.6×10^{-15}	0.76*	5.4×10^{-7}	$y = 660.6.e^{-0.22\,x}$	-0.88**	2.7×10^{-7}
CF1	0.89*	4.6×10^{-10}	$y = 191.6.e^{-0.21\,x}$	-0.95**	9.5×10^{-11}	0.88*	4.3×10^{-10}	$y = 416.6.e^{-0.16\,x}$	-0.95**	1.4×10^{-10}
CF2	0.68*	6.9×10^{-6}	$y = 138.4.e^{-0.14\,x}$	-0.84**	4.0×10^{-6}	0.70*	3.9×10^{-6}	$y = 327.5.e^{-0.14\,x}$	-0.85**	2.0×10^{-6}
CP	0.85*	8.3×10^{-9}	$y = 175.3.e^{-0.22\,x}$	-0.89**	7.7×10^{-8}	0.36	0.06	ns	-0.68**	0.0009

** on Pearson's r indicated significantly different given at $p < 0.01$
* on r^2 indicated significantly different given at $p < 0.05$
ns = not significantly different
y = leaf-litter mass remaining (g)
x = time (month)

Table 4.3. Leaf-litter mass remaining and decay-rate coefficient (*k*) in the natural forest (NF) and cacao agroforestry systems (CF1, CF2, and CP).

Land-use types	Mass remaining (%) after 3 months		*k* after 3 months	
	First period	Second period	First period	Second period
NF	36.0±1.7[a]	55.0±5.7[a]	3.07±0.14[c]	1.85±0.30[a]
CF1	53.2±2.7[b]	62.0±2.8[a]	1.90±0.15[b]	1.44±0.14[a]
CF2	66.4±1.5[c]	68.3±0.8[ab]	1.23±0.06[a]	1.14±0.03[a]
CP	50.0±1.7[b]	70.4±7.6[b]	2.21±0.1o[b]	1.14±0.40[a]

First period: March to June 2005, second period: September to December 2005. Different superscript(s) on the same column indicate significant differences. Values are mean ± SE. Significance of Tukey-test given at $p < 0.05$.

The rate decrease of the mass remaining under NF was faster than those of cacao agroforestry systems during the first period. The rate of decrease of the mass remaining of cacao agroforestry system under CP was faster than those of other cacao agroforestry systems, however, in the second period, the decrease rate of the mass remaining was not statistically different. Decay-rate coefficient (*k*) of decomposing leaf-litter is presented in Table 4.3. The decay-rate coefficient of leaf-litter during the first period, NF was the highest ($p < 0.05$) among the land use system, the decay-rate coefficient of leaf-litter from CF1 and CP did not differ, and CF2 showed the lowest value (1.23). On the other hand the decay-rate coefficient of leaf-litter in the second period from all land use types did not differ significantly.

Table 4.4. The percentage of carbon, nitrogen and C/N ratio in the initial and the end of leaf-litter decomposition, first period (March to June 2005), second period (September to December 2005).

	NF			CF1			CF2			CP		
	C (%)	N (%)	C/N	C (%)	N (%)	C/N	C (%)	N (%)	C/N	C (%)	N (%)	C/N
First period												
March	34.5±0 ^{pq}	1.3±0 ^{Q}	27.6±0 ^{m}	31.3±0 ^{p}	0.9±0 ^{P}	32.2±0 ^{mn}	30.7±0 ^{p}	0.9±0 ^{P}	31.3±0 ^{mn}	38.1±0 ^{q}	1.0±0 ^{P}	36.3±0 ^{n}
June	35.4±1.2 ^{b}	0.8±0.3b ^{A}	42.7±2.1$^{\beta}$	31.1±0.4 ^{a}	0.9±0.2^{A}	33.9±1.3$^{\alpha}$	34.4±2.3 ^{b}	0.8±0.02^{A}	43.4±2.3$^{\beta}$	35.6±1.9^{b}	1.1±0.02^{B}	32.7±1.7$^{\alpha}$
Second period												
September	28.6 ± 0 ^{b}	0.7± 0 ^{A}	41.4 ± 0$^{\beta}$	24.3 ± 0 ^{a}	0.8 ± 0 ^{A}	30.4±0 $^{\alpha}$	29.5± 0 ^{b}	0.8±0 ^{A}	37.7±0 $^{\beta}$	31.0±0 ^{b}	0.8±0 ^{A}	37.8±0 $^{\beta}$
December	29.8±1.8 ^{b}	0.9±0.05 ^{A}	33.1±1.8$^{\beta}$	30.8±0.8 ^{b}	0.9±0.07^{A}	32.2±0.8$^{\beta}$	28.4±1.8^{ab}	0.8±0.01^{A}	33.7±1.8$^{\beta}$	26.3±0.7^{a}	0.8±0.05^{A}	31.8±0.7$^{\alpha}$

