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Research article

Temporal changes in litterfall and potential nutrient return in cocoa agroforestry systems under organic and conventional management, Ghana

Michael Asigbaase [a,b], Evans Dawoe [c,*], Barry H. Lomax [a], Sofie Sjogersten [a]

[a] Department of Agriculture and Environmental Science, School of Biosciences, University of Nottingham, Nottingham, UK
[b] Department of Forest Science, School of Natural Resources, University of Energy and Natural Resources, Suyani, Ghana
[c] Department of Agroforestry, Faculty of Renewable Natural Resources, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

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ABSTRACT

Litterfall is a critical link between vegetation and soils by which nutrients are returned to the soils, thus the amount and pattern of litterfall regulates nutrient cycling, soil fertility and primary productivity for most terrestrial ecosystems. We quantified, analyzed and compared macro- and micro-nutrients return through litterfall in organic and conventional cocoa agroforestry systems in Suhum, Ghana. We further assessed the contribution of shade tree species to litterfall and nutrient dynamics. The annual pattern of litterfall was affected by seasonality, with a major peak in the dry season and minor peaks during the rainy season. In terms of annual fractional litterfall, mean leaf litter from shade tree species was significantly higher (50 %) in organic systems (5.0 ± 0.5 Mg ha^{-1} yr^{-1}) compared to conventional systems (3.3 ± 0.6 Mg ha^{-1} yr^{-1}). Whereas cocoa leaves (45.0 %) were the predominant fraction of annual litterfall from conventional farms, both shade leaves (40.0 %) and cocoa leaves (39.4 %) dominated litterfall from organic farms. The return of primary macro-nutrients (P and K), secondary macro-nutrients (Ca, Mg and S) and micro-nutrients (Mn, B, Cu, Zn and Mo) via litterfall varied significantly with season, and annual return of nutrients were similar in organic and conventional cocoa systems. Shade tree leaf litter accounted for 30–47 % of annual macro- and micro-nutrient return (except Ni and Zn) in organic cocoa systems versus 20–35 % in conventional cocoa systems. The results emphasize the complementary role of the different shade tree species which compose organic and conventional cocoa systems in nutrient recycling. We conclude that organic management of cocoa agroforestry systems ensure nutrients return similar to those receiving synthetic fertilizer inputs, highlighting its potential to support cocoa production.

1. Introduction

The transfer of energy and nutrients between the biological and non-biological components of an ecosystem is crucial for its existence and resilience (Fontes et al., 2014; Hartemink, 2005; Owusu-Sekyere et al., 2006). Plant litter acts as an input-output system for organic matter and humus, thus influencing the soil quality of an ecosystem (Becker et al., 2015; Fontes et al., 2014; Ofori-Frimpong et al., 2007; Hartemink, 2005). Litterfall and its attendant processes such as decomposition and nutrient mineralization are key components of the plant-soil system (Becker et al., 2015; Kumar, 2008). Therefore, understanding the dynamics of litterfall in cocoa agroforestry systems is a critical step in promoting management approaches which enhance the functioning of these systems.

The primary sources of litter in cocoa agroforestry systems are the cocoa and shade trees. The amount of litter produced in cocoa agroforestry systems is moderated by tree species type, density, basal area, and canopy cover (Mamani-Pati et al., 2012; Triadiati et al., 2011).

Litterfall production in ecosystems is strongly related to rainfall seasonality, with the dry and rainy seasons being the peak periods of litterfall in stands under climates with and without dry a season (Becker et al., 2015; Muoghalu and Odiwe, 2011; Owusu-Sekyere et al., 2006). Specifically, low air humidity, high temperature and their interaction moderate litterfall production in cocoa agroforestry systems by stimulating abscisic acid synthesis (Dawoe et al., 2010; Triadiati et al., 2011; Yang et al., 2003). Leaf litterfall is also affected by elevation, wind and foliar diseases (Becker et al., 2015; Mamani-Pati et al., 2012).

The amount and quality of litter produced in an ecosystem depends on soil quality and management (Domínguez et al., 2014; Kumar, 2008; Muoghalu and Odiwe, 2011). Stands on fertile soils produce greater

* Corresponding author.
E-mail address: elkdawoe.canr@knust.edu.gh (E. Dawoe).

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amount of high-quality litter when compared to stands on poor soils due to higher biomass production and/or low rate of nutrient resorption from litter before abscission (Fontes et al., 2014; Kumar, 2008). Wood et al. (2007) asserted that soil fertility is positively related to the amount of litterfall, leaf litter quality, the rate of decomposition and nutrient mineralization. Plants in natural systems, such as forests, depend solely on nutrient cycling to meet their nutritional needs thus nutrient supply rate and nutrient limitation are moderated via species composition and diversity and moisture supply (Becker et al., 2015; Kumar, 2008; Wood et al., 2007). However, in agroforestry systems such as cocoa agroforestry, the management approach affects litter decomposition, which in turn, enhances or reduces nutrient supply rate through nutrient cycling (Becker et al., 2015; Fontes et al., 2014; Ofori-Frimpong et al., 2007). For example, non-synthetic agrochemical use was enough to enhance litter decomposition and nutrient mineralization in organic systems compared to conventional systems due to the presence of more well adapted decomposer communities in organic systems (Domínguez et al., 2014; Asigbaase et al., 2021a). Moreover, Muoghalu and Odiwe (2011) attributed greater accumulation of litter on the floor of cocoa stands than kola nut plantations to greater agrochemicals use in cocoa systems and differences in litter quality. In Tanzanian agroforestry systems, Becker et al. (2015) reported greater macronutrient content and return rates than natural forests and attributed the differences to fertilization and dominant tree species. Thus, dominant tree species in cocoa systems could regulate nutrient return.

Leaf litter is the major component of litterfall material in agroforestry systems, comprising more than 60 % of total annual litterfall (Fontes et al., 2014; Muoghalu and Odiwe, 2011). Cocoa leaf litter predominates leaf litterfall in cocoa agroforestry plantations (Dawoe et al., 2010) but inputs from the shade tree component can improve litter quality and enhance nutrient cycling in these systems. For example, litterfall from the middle and upper canopy strata are a mechanism for returning nutrients to the soil in certified organic coffee systems in Bolivia (Mamani-Pati et al., 2012). The shade trees enhance the capture of solar energy and at the same time increase the absorption and retention of carbon and nitrogen in both above- and below-ground components (Becker et al., 2015; Fontes et al., 2014; Hartemink, 2005; Ofori-Frimpong et al., 2007; Asigbaase et al., 2021a, b). Fallen leaves on the floor of agroforestry systems cover the soil and thereby maintain soil moisture, reduce erosion and serve as habitats for beneficial organisms (Mamani-Pati et al., 2012).

Cocoa in Ghana is mostly cultivated under a variety of shade trees and is either organically or conventionally managed. The conventional systems depend on synthetic agrochemicals to maintain soil fertility, suppress weeds and control pests and diseases whilst the organic systems rely on ecological processes and organic products for these services. Increasingly, there is a tilt towards the maintenance of high shade tree diversity on the organic farms because farmers perceive shade trees as a cheaper means to replenishing soil nutrients (Djokoto et al., 2016; Asigbaase et al., 2019). Many researchers (e.g., Dawoe et al., 2010; Muoghalu and Odiwe, 2011; Ofori-Frimpong et al., 2007; Owusu-Sekyere et al., 2006) have assessed nutrient returns through litter inputs in cocoa systems but studies focusing on organic and conventional cocoa systems are rare, especially in Africa. This makes it difficult to evaluate the impact of organic cocoa production on nutrient cycling. To address this knowledge gap, we quantified and analyzed the patterns of nutrient return/addition via litterfall in organic and conventional cocoa agroforestry systems. Specifically, we explored the effect of seasonality and farm management type (organic *versus* conventional) on litterfall and nutrient return, and the contribution of shade tree species to nutrient return via litterfall. We postulated that litterfall and nutrient return will follow a seasonal pattern with greater nutrient concentrations and stocks during the rainy seasons than the dry season. It was also posited that litterfall from shade tree species and their contribution to annual nutrient return will be greater on organic systems than conventional systems.

