Chapter

Leaf Litter Decomposition and Mitigation of CO_2 Emissions in Cocoa Ecosystems

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Abstract

Studies simultaneously quantifying litter weight losses and rates of CO_2-C evolved are few, though essential for accurate estimates of forest carbon budgets. A 120-day dry matter loss and a 130-day carbon emission experiments were concurrently conducted at the soil laboratory of the University of Reading, UK. Leaf litters of tree species comprising cocoa (*Theobroma cacao*), *Newbouldia laevis* (dominant shade tree in Eastern region (ER)) and *Persea americana* (dominant shade tree in Western region (WR)) of Ghana were incubated using a single tree leaf litter and/or a 1:1 mixed species leaf litters to determine and predict the litter decomposition and C dynamics in cocoa systems with or without the shade trees. Decomposition and C release trends in the ER systems followed: shade > mixed cocoa-shade = predicted mixed litter > cocoa; and in the WR, the order was: cocoa = mixed cocoa-shade > predicted mixed > shade. Differences between released C estimated from litter weight loss and CO_2-C evolution measurement methods were not consistent. Regression analysis revealed a strong (R^2 = 0.71) relationship between loss of litter C and the CO_2-C evolution during litter decomposition. The large C pool for shaded cocoa systems indicates the potential to store more C and thus, its promotion could play a significant role in atmospheric CO_2 mitigations.

Keywords: cocoa system, mineralization, mineralizable C, oxidizable C

1. Introduction

Soil organic matter is the main source of plant nutrients in low input agriculture [1], whilst the primary regenerative source of soil organic matter on agricultural lands is the decomposition of retained plant residues. Therefore, sustainable agricultural production based on nutrient cycling would operate only in systems where enough plant biomass is generated and retained on agricultural land. Hence, the success of forest ecosystems lies on their ability to store large amounts of organic matter aboveground in woody plant tissue and fibrous litter. Conceivably, biomass production, leaf litter decomposition and root biomass turnover in forest ecosystems have much influence on agro ecosystems' nutrient cycling and sustainability [2].

Nutrients are returned to soil through leaf falls and decomposition processes. Thus, their nutrient cycling starts during litter decomposition, where organically bound nutrients are released as free ions to the soil solution that then become

available for uptake by plants. As the bulk of cocoa farmers are poor and therefore, do not apply external fertilizers to their croplands because of its high cost, litter decomposition from both cocoa and non-cocoa (or shade) trees plays a central role in the nutrition of the system. Although cocoa systems accumulate less leaf biomass than native forests, several studies have reported sizeable leaf litter-falls per hectare in cocoa systems (**Table 1**). The high biomass of leaf litter in cocoa systems indicates a high potential source of nutrient cycling when retained to undergo decomposition on the floor of the ecosystem but also a lot of CO_2 emissions.

Land use change is arguably the most common anthropogenic activity that interferes greatly with most biogeochemical cycles. Its impact on C and nutrient cycling in the soil has been the subject of much attention [3–6]. Understanding the effects of land use/land cover change on ecosystem functions is often derived by quantifying changes in C and nutrient stocks and fluxes. Indeed, changes in forest cover have been implicated in the rising levels of carbon dioxide (CO_2), the main greenhouse gas (GHG), in the atmosphere [4, 7, 8]. This is because large amounts of organic C are often stored in forest trees and which upon clear-felling, decompose and release the stored C to the atmosphere [9].

Since plant litter decomposition involves carbon dioxide (CO_2) emissions, and fragmentation and leaching of organic matter to the soil, many studies have been conducted to investigate the factors controlling litter decomposition. These studies have often followed one of three approaches. The first approach simply measures the annual litter-fall in vegetation and equates that to the amount of organic material being decomposed. This approach acknowledges that the soil organic matter level in most natural vegetation types attains an equilibrium state where the amount of material being decomposed annually is equal to the amount of annual litter-fall. The second approach is the weight loss of buried litter over time, whilst the third approach measures the microbial activity on litter via CO_2 evolution.

Using weight loss of buried litter contained in nylon mesh bags over time, many studies concluded that the rate of leaf litter decomposition depended on tree species, the chemical composition of the leaves, and environmental factors such as temperature and soil moisture [2, 10, 11]. Hitherto, several researchers considered the C/N ratio of plants as the main plant composition factor that controls decomposition rates [10]. Increasingly, other litter constituents such as lignin and polyphenol concentration, especially in the tropics, are considered to play important roles in the decomposition process [11–14].

Country		**Annual litter-fall**			
	Age cocoa (years)	**Cocoa tree**	**Shade tree**	**Total**	**Reference**
Malaysia	8–10	5460	2660	8120	[17]
Venezuela	30	7630	13,571	21,201	[18]
Costa Rica[a]	10	nd[b]	nd	7071	[19]
Costa Rica[c]	10	nd	nd	8906	[19]
Brazil	nd	nd	nd	9000–14,000	[20]
Ghana	nd	nd	nd	5000	[21]

[a]*Cocoa with* Cordia alliodora *as shade tree.*
[b]*No data.*
[c]*Cocoa with* Erythrina poeppigiana *as shade tree.*
Source: from [22].

Table 1.
Annual litter-fall of cocoa ecosystems (in kg dry matter (DM)/ha).