Different superscript(s) on the same variable indicate significantly different. Values are mean ± SE. Significance of Tukey-test given at $p < 0.05$.

Table 4.4 shows the percent of organic carbon, nitrogen and C/N ratio in the initial and the end of leaf-litter decomposition. The C/N ratio in cacao agroforestry CP sharply decreased in June. On the other hand, C/N ratio in NF, CF1, and CF2 sharply increased in June and significantly different ($p < 0.05$). Although in the second period, C/N ratio revealed the same pattern in all land-use types, however, it was significantly different ($p < 0.05$). The C/N ratio decreased in December in the NF and the cacao agroforestry CF1, CF2, and CP. The different pattern of C/N ratio between two periods was influenced by seasonal differences.

Nutrient released

Based upon the content of nutrient (carbon and nitrogen) remaining in the litter, there was a release of carbon and nitrogen as decomposition proceeded in all study sites (Figure 4.7).

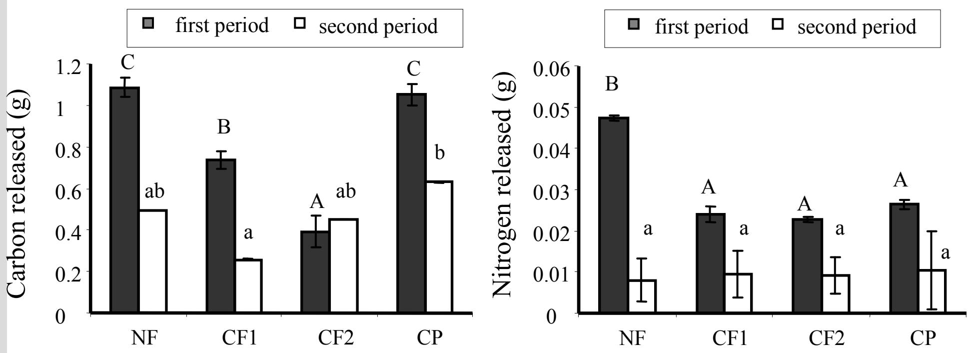


Figure 4.7. The amount of carbon and nitrogen released (g) in two periods decomposition in natural forest (NF) and cacao agroforestry systems (CF1, CF2, and CP).
First period (March-June 2005), second period (September-December 2005). Value represent mean ± SE. Different letters indicate significantly different (Tukey-test, $p < 0.05$).

The amount of carbon released in first and second period was significantly different ($p < 0.05$) in all land use types. The carbon released under NF (1.08 g/5 g leaf-litter) similar to that under CP (1.05 g/5 g leaf-litter), while under CF1 was 0.73 g/5 g leaf-litter and the lowest under CF2 (0.39 g/5 g leaf-litter). In the second period, carbon released under CF1 (0.26 g/5 g leaf-litter) and CP (0.63 g/5 g leaf-litter) was differ significantly, but under NF (0.49 g/5 g leaf-litter) and CF2 (0.45 g/5 g leaf-litter) did not significantly.

The nitrogen released in first period under NF (0.05 g/5 g leaf-litter) differed significantly and higher than CF1 (0.02 g/5 g leaf-litter), CF2 (0.02 g/5 g leaf-litter) and CP (0.03 g).The nitrogen released in second period was quite similar in NF (0.008 g/5 g leaf-litter) and cacao agroforestry systems (0.009 g, 0.009 g, 0.01 g/5 g leaf-litter respectively).

Fine root biomass

Fine roots biomass (FR) varied with times of sampling and land use systems ($p < 0.05$, Table 4.5). In the NF, FR decreased consistently with time from March to December. FR under cacao agroforestry systems of CF1 were constantly from March to September, and decreased only in December, while under CF2 increased from March to September and sharply decreased in December, and under CP showed a similar pattern to than under CF1 (Figure 4.8). The annual FR varied in all study sites, which were 13.66, 6.07, 16.53, and 7.4 g m^{-2} respectively ($p < 0.05$, Tukey–test, Figure 4.9).