2. Methods

2.1. Description of study area

The study was conducted in Suhum Municipality (400 square kilometres), which is 60 km north-north-west of Accra (the capital of Ghana) 60° 5′ N and Longitude 00° 27′ W. Suhum is located within the Semi-deciduous forest zone but the original vegetation has been reduced to patches of secondary forests through anthropogenic activities such as agriculture. The mean annual temperature, precipitation, dry season relative humidity and wet season relative humidity range from 24-29 °C, 1270–1651 mm, 48–52 % and 87–91 % respectively. Rainfall in the study area is bimodal with the major rainy season beginning in March or April and continuing until mid-July; this is followed by a short dry period in July–August; a minor rainy season in September–October and then a long dry season (harmattan) from November to March. The major activity of Suhum municipality is rain-fed farming of subsistence and cash crops and cocoa production.

Certified organic cocoa farming was pioneered in Suhum thus it has the oldest organic farms in Ghana. In brief, the organic farms use shade trees and organic products to improve soil fertility, organic pesticides (e.g., *Azadirachta indica* extracts) to control pests and diseases, and regular weeding while the conventional farms use synthetic agrochemicals such as fertilizers, herbicides and fungicides. In both systems, cocoa trees are generally planted at a density of 1100 trees/hectares (at a spacing of 3 m × 3 m) with the recommended 12–18 shade trees *per* hectare providing a canopy cover of 30–40% (Asigbaase et al., 2019). Detailed description of the organic and conventional systems in the study area in terms of biophysical characteristics and cultivation practices are provided in Appendix Table 1, Asigbaase et al. (2019) and Djokoto et al. (2016). The soils of the study area were formed from well weathered parent material; they are well drained, porous and loamy and are classified as forest ochrosols (FAO, 1991).

2.2. Selection of cocoa farms

A multi-stage approach was used to select the study communities and farms. First, Suhum was purposively selected because it is the area where organic cocoa farming was pioneered in Ghana and the oldest organic cocoa farms are found within the Municipality. Next, two cocoa farming communities (Nsuta-Wawase and Kuano) were randomly selected from a list of cocoa producing areas within the Municipality provided by the local office of Ghana Cocoa Board (COCOBOD), the regulator of the sector. Cocoa farms were randomly selected from separate lists of organic and conventional farmers at the two cocoa communities. Selected farmers consented to the research and plots (25 m × 25 m) were established on their farms; one plot *per* farm. The age of the cocoa plantations worked in (8 organic and 8 conventional) ranged from 20-30 years in each farm management type. The size of the farms ranged from 0.3 – 3.0 ha with an average of 1.1 ha in the conventional systems and 0.6–2.4 ha with an average of 1.2 ha in the organic systems.

2.3. Collecting, processing and chemical analysis of litterfall

Data on stand characteristics (canopy cover, shade tree, cocoa and fruit densities, number of strata, shade and cocoa tree basal areas and Shannon diversity) were obtained from Asigbaase et al. (2019) and data on the depth of standing litter on organic farms were obtained from Asigbaase et al. (2021b). To collect litterfall, four (4) wooden litter boxes of dimensions 50 cm × 50 cm x 30 cm with a 2 mm mesh at the bottom were installed in each plot. The boxes were 40 cm above the ground. The litter traps were emptied every month from March 2017 to February 2018. Litterfall material from fruit and forest trees were considered as shade tree litter. The samples were separated into four fractions; cocoa tree leaves, shade tree leaves, twigs and small branches (TSB), and reproductive parts and others (RPO). Each fraction was weighed to determine their wet weight and oven-dried at 70 °C for 48 h to determine their oven-dry weights.

The nutrient composition of the oven-dried litter fractions was determined after milling with agate ball mill (Retch PM 400) for 15 min at 290 rpm. We estimated total C and N contents (%) by using CN analyzer (Thermo Scientific™ Flash™ 2000 Organic Elemental Analyzer (OEA)) and macro- and micro-nutrients via ICP-MS (Thermo Scientific™ iCAP™ TQ). Prior to the ICP-MS, the samples (0.2 g) were microwave-digested after adding 6 ml of concentrated HNO_3 acid (Fisher Chemical™, CAS Number-7697-37-2, Product code: 10098862). Chemical analysis for total C and N contents was conducted quarterly (not cumulatively for the period) whilst chemical analysis for macro- and micro-nutrient contents were conducted on a monthly basis.

2.4. Data analysis

The mean seasonal litterfall and nutrient contents were analyzed using repeated measures ANOVA in GenStat (19th Edition, VSN International, 2019). To correct for violations of sphericity, the degrees of freedom were multiplied by Greenhouse-Geisser epsilon. The effect of farm management type on annual total litterfall, fractional litterfall and stand parameters was analyzed via one-way ANOVA while the effect of seasonality and farm management type on nutrient return was analyzed through two-way repeated measures ANOVA. The assumptions of normality were assessed through visual inspection of scatter plots and histograms of data and residuals; variables which were not normally distributed were Box-Cox transformed. Spearman rank correlation was used to assess the strength and direction of the monotonic relationship between annual fractional litterfall, stand characteristics and nutrient return in the two farm management types. The strength of the correlation was described as: i) very weak (r = 0.00–0.19), ii) weak (r = 0.20–0.39), iii) moderate (r = 0.40–0.59), iv) strong (r = 0.60–0.79) and v) very strong (r = 0.80–1.0) (Evans, 1996). Annual stocks of cocoa and shade tree leaves as well as nutrient stocks were related to standing litter depth via regression analysis. Differences in mean values were considered significant at $p < 0.05$.

3. Results

3.1. Stand characteristics and temporal dynamics of litterfall

Organic farms had greater fruit density ($F_{1\ 14} = 8.53$, $p = 0.011$), shade stand basal area ($F_{1\ 14} = 11.57$, $p = 0.004$), total basal area ($F_{1\ 14} = 14.4$, $p = 0.002$), shade tree species richness ($F_{1\ 14} = 6.08$, $p = 0.027$), Shannon diversity ($F_{1\ 14} = 7.48$, $p = 0.016$) and number of strata ($F_{1\ 14} = 9.0$, $p = 0.01$) (Appendix Table 2). However, farm size, cocoa tree basal area, and total, shade and cocoa tree densities were similar on both farm management types.

Seasonality influenced the magnitude of the litter inputs, with greater inputs during the dry season than both the major and minor rainy seasons (Figure 1; $F_{2\ 28} = 14.88$, $p < 0.001$). Specifically, whereas litterfall peaked in both November and March (i.e. at the beginning and at the end of the dry season) on conventional farms, it peaked only in November on organic farms (Figure 2). Three smaller peaks appeared during January (mid-dry season), March (end of dry season), and June (peak major rainy season) on organic farms whilst on conventional farms two smaller peaks appeared during January to February and April to May (i.e. at the beginning of the major rainy season). The deposition of both shade and cocoa leaves were highest during November on organic farms whilst on conventional farms, cocoa leaf litter production was highest in March and shade tree species leaf litterfall was highest in February.