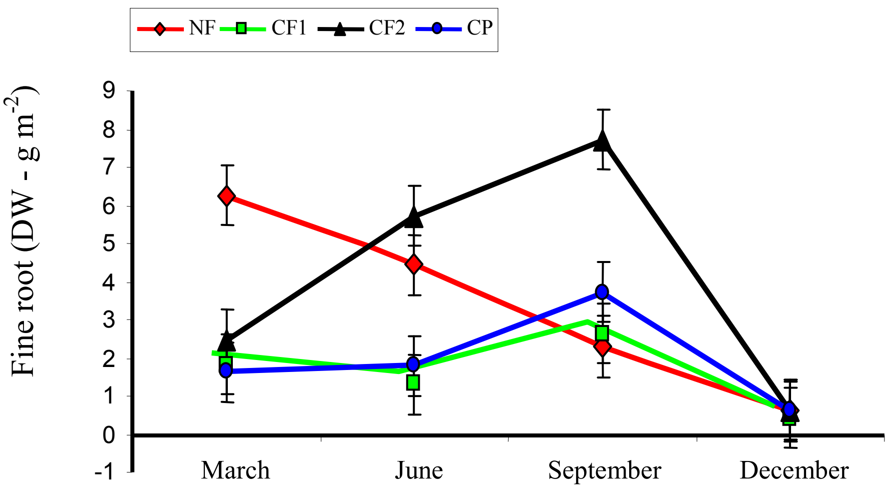


Figure 4.8. Seasonal distribution of fine roots biomass in natural forest (NF) and cacao agroforestry systems (CF1, CF2, and CP).

Table 4.5. Fine roots biomass (DW – g m^{-2}) sampled from four different land use types (NF, CF1, CF2, and CP).

	Fine roots biomass (DW – g m^{-2})			
	March	June	September	December
NF	6.26±0.02^{d}	4.45±0.01^{c}	2.29±0.01^{b}	0.64±0.004^{a}
CF1	1.83±0.01^{b}	1.30±0.02^{b}	2.63±0.01^{b}	0.42±0.004^{a}
CF2	2.47±0.01^{b}	5.71±0.02^{c}	7.72±0.02^{e}	0.62±0.004^{a}
CP	1.63±0.01^{b}	1.78±0.03^{b}	3.72±0.01^{bc}	0.59±0.004^{a}

Numbers (mean ± SE) followed by different letter indicate significant difference (Tukey-test, $p < 0.05$).

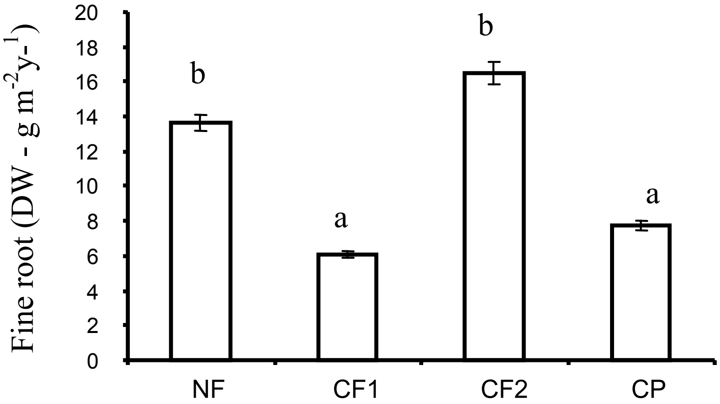


Figure 4. 9. Annual fine roots biomass (g m^{-2} y^{-1}) under different land use types (NF, CF1, CF2, and CP). Values are mean ± SE, different letters indicate significantly different among study sites (Tukey-test, $p < 0.05$).

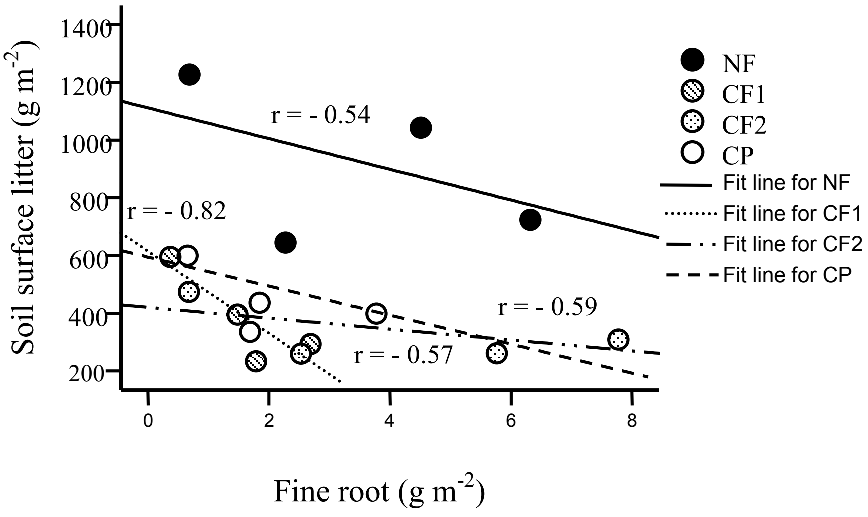


Figure 4.10. The relationship of fine roots biomass with soil surface litter in the natural forest (NF) and cacao agroforestry systems (CF1, CF2, and CP).

The FR in relation to SSL was shown in Figure 4.10. The correlation between fine root biomass with SSL was a negatively significant (Pearson's r = - 0.54, - 0.82, - 0.6, and - 0.58). It means that lower fine root biomass was correlated with higher soil surface litter.

DISCUSSIONS

Annual litterfall in this study (NF, CF1, CF2, and CP) were 1367.4, 693.4, 497.7, and 822.9 g m^{-2} respectively. The tree density (number ha^{-1}) in the study sites were 1184, 608, 488, and 1208, respectively. The number of tree in cacao agroforestry system under CP was greater than that in the NF, on the contrary; litterfall production in the NF was greater than that in cacao agroforestry system under CP, because trees in the NF were bigger than that in CP as reflected by the value of basal area, which were 58.4, 31.5, 6.6, and 13.2 for NF, CF2, CF2, and CP. Basal area is reflected tree size, stand volume and biomass, therefore NF had a higher litterfall production. The tree density in the cacao agroforestry systems under CF1 and CF2 were lower than those in the NF or cacao agroforestry system CP, therefore their litterfall were also lower than those the NF and CP. In this study, increasing litterfall production was influenced by basal area, canopy cover, and tree density.

This study showed that the monthly litterfall production at four studied sites was influenced by interactions of monthly climatic factors (Figure 4.4). In the natural forest and cacao agroforestry systems high litterfall coincided with low air humidity, high wind, and high temperature. It seems that atmospheric conditions are more of the proximate cue for leaf fall, rather than that of rainfall and soil drought. Similar observations were reported by (Wright 1996) in tropical forest of western Africa. The possible mechanism is that increases in potential evapotranspiration during low air humidity, may create temporary water deficits that trigger abscission of senescent leaves. This also could trigger bud break, particularly in species where bud break is suppressed by the presence of old leaves (Wright 1996).

The contribution of leaf-litter to the total litterfall was greater in the NF and cacao agroforestry system under CF2 that is 95.82% (Table 4.2). The lowest leaf-litter component was in the cacao agroforestry system under CP that is 89.0%. Leaf-litter constituted a substantial portion of total litter production in the present study, which is also in agreement with the results of others (Morellato 1992, Scott et al. 1992, Khiewtam and Ramakrishnan 1993, Muoghalu et al. 1993, Visalakshi 1993, Stocker et al. 1995, Sundarapandian and Swamy 1999). According to Bray and Gorham (1964), O'Neill and DeAngelis (1980), on the average, the leaf-litter is ≈ 70% of fine litterfall, and the woody component of total litterfall is heterogeneous both spatially and temporarily (Vitousek 1984). The significantly higher leaf-litter and stem-litter in study sites reflected vegetation growth in the tropic. Fruit-litter did not differ significantly as cacao fruit was harvested and taken out of the system.

Leaves and other organic materials fall to the ground and decompose to form SSL (Mund 2004). The amount of annual SSL reflected the amount of annual litterfall production in this study. The litterfall and SSL were the highest in the NF. Among cacao agroforestry systems, the CP had the highest litterfall production as well as the SSL.