3.2. Nutrient contents and seasonal dynamics

The concentration of each macro-nutrient in litterfall for both systems was generally higher during both the major and minor rainy seasons than the dry season (Figures 3 and 4; Table 1). Specifically, the nutrients P, K, Ca, Mg, S, Cu, Mo and Zn had greater concentrations during the rainy seasons than the dry season whereas the concentrations of N, B, Mn, Fe and Ni remained unaffected by seasonality. The interaction effect of farm management type and seasonality on the concentrations of deposited nutrients were significant for the macro-nutrients S and Mg as well as the micro-nutrients Cu, Zn and Ni (Table 1); that means during the minor rainy season, the concentration of these nutrients were broadly higher on conventional farms but similar on both farm management types during the major rainy and dry seasons. The concentration of C was greater in organic cocoa systems during the minor rainy season than conventional cocoa systems.

The return of mean stock of primary macro-nutrients (N, P and K), secondary macro-nutrients (Ca and S) and micro-nutrients (Mn, B, Cu, Zn and Mo) via litterfall varied significantly with season (Appendix Table 3; Figures 5 and 6). The mean seasonal return of P and Zn stocks were greater on conventional farms than organic farms. There was a significant interaction effect of farm management type and season on the return of the macro-nutrients, Mg and S, and the micro-nutrients, Cu and Zn; higher stocks of Mg, S, Cu and Zn were returned via litterfall during the minor rainy season on conventional farms than organic farms whiles greater stocks of Cu was returned on organic farms than conventional farms during the dry season (Appendix Table 3; Figures 5 and 6).

Spearman's rank correlation between monthly nutrient return for all nutrients (except Cu and P) and fractional litterfall showed a strong to very strong positive correlation with cocoa leaves (r = 0.64–0.92, $p < 0.03$) on conventional farms (Table 2). On organic farms, the nutrients Ca, S, Mg, B and Mn were positively correlated with both cocoa and shade tree species leaf litterfall whilst Ni, and Zn were correlated with cocoa leaves but not with shade tree species litter, TSB or RPO. Furthermore, the primary macro-nutrient, P, strongly correlated with TSB; and Cu with RPO in only the organic systems.

3.3. Annual litterfall and nutrient return

In terms of annual fractional litterfall, mean leaf litter from shade tree species was significantly higher (50 %) in organic systems compared to conventional systems (Figure 7a; $F_{1\ 14} = 4.76$, $p = 0.047$). Whereas cocoa leaves (45.0 %) were the predominant fraction of litterfall on conventional farms, both shade (40.0%) and cocoa (39.4%) leaves dominated litterfall on organic farms. The annual mean total litterfall was similar in both organic and conventional cocoa agroforestry systems (Org. 12.4 ± 0.44 Mg ha^{-1} yr^{-1} vs. Con. 12.7 ± 0.75 Mg ha^{-1} yr^{-1}, $p > 0.05$). Annual leaf litter production of cocoa trees decreased with annual leaf litter production of shade trees (Figure 7 b; $F_{1\ 14} = 10.09$, $p = 0.007$) and canopy cover (Figure 8 a; $F_{1,\ 14} = 6.51$, $p = 0.020$). Similarly, annual leaf litter production of cocoa trees decreased with litter depth on organic farms (Figure 8 c; $F_{1,\ 5} = 18.64$, $p = 0.008$).

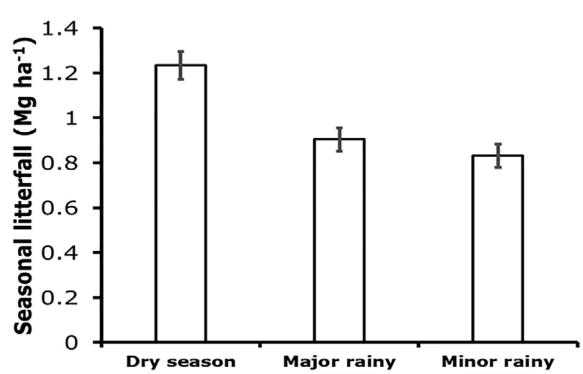

Figure 1. Mean seasonal litterfall (±SEM) in cocoa agroforestry farms at Suhum.

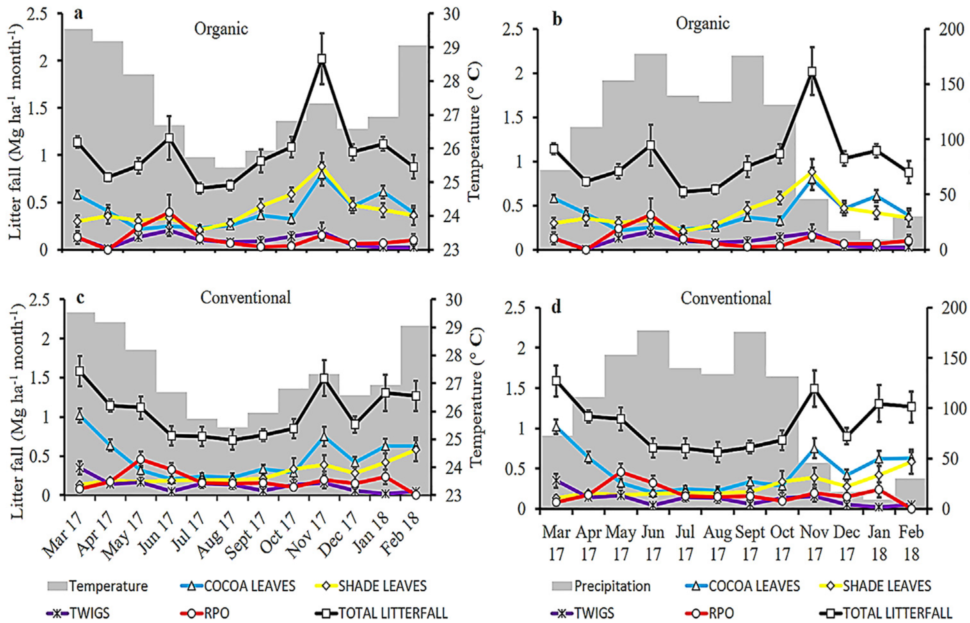

Figure 2. Monthly litterfall (Mean ± SEM) from March 2017 to February 2018 on organic and conventional cocoa agroforestry farms at Suhum. Total litterfall (squares) is comprised of leaf litter from cocoa (triangles) and shade tree species (diamonds), twigs and small branches (TSB, asterisks), and reproductive parts and others (RPO, circles). The mean long term monthly temperature (a and c) and precipitation (b and d) (1901–2018; World Bank Group, 2018 and Web 1, 2018) are indicated as bars.

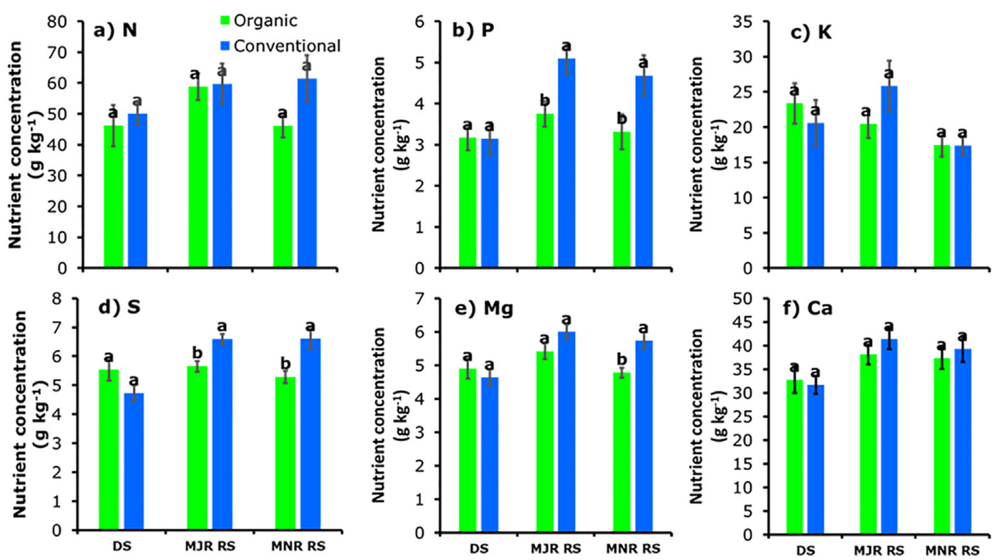

Figure 3. Seasonal macro-nutrients return (panel a–f, mean ± SEM) in organic and conventional cocoa agroforest systems at Suhum. The panels, a-f represents N, P, K, S, Mg and Ca, respectively. The green bars represent organic farms and the blue bars represent conventional farms. DS is dry season, MJR RS is major rainy season and MNR RS is minor rainy season.

Leaf litter of shade trees increased with canopy cover (Figure 8 b; $F_{1,\,14} = 5.58$, $p = 0.028$) and similarly, it increased with letter depth on organic farms (Figure 8 d; $F_{1,\,5} = 7.44$, $p = 0.041$). Annual deposition of twigs and small branches was less than 12 % of total litterfall on both farm management types. Spearman's rank correlation of stand characteristics and annual fractional litterfall showed that leaf litter from shade tree species was positively related to tree density, stand basal area and Shannon diversity (Table 3). RPO was negatively related to stand basal area and Shannon diversity. In general, shade trees contributed 30–47 % of total annual macro- and micro-nutrients return on organic farms and 20–35 % on conventional farms.

In terms of litter fractions, annual macro- and micro-nutrient return via cocoa or shade tree leaf litter were greater than RPO and TSB (Figures 9 and 10; Table 4). The interaction effect of farm management type and litterfall fraction were significant for all nutrients except Mn, Fe and Zn; the return of N, S, P, Mg, K, Ca, B and Cu via shade tree leaf litter were greater on organic farms than conventional farms while the return of N and P through cocoa tree leaf litter were greater on conventional farms than organic farms. The return of N, S, P and Cu through RPO was greater on conventional farms than organic farms. Annual macro- and micro-nutrient returns through litterfall production were similar on both organic and conventional cocoa farms (Figures 9 and 10; Table 4). Spearman's rank correlation showed that annual return of Mn ($r = 0.571$, $p = 0.021$) and B ($r = 0.600$, $p = 0.014$) were related to the basal area of pioneer shade trees while Cu correlated with pioneer shade tree density ($r = 0.541$, $p = 0.031$). On organic farms, there was a significant

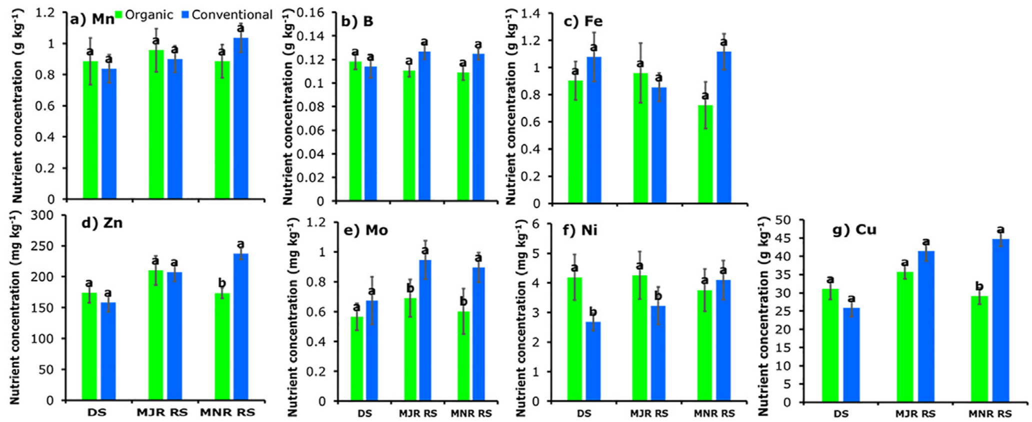

Figure 4. Seasonal micro-nutrients return (mean ± SEM) in organic and conventional cocoa agroforestry systems at Suhum. The green bars represent organic farms and the blue bars represent conventional farms. The panels, a-f represents Mn, B, Fe, Zn, Mo, Ni and Cu, respectively. DS is dry season, MJR RS is major rainy season and MNR RS is minor rainy season.

Table 1. Repeated measures ANOVA of concentrations of seasonal nutrient return and farm management type (FM type). ‘a’ degree of freedom is $F_{1, 14}$ for all parameters except C and N ($F_{1, 10}$); ‘b’ degree of freedom is $F_{2, 28}$ for all parameters except C and N ($F_{2, 20}$). The given ‘b’ d.f. were multiplied by the Greenhouse-Geisser epsilon values (GGE) before the estimation of *p*-values shown in parenthesis and significant values ($p < 0.05$) are italicised. Annual nutrient return is in g kg^{-1}, except Zn, Mo, Ni and Cu (mg kg^{-1}).

Parameter	Nutrient	GGE	F-value		
			FM type[a]	Season[b]	FM type x Season[b]
Primary macro-nutrients	C	0.8750	0.42 (0.533)	11.97 (< *0.001*)	5.27 (*0.019*)
	N	0.9628	1.62 (0.232)	2.27 (0.132)	1.06 (0.362)
	P	0.7375	4.55 (0.051)	8.54 (*0.004*)	3.25 (0.072)
	K	0.8688	0.08 (0.779)	5.13 (*0.017*)	2.43 (0.115)
Secondary macro-nutrients	Mg	0.8428	3.78 (0.072)	9.02 (*0.002*)	3.94 (*0.040*)
	Ca	0.9525	0.29 (0.596)	9.38 (<*0.001*)	0.75 (0.478)
	S	0.7641	3.30 (0.091)	8.51 (*0.004*)	9.78 (*0.002*)
Micro-nutrients	Mn	0.9971	0.01 (0.920)	1.60 (0.220)	2.20 (0.130)
	Fe	0.8939	1.12 (0.309)	0.17 (0.818)	1.34 (0.279)
	B	0.8417	1.67 (0.217)	0.12 (0.853)	2.34 (0.125)
	Ni	0.8593	0.66 (0.429)	1.94 (0.170)	7.12 (*0.005*)
	Cu	0.7509	5.14 (*0.040*)	13.41 (<*0.001*)	12.33 (< *0.001*)
	Zn	0.9431	1.00 (0.338)	7.45 (*0.003*)	4.78 (*0.018*)
	Mo	0.8900	1.80 (0.201)	4.63 (*0.023*)	1.09 (0.345)

relationship between litter depth and annual return of the micro-nutrients Mn ($F_{2, 5} = 10.67$, $p = 0.016$, $R^2 = 73.4\%$), Fe ($F_{1, 6} = 6.81$, $p = 0.040$, $R^2 = 45.3\%$) and Ni ($F_{2, 4} = 10.59$, $p = 0.025$, $R^2 = 76.2\%$) through the regression Eqs. (1), (2) and (3), respectively.

$$\text{Log}_{10}\ \text{Mn (kg ha}^{-1}\ \text{yr}^{-1}) = -\ 2.281 + 0.8838\text{LD} - 0.06484\text{LD}^2 \quad (1)$$

$$\text{Log}_{10}\ \text{Fe (kg ha}^{-1}\ \text{yr}^{-1}) = 0.8411 - 0.05452\text{LD} \quad (2)$$

$$\text{Log}_{10}\ \text{Ni (kg ha}^{-1}\ \text{yr}^{-1}) = -\ 4.937 + 0.9279\text{LD} - 0.06607\text{LD}^2 \quad (3)$$

LD = Litter depth (cm).