The breakdown of the leaf-litter varied among forest systems (Attignon et al. 2004). In this present study, the remaining mass of the leaf-litter during decomposition decreased with the increasing incubation time similar result was reported by Alhamd et al. (2004). Gillon et al. (1994) reported that decomposing leaf-litter is influenced by the internal physicochemical properties of the substrate and by the environmental factors under which decomposition takes place. The initial C/N ratio of leaf-litter during three months incubation in the NF, CF1, CF2 and CP were 27.6, 32.2, 31.3, and 36.3 respectively. These figures were lower than those reported by Sangha et al. (2006). The higher C/N ratio of litter indicates low quality and therefore, low decomposability (Torreta and Takeda 1999, Beck 2000, Xuluc-Tolosa et al. 2003). When C/N ratio is higher than 30-40, microbial activity is significantly reduced, leading to N-immobilization and impeded decomposition (Torreta and Takeda 1999). The initial C/N ratio of leaf-litter in the first and second period were more than 30, except in the NF in the first period.

In this present study, during the first two months in each period of incubation decomposing rate was faster; thereafter, followed by slower rate. This could be due to a higher initial content of water-soluble materials, simple substrates that were easily decomposed by, especially microflora (Songwe et al. 1995). The relatively slower rate may be due to the accumulation of more recalcitrant constituents in the residual litter mass (Sundarapandian and Swamy 1999). The higher rate of loss of mass during the first period than second period (Table 4.3) was due to environment factors. The first period (March to June) was wet period (low temperature, high precipitation and high air humidity), on the contrary the rate of mass loss in second period was lower as this the dry period (September to December) (Figure 4.4). Facelli and Pickett (1991) stated that activity of decomposers were affected by environment factors particularly soil moisture, temperature and evapotranspiration.

The decomposition rate of leaf-litter is controlled by the interacting influences of the soil physicochemical environment, decomposers organisms, and the quality of leaf-litter (Berg and McClaugherty 2003, Mitchell et al. 2005). Comparison of decay rate coefficient (*k*), however; may be confounded by differences in the length of the decomposition period. Extrapolation of decay rate coefficient from short decomposition period yields a higher *k* values than that the extrapolation from long period (Lisane and Michelsen 1994). There were studies of short duration range from 98 days (Tian et al. 1998) to 180 days (Yamashita and Takeda 1998), and those of long duration usually extend over more one year (Loranger et al. 2002). The decay rate coefficient, *k*, varied significantly among litter collected from different land use types, during the first period of incubation, ranging from 1.23 to 3.07. With the decomposition period of 90 days, our result was better compared to that from short-term studied by Sundarapandian and Swamy (1999) in tropical forest in India, but lower than reported by Attignon et al. (2004) in rainforest West African. According to Verhoef and Gunadi (2001) that the value of decay rate coefficient in this study was medium to high (k = 1 - 3). The annual decay rate coefficient of temperate hardwood species ranged from 0.08 to 0.47 (Melillo et al. 1982), subtropical forest ranged from 0.66 to 1.09 (Alhamd 2004), and Mediterranean ecosystem ranged from 0.30 to 0.75 (Fioretto et al. 2005). Alvarez et al. (1992) reported that in the tropical forest, *k* values were often greater than 1.0, indicating that leaf-litter turnover occurred in a year or less than a year. The varying *k* value seemed due to the nutrient content of leaves (Songwe et al. 1995). The large differences in *k* value could be attributed to decomposer population dynamics (Kumar and Deepu 1992).

As decomposers, microbes are a key factor in nutrient cycling in ecosystems. The main source of energy for microbial life in soil is organic matter. The quantity and the quality of the organic matter in a certain ecosystem determine the population and activity of the soil microbes. Anas et al. (2005) reported that soil microbial population in the NF was rather low (18,180 cfu g^{-1}), but the soil microbial respiration was high (7.1 mg CO_2-C kg^{-1}). The highest soil microbial population occurred in CF1 (362,108 cfu g^{-1}) with soil microbial respiration quite similar to the NF, that was 7.3 mg CO_2-C kg^{-1}. This information supports the fact that leaf-litter decomposition in the NF was faster than those of cacao agroforestry systems.