4. Discussion

4.1. Litterfall characteristics and the effect of farm management type on litterfall and nutrient return

The significant relationship between annual return of the micro-nutrients, Mn, Fe and Ni and litter depth shows the dynamics of these nutrients on the cocoa farms as litter accumulates; the correlation between cocoa and shade tree leaves and micro-nutrients (Table 2) lends support to this notion. Our data show that annual litterfall and nutrient return were independent of farm management type (organic compared to conventional systems) but that significant variations in fractional litterfall and nutrient return exists between farm management types. These findings are in line with findings from agroforestry systems in Brazil (Fontes et al., 2014) and India (Nesper et al., 2019). Specifically, Fontes et al. (2014) found no significant differences in litterfall between fertilized and unfertilized cocoa agroforests (means of 9.9 and 9.9 Mg ha^{-1} yr^{-1}, respectively) in southern Bahia, Brazil. Nesper et al. (2019) reported similar total litterfall in organic and conventional coffee agroforestry systems (Org. 5.7 ± 0.5 vs. Con. 5.0 ± 0.5 Mg ha^{-1} yr^{-1}) in Western Ghats, India. Similarly, Schneidewind et al. (2019) found that organic and conventional management had no effect on annual litterfall in cocoa systems in Bolivia.

The annual litterfall results reported in this study for both organic and conventional cocoa systems are higher than the values (3.3–7.0 Mg ha^{-1} yr^{-1}) reported for most tropical and temperate forests (Zhang et al., 2014), secondary mixed forests (4.2 ± 0.2 Mg ha^{-1} yr^{-1}) in Thailand (Podong et al., 2013), cocoa and kola plantations (4.7–7.3 Mg ha^{-1} yr^{-1}) in Nigeria (Muoghalu and Odiwe, 2011) and cocoa agroforests (5.0 ± 0.4–10.4 ± 0.6) in the Ashanti region of Ghana (Dawoe et al., 2010). But similar amounts of annual litterfall similar to our results have also been reported for agroforests and forest ecosystems in Tanzania (Becker et al., 2015), Indonesia (Triadiati et al., 2011), Central Africa (Averti and Dominique, 2011) and Bangladesh (Hasanuzzaman and Mahmood, 2014). These differences (organic *versus* conventional cocoa systems) in mean annual litterfall production are possibly due to differences in tree species composition and diversity, plantation age, canopy cover and soil characteristics (Kumar, 2008; Averti and Dominique, 2011; Triadiati et al., 2011).

The annual leaf litterfall on organic farms (9.8 Mg ha^{-1} yr^{-1}, 79 % of total annual litter) and conventional farms (9.0 Mg ha^{-1} yr^{-1}, 71 % of

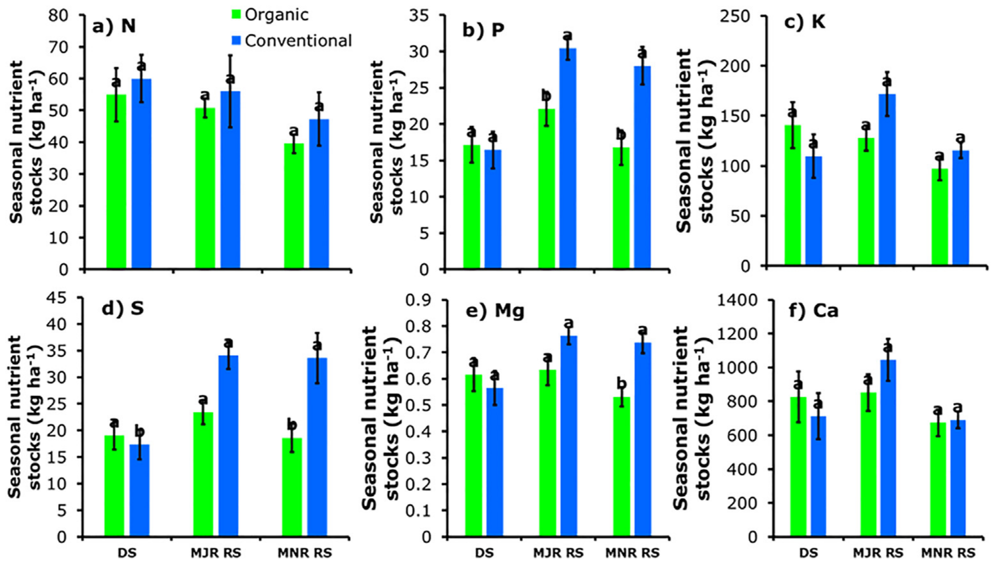

Figure 5. Seasonal return of macro-nutrients stock (panels a–f, mean ± SEM) in organic and conventional cocoa agroforest systems at Suhum. The panels, a-f represents N, P, K, S, Mg and Ca, respectively. The green bars represent organic farms and the blue bars represent conventional farms. DS is dry season, MJR RS is major rainy season and MNR RS is minor rainy season.

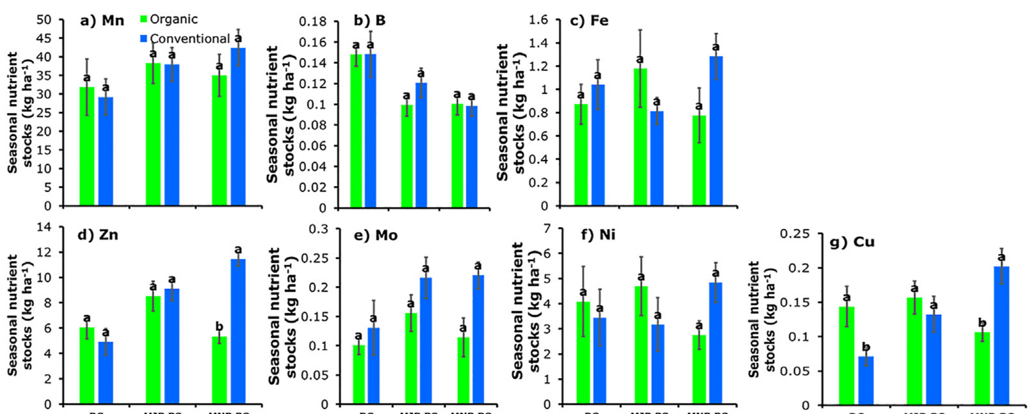

Figure 6. Seasonal return of micro-nutrients stock (mean ± SEM) in organic and conventional cocoa agroforestry systems at Suhum. The green bars represent organic farms and the blue bars represent conventional farms. The panels, a-g represents Mn, B, Fe, Zn, Mo, Ni and Cu, respectively. DS is dry season, MJR RS is major rainy season and MNR RS is minor rainy season.

Table 2. Spearman's rank correlation between nutrient return (kg ha^{-1} $month^{-1}$) and fractional litterfall (Mg ha^{-1} $month^{-1}$) on organic and conventional cocoa agroforestry farms at Suhum. Correlation coefficients (r^2) are shown with *p*-values presented in parenthesis and significant correlations ($p < 0.05$) italicised. LCT, LST, TSB and RPO refer to the fractions, leaf litter of cocoa trees, leaf litter of shade trees, twigs and small branches and reproductive parts and others, respectively.

Nutrient	Organic				Conventional			
	LCT	LST	TSB	RPO	LCT	LST	TSB	RPO
P	-0.007 (0.983)	0.427 (0.167)	0.797 (*0.002*)	0.469 (0.124)	0.524 (0.080)	0.126 (0.697)	0.133 (0.681)	0.294 (0.354)
K	0.455 (0.138)	0.364 (0.245)	0.413 (0.183)	0.573 (0.051)	0.755 (*0.005*)	0.154 (0.633)	0.077 (0.812)	0.280 (0.379)
Mg	0.727 (*0.007*)	0.587 (*0.045*)	0.308 (0.331)	0.154 (0.633)	0.881 (*<0.001*)	0.224 (0.484)	0.343 (0.276)	0.007 (0.983)
Ca	0.608 (*0.036*)	0.720 (*0.008*)	0.441 (0.152)	0.021 (0.948)	0.867 (*<0.001*)	0.448 (0.145)	0.084 (0.795)	-0.021 (0.948)
S	0.629 (*0.028*)	0.615 (*0.033*)	0.441 (0.152)	0.175 (0.587)	0.671 (*0.017*)	0.238 (0.457)	0.119 (0.713)	0.119 (0.713)
B	0.748 (*0.005*)	0.706 (*0.010*)	0.203 (0.527)	-0.021 (0.948)	0.867 (*<0.001*)	0.462 (0.131)	-0.007 (0.983)	-0.021 (0.948)
Mn	0.888 (*<0.001*)	0.608 (*0.036*)	-0.021 (0.983)	0.007 (0.983)	0.916 (*<0.001*)	0.343 (0.276)	0.189 (0.557)	-0.168 (0.602)
Fe	0.273 (0.391)	0.168 (0.602)	0.168 (0.602)	0.455 (0.138)	0.860 (*<0.001*)	0.231 (0.471)	0.042 (0.897)	-0.294 (0.829)
Ni	0.930 (*<0.001*)	0.531 (0.075)	-0.119 (0.713)	-0.042 (0.897)	0.839 (*<0.001*)	0.252 (0.430)	0.182 (0.572)	0.007 (0.983)
Cu	0.427 (0.167)	0.336 (0.286)	0.538 (0.071)	0.636 (*0.026*)	0.399 (0.199)	0.063 (0.846)	0.392 (0.208)	0.105 (0.746)
Zn	0.650 (*0.022*)	0.531 (0.075)	0.413 (0.183)	0.308 (0.331)	0.657 (*0.020*)	0.091 (0.779)	0.448 (0.145)	0.014 (0.966)
Mo	0.469 (0.124)	0.559 (0.059)	0.573 (0.051)	0.308 (0.331)	0.713 (*0.009*)	0.413 (0.183)	0.196 (0.542)	-0.189 (0.557)

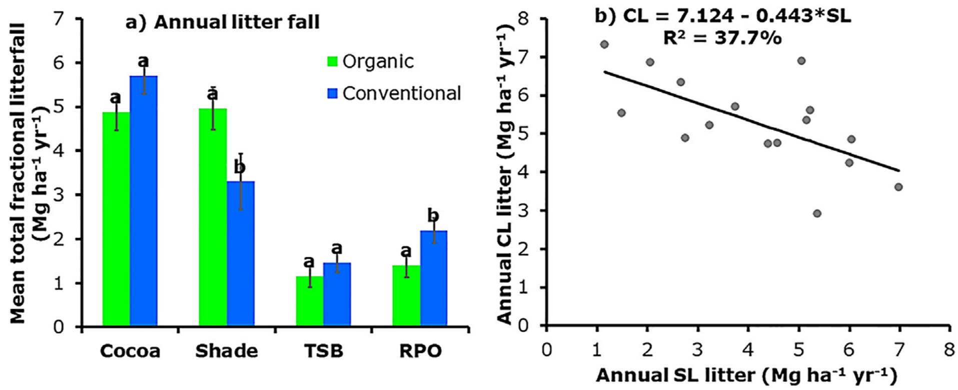

Figure 7. (a) Annual fractional litterfall (2017–2018, Mean ± SEM) in organic and conventional cocoa agroforestry systems at Suhum. (b) Relationship between annual cocoa (CL) and shade trees (SL) leaf litter production. Litter fractions with different letters indicate significant difference ($p < 0.05$) based on one-way ANOVA. TSB, RPO, SL and CL are twigs and small branches, reproductive parts and others litterfall fractions, leaf litter of shade trees and leaf litter of cocoa trees, respectively.

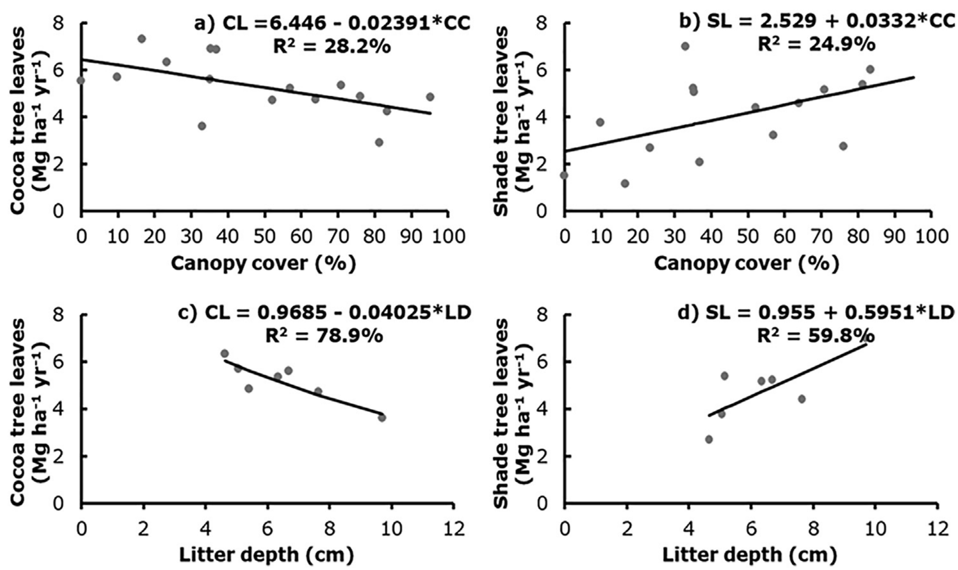

Figure 8. Relationship between selected stand parameters of smallholder cocoa systems at Suhum. Panel a) annual cocoa leaf litter (CL, Mg ha^{-1} yr^{-1}) and canopy cover (CC, %), panel b) annual leaf litter of shade trees (SL, Mg ha^{-1} yr^{-1}) and canopy cover, panel c) litter depth (LD, cm) and cocoa leaf litter, and panel d) litter depth and leaf litter of shade trees. The relationship between litter depth and cocoa and shade tree leaves (panels c and d) was assessed in organic farms.

total annual litter) fall within the commonly reported range of 60–90 % regarding the leaf litter portion of annual litterfall for most tropical forests and agroforestry systems (Hasanuzzaman and Mahmood, 2014; Becker et al., 2015). Our values for leaf litter portion are however lower than the range (96–99 %) reported as leaf litter portion for forest systems in Central Africa (Averti and Dominique, 2011). The amount of litterfall in an ecosystem is dependent on stand characteristics and environmental factors and their interaction (Averti and Dominique, 2011; Hasanuzzaman and Mahmood, 2014; Triadiati et al., 2011). The organic and conventional farms we evaluated had similar ages, cocoa tree basal area, and shade and total tree densities. Moreover, although organic farms maintained more fruit plants (e.g. *Musa spp.*), litter from *Musa spp.* were not accounted for by our litter traps as they were manually removed by farmers. The fact that the organic cocoa systems returned both macro- and micro-nutrients via litterfall similar to that of the conventional farms indicate their potential to efficiently recycle nutrients which is critical for sustainable cocoa production.