The highest initial nitrogen concentration had the highest decomposition rate (Alhamd et al. 2004), however; in the present study their initial nitrogen concentration did not reflect decay-rate coefficient. During decomposition, carbon is used as an energy source by decomposers while nitrogen is assimilated into cell proteins which is essential for microbial function, thus a higher nitrogen concentration in the leaves promotes decomposition (Singh and Gupta 1977). In the present study, the initial C/N ratio in all study sites in two periods incubation was greater than 20. If the ratio of C/N is below 20 or the N concentration is above 2.5%, nitrogen will be released and the material decomposes rapidly. If C/N is much greater than 20, nitrogen is likely to be immobilized until decomposition and respiration is lower than the C/N ratio (Heal et al. 1997). The C/N ratio at the end of the two periods incubation increased, except in the cacao agroforestry under CP. Overall, the organic carbon and nitrogen content in litter mass remaining during three months decomposition period was higher than that at the beginning of the experiment, except in the cacao agroforestry system under CP. This result was similar with that conducted by Sangha et al. (2006). They reported that there was no carbon and nitrogen released when both nutrients content tended to raise during decomposition.

During litter decomposition, microbes convert organic carbon into total CO_2. This process also releases nutrient in various forms, for example NH_4^+, N_2, and PO_4^{3-} (Murray et al. 2005). The highest carbon and nitrogen released in the first period in the NF indicate that the microclimate in those site trigger litter decomposition and nutrient release. Decomposition of litter and release of nutrients not only depends upon litter composition but also upon soil type, microbial communities, incubation time, and soil properties (Sangha et al. 2006). Microbial and other decomposition processes depend upon the type of material available for decomposition and on other factors such as climate and water availability (Bardgett et al. 1999). Thus, the quality of litter influences microbial processes and nutrient retention in a system. The effects of soil properties, for example water availability or pH, on litter decomposition or on growth of particular microbes and their activities responsible for litter decomposition, vary with seasons and can play an important role in moderating nutrient return to a system (Sangha et al. 2006).

Fine root biomass under NF decreased steadily from March to December (Figure 4.8 and Table 5.5). This low FR in December in NF coincided with a high litter production. This condition supports the balance concept that FR only grows when enough energy available from shoot (leaves) and shoot only grows when enough water and nutrient supplied by root (FR). The month of December in this experiment was dry month. Less water was available for FR to absorb and less water to support the growth of shoot, and shoot (leaves) must be shaded to produce high litterfall. In turn this high litterfall will not produce enough energy to support the growth of FR. FR under agroforestry systems of CF1 and CP was relatively low compared to that under NF. The rate of uptake must be lower than that of NF. Assuming the capacity of soil water stored under the area was similar, less FR density of CF1 and CP (1.83 and 1.63 g m^{-2}) will absorb less water than NF (6.26 g m^{-2}) and lengthen the supply for about more six month, counted from March, when the capacity of soil water status was similar. In September, the amount of FR under NF, CF1, and CP were similar and all decreased consistently in December at the same extent. Under CF2, however was different. This was so, because the area was dominated by grasses mainly *Imperata cylindrica* which grew prolifically when moisture available, but succumb to dryness in December, because soil moisture was very low.

CONCLUSIONS

Annual litterfall varied among land-use types. Natural forest had the highest annual litterfall (1367.6 g m^{-2} y^{-1}), while among cacao agroforestry systems; cacao agroforestry system without forest cover but with planted shade trees (CP) had the highest annual litterfall (822.8 g m^{-2} y^{-1}). Monthly litterfall in natural forest and cacao agroforestry systems were influenced by climate.

Leaf was predominant litter component. The leaf-litter was ranged from 41.9 to 95.8% of total litterfall.

Natural forest had the highest coefficient of decomposition or the fastest rate of decomposition, whereas cacao agroforestry systems under local shade trees (CF2) had the lowest one.

Among cacao agroforestry systems, cacao agroforestry system under local shade trees (CF2) had the highest fine root biomass, because it was infested by weed. The cacao agroforestry CF1 had the lowest fine root biomass.

Fine root biomass under NF decreased in the dry season (December) coincided with a high litterfall. Lower FR density under agroforestry systems lengthen the time to survive. Fine root biomass under CF2 increased steadily until September and decreased sharply in December.