4.2. Seasonal variations of nutrient return via litterfall

The pattern and amount of litterfall varied with season with greater inputs during the dry season (Figures 1 and 2). Several studies have demonstrated that litter fall in cocoa agroforests and tropical forests follow a seasonal pattern, i.e., having greater litterfall in the dry season compared to the wet season (Becker et al., 2015; Dawoe et al., 2010; Podong et al., 2013; Triadiati et al., 2011; Zhang et al., 2014). Triadiati et al. (2011) showed that litterfall production was influenced by monthly variations in climatic factors such as temperature, humidity, wind speed and precipitation as well as their interaction. Furthermore, Zhang et al. (2014) demonstrated that litter peaks in most temperate and tropical forest types are influenced by precipitation, temperature and solar radiation. The peak litterfall production during the dry season reported in this study may be an indication of the physiological response of the trees to increased temperature and reduced humidity (Zhang et al., 2014), although these parameters were not measured in our study. Plants shed their leaves during the dry season as an adaptation mechanism to limited water availability (Wang et al., 2008). The litterfall peaks observed during the rainy season may be as a result of the mechanical action of strong winds and thunderstorms (Dawoe et al., 2010; Nesper et al., 2019), but again these parameters were not measured. Tree species may also respond to changes in soil properties such as pH or salinity thus within-year variations in litterfall in tropical stands may mirror pronounced edaphic cues (Kumar, 2008).

Table 3. Spearman's rank correlation between selected stand characteristics and mean annual fractional litterfall of organic and conventional cocoa agroforestry systems at Suhum. Correlation coefficient (r^2) are shown with *p*-values presented in parenthesis and significant values ($p < 0.05$) are italicised. LCT, LST, TSB and RPO represent the fractions, leaf litter of cocoa trees, leaf litter of shade trees, twigs and small branches and reproductive parts and others, respectively.

Parameter	LCT (Mg ha^{-1} yr^{-1})	LST (Mg ha^{-1} yr^{-1})	TSB (Mg ha^{-1} yr^{-1})	RPO (Mg ha^{-1} yr^{-1})
Strata (no. $plot^{-1}$)	0.072 (0.792)	0.314 (0.236)	0.024 (0.930)	-0.383 (0.144)
Fruit density (no. ha^{-1})	-0.132 (0.625)	0.193 (0.473)	-0.184 (0.494)	-0.388 (0.137)
Tree density (no. ha^{-1})	-0.268 (0.315)	0.602 (*0.014*)	0.097 (0.721)	-0.279 (0.296)
Cocoa density (no. ha^{-1})	0.289 (0.277)	-0.229 (0.394)	-0.125 (0.643)	0.022 (0.935)
Stand basal area (cm^2 ha^{-1})	-0.468 (0.068)	0.771 (*<0.001*)	-0.003 (0.991)	-0.568 (*0.022*)
Cocoa basal area (cm^2 ha^{-1})	0.265 (0.322)	-0.418 (0.107)	-0.179 (0.506)	0.150 (0.579)
Shannon diversity (H $plot^{-1}$)	-0.177 (0.513)	0.599 (*0.014*)	-0.077 (0.778)	-0.543 (*0.030*)

Nutrient return via litterfall varied according to season due to differences in litterfall and nutrient concentration (Figures 3, 4, 5, and 6; Table 1; Appendix Table 3). The concentration of nutrients in litter depends on the rate of nutrient resorption, tree species and the age of the leaves (Hartemink, 2005; Kumar, 2008; Nesper et al., 2019). Fresh leaves contain greater levels of nutrient contents than old leaves due to minimal nutrient resorption in fresh leaves (Hartemink, 2005; Kumar, 2008). This implies that periods of greater fresh leaves deposition due to mechanical action of strong winds or thunderstorms are likely to show greater levels of nutrient concentration compared to periods where defoliation is due to leaf ageing (Kumar, 2008). Our finding of higher nutrient concentrations in litter material during the rainy season than the dry season supports this notion (Figures 3, 4, 5, and 6; Table 1). In their review, van Vliet et al. (2015) suggested that temporal changes in nutrient contents of litter in cocoa systems are associated with leaf flushing, cocoa pod production dynamics and light intensity. For example, light intensity, which is regulated by radiation from the sun, tree density and canopy cover (Wessel 1971; van Vliet et al., 2015), has been shown to be inversely related to the concentrations of N and K and positively associated with Ca in leaf litter whilst having no effect on leaf Mg and P. Climatic factors moderated by stand characteristics such as shade tree species composition and diversity and canopy cover may also interact with leaf flushing and cocoa fruit bearing to regulate changes in nutrient concentrations and stocks over time in the two systems. The greater nutrient concentrations during the rainy seasons may also be related to fertilization, especially on the conventional farms.

4.3. *The role of shade tree species in nutrient return dynamics*

The contribution of shade tree species to leaf litterfall on organic (5.0 Mg ha^{-1} yr^{-1}) farms was similar to the value (5.8 Mg ha^{-1} yr^{-1}) reported by Mamani-Pati et al. (2012) on organic coffee systems in Bolivia. Compared to Ofori-Frimpong et al. (2007) who reported a range of 1–2 Mg ha^{-1} yr^{-1} as the amount of shade tree species litter in cocoa systems in the same region as our study, our values are higher possibly due to differences in stand composition. The fact that annual shade tree species litterfall was positively correlated with tree density, shade species basal area and shade tree species diversity (Table 3), suggests that these factors influenced annual shade tree litterfall production in the cocoa farms (Kumar, 2008). Thus, the greater deposition of shade tree species leaf litter in organic systems compared to conventional systems is attributable to these factors (Asigbaase et al., 2019). The fact that the leaf litter of shade trees increased with canopy cover whilst leaf litter of cocoa trees decreased (Figure 7 a and b) indicates the effect of shade trees canopy cover on cocoa leaf abscission; with an increase shade tree canopy cover possibly ameliorating the micro-climate within the cocoa systems resulting in reduced cocoa leaf litterfall (Kyereh, 2017). Furthermore, the finding that the leaf litterfall of cocoa trees decreased with increased leaf litter of shade trees supports this notion.

Both monthly macro- and micro-nutrients stock were significantly associated with only the cocoa leaf litter fraction on conventional farms, but they were significantly related to both shade and cocoa leaf litter fractions in the organic systems (Table 2), suggesting that cocoa leaf litter

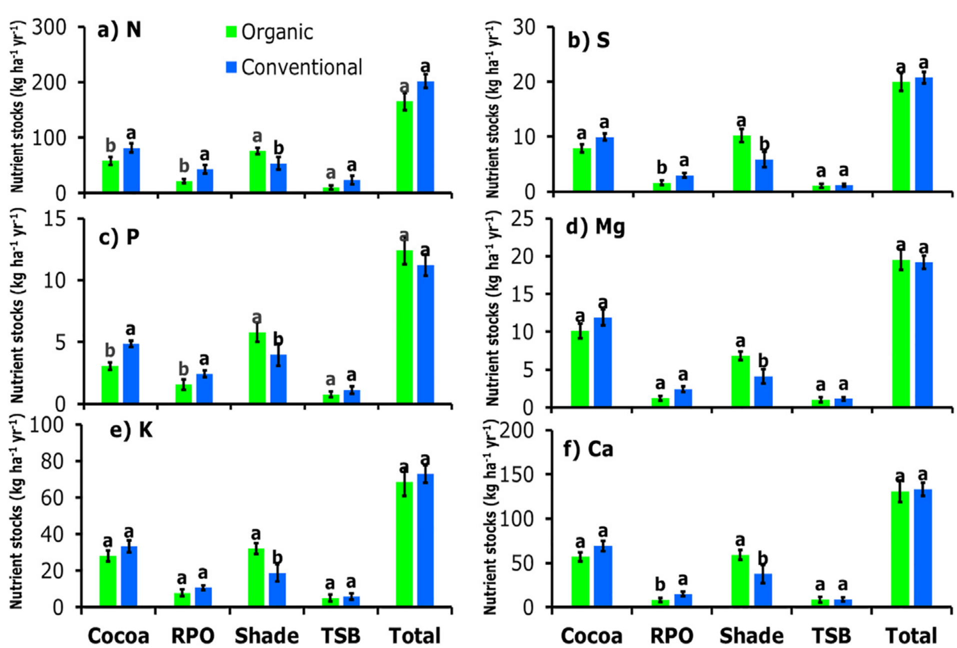

Figure 9. Mean annual macro-nutrient return via fractional and total litterfall on organic and conventional cocoa agroforestry systems at Suhum. TSB is twigs and small branches, and RPO is reproductive parts and others. Bars with different letters within each litter fraction category indicate significant interaction effect of (Two-way ANOVA, $p < 0.05$) farm management type and fractional litterfall, and those with the same letters indicate no significant differences.

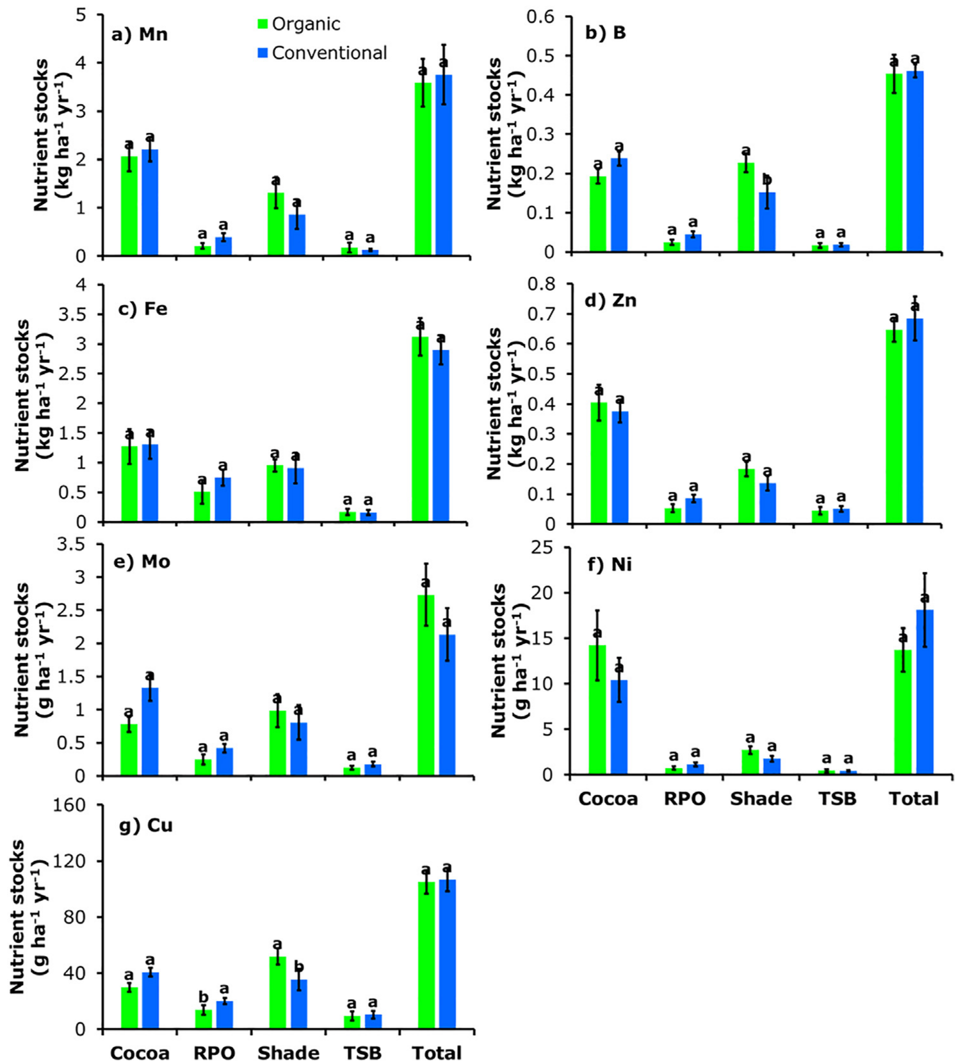

Figure 10. Mean annual micro-nutrient return via fractional and total litterfall on organic and conventional cocoa agroforestry systems at Suhum. TSB is twigs and small branches, and RPO is reproductive parts and others. Bars with different letters within each litter fraction category indicate significant interaction effect of (Two-way ANOVA, $p < 0.05$) farm management type and fractional litterfall, and those with the same letters indicate no significant differences.

Table 4. Two-way ANOVA of stocks of annual nutrient return via fractional and total litterfall and farm management type (FM type). 'a' degree of freedom is $F_{1, 14}$ for all parameters except N ($F_{1, 10}$); 'b' degree of freedom is $F_{3, 42}$ for all parameters except N ($F_{3, 30}$). *P*-values are shown in parenthesis and significant values ($p < 0.05$) are italicised. Annual nutrient return is in kg ha^{-1} yr^{-1}, except Mo, Ni and Cu (g ha^{-1} yr^{-1}).

Parameter	Nutrient	F-value		
		FM type[a]	Fraction[b]	FM type x fraction[b]
Primary macro-nutrients	N	3.22 (0.103)	24.19 (*<0.001*)	4.17 (*0.014*)
	P	1.58 (0.229)	34.76 (*<0.001*)	4.55 (*0.008*)
	K	0.23 (0.635)	41.88 (*<0.001*)	4.83 (*0.006*)
Secondary macro-nutrients	Mg	0.05 (0.830)	81.60 (*<0.001*)	3.87 (*0.016*)
	Ca	0.11 (0.746)	57.84 (*<0.001*)	4.42 (*0.009*)
	S	0.28 (0.606)	59.77 (*<0.001*)	5.66 (*0.002*)
Micro-nutrients	Mn	0.05 (0.834)	45.46 (*<0.001*)	1.17 (0.334)
	Fe	0.30 (0.590)	10.98 (*<0.001*)	0.19 (0.900)
	B	0.02 (0.882)	50.72 (*<0.001*)	3.23 (*0.032*)
	Ni	<0.00 (0.979)	68.40 (*<0.001*)	2.02 (0.125)
	Cu	0.02 (0.888)	25.77 (*<0.001*)	3.73 (*0.018*)
	Zn	0.21 (0.657)	59.41 (*<0.001*)	0.79 (0.509)
	Mo	1.43 (0.252)	43.16 (*<0.001*)	3.28 (0.030)

is a major source of these nutrients on conventional farms whilst both cocoa and shade leaves are the major sources in the organic systems. This is confirmed by the fact that shade tree leaf litter accounted for 30–47 % of annual macro- and micro-nutrient return (except Ni and Zn) in organic cocoa systems versus 20–35 % in conventional cocoa systems (Figures 9 and 10). Fontes et al. (2014) reported higher nutrient quality in shade tree species leaves than cocoa and concluded that leaves of shade tree species served as a source of nutrients while cocoa tree leaves functioned predominantly as a sink.

In an earlier study, Asigbaase et al. (2019) reported that food and fruit species and pioneer tree species dominated both organic and conventional cocoa systems at Suhum, Ghana. We found a significant correlation between the density and basal area of pioneer shade trees and annual return of Mn, B and Cu. This suggests that pioneer tree species as well as food and fruit species play a critical role in nutrient return via litterfall in the studied systems, thus their integration in cocoa systems will contribute to nutrient recycling.

5. Conclusion

Litterfall production and nutrient return via litterfall followed a seasonal pattern with peak deposition during the dry season. Overall litterfall production and return of macro- and micro-nutrients were similar in both organic and conventional cocoa systems but significant variations in fractional litterfall and nutrient return existed between the two farm management types. Shade tree species leaves served as a major source of annual litterfall and nutrient return, indicating a critical complementary role of the different shade tree species which are maintained in cocoa systems, particularly in the organic systems. We concluded that organic management of cocoa agroforestry systems ensure nutrient return similar to those receiving synthetic fertilizers.

Declarations

Author contribution statement

Michael Asigbaase; Evans Dawoe; Barry H. Lomax; Sofie Sjogersten: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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