Although the use of litter bags makes it possible for buried litter recovery, their use for decomposition studies has been criticized for creating unrealistic 'microclimate' conditions; e.g. moisture may be elevated to levels not found in unconfined conditions and can contribute to litter decomposition [15, 16]. Losses due to earthworm consumption or litter fragmentation overestimate those mediated by microbial activities. Frankland [23] studied the weight loss pattern of *Bracken rachids* through the unconfined method i.e., using plastic labels to mark the litter before placing it on the soil surface. The study noted that retrieval of decomposing litter under this method is tedious and presents large potential errors in estimating the decomposition rates. Also, it does not protect the litter from the interferences of larger organisms and fragmentation. Therefore methods to overcome these drawbacks are imperative when investigating the factors that control leaf litter decomposition.

As an alternative, numerous studies have measured decomposition rates of litter by the CO_2 evolution or carbon mineralization method [14, 24–29]. This method has the advantage of measuring decomposition during shorter periods (hour scale); i.e., through early decomposition stages when weight loss cannot be accurately quantified [30]. However, the CO_2 evolution method requires an experimental set-up that often deviates farther from the natural conditions than weight loss measurement. Studies simultaneously quantifying litter weight losses and investigating rates of CO_2-C evolved are few; however they are essential for accurate estimates of forest nutrient cycling. Nonetheless, results from the few studies on litter decomposition studies using the CO_2 releasing method have been comparable to the weight loss method [27, 31, 32].

Many litter decomposition studies have focused on individual plant species when investigating the factors influencing litter decay [33–38]. However, leaf litters in ecosystems with more than one dominant plant species do not fall separately, either in time or space, but create an admixture of litters. Although the potential of litter interactions was hypothesized to have a marked effects on their decomposition in agro ecosystems many years ago by Thomas [39], Staaf [40], Seastedt [41] and many others, studies on potential interactions in mixed leaf litter decomposition are still few and not well understood, and so require further investigations to aid planning for nutrient management through decomposition and nutrient release in agroforestry and similar systems [42]. Hansen and Coleman [43] noted some changes in the chemical environment (increased nutrient availability) due to litter mixing during decomposition studies of mixed litters of yellow birch (*Betula alleganiensis* Britton), red oak (*Quercus rubra* L.) and sugar maple (*Acer saccharum* Marsh).

This chapter reports on the findings from laboratory incubation experiments carried out on separate leaf samples of cocoa and shade species and 1:1 mixed cocoa-shade leaf litters. Dry mass loss and C emission from unconfined leaf samples were analyzed to (i) determine the decomposition dynamics of cocoa litter, and of the dominant shade species in cocoa ecosystems, (ii) investigate the effects of leaf interactions on decomposition (iii) assess the relationship between decomposition rates and C release patterns, (iv) determine the C emission rates during leaf decomposition, and (v) assess the relationship between leaf weight loss and C emissions during decomposition, and (vi) determine the CO_2 mitigation potentials of cocoa systems. The study hypothesized that the decomposition rates of the mixed leaves of cocoa-shade systems would (1) differ from the rates of decomposition of the separate litter components decomposing alone (i.e., separate cocoa and shade leaves), (2) be equal to the pooled rates of the separate litter components decomposing alone, (3) the amount of C in the litter loss is the same as the C emitted during litter decomposition and (4) cocoa systems have the potential to mitigate CO_2 emissions.

2. Materials and methods

2.1 Leaf sampling and site

Leaf samples from three tree species (cocoa, *Newbouldia laevis* dominant species in Eastern Region (ER) and *Persea americana* dominant in Western Region (WR)) were collected from cocoa ecosystems in ER and WR of Ghana. Farms were selected in the ER at the Duodukrom community within the Suhum District (6°2′ N, 0°27′ W), and the in WR at Anyinabrim found in the Sefwi-Wiawso District (6°57′ N, 2°35′ W).

The ER covers a land area of 19,323 km^2 representing 8.1% of the total land area of Ghana [44]. It lies between latitude 6° and 7° N and longitude 1°30′ W and 0°30′ E. The region has been producing cocoa long before cultivations started in the Western region. The WR occupies a land area of 23,921 km^2 which is approximately 10% of the total land area of Ghana [44]. The region is the wettest part of Ghana and harbors about 24 forest reserves that account for about 40% of the forest reserves in Ghana. The sampled leaf litters from these regions were transported to the Soil Research Centre of the University of Reading, UK, where the following experiments were conducted.

2.2 Initial chemical properties of the oven-dried leaf litters

2.2.1 Total carbon

The total carbon (C) in the samples was determined using the Europa Roboprep connected to a VG 622 Mass Spectrophotometer. Weights of 0.90–1.10 mg (oven dry) of plant components (root, stem, branch, leaf and litter), and 8.00–12.00 mg (air dry) of soil samples, in triplicate, were put into small pre-weighed aluminum cups and pressed to seal completely using forceps. The sealed samples were arranged in a labeled sample holder and transferred to the Mass Spectrometry System for analysis. The analytical output was in % C of the samples.

2.2.2 Total nitrogen

The total N in the leaf and soil samples was determined using the Europa Scientific ANCA System. Samples of 5–6 mg leaf and 8–12 mg soil were weighed into small aluminum cups and pressed to seal using forceps. The sealed samples were transferred to the Europa system for analysis. The analyzed data were expressed as % N (w/w).

2.2.3 Total P, K, Ca, Mg and S

Approximately 0.5 g oven dry plant samples (i.e., root, stem, branch, leaf) were accurately weighed and transferred into 100 mL Kjeldahl digestion tubes. About 10 mL of concentrated AnalaR nitric acid were added to each tube in a fume hood. Each tube was then covered with a glass marble and left to stand overnight. The tubes were placed on a digestion block the next day and cautiously heated to 60°C for 3 h followed by a gradual increase to 110°C and allowed to digest for 6 h. The digestion tubes were then removed, allowed to cool and the digest filtered through prewashed No. 540 (12.5 cm diameter) filter papers into 100 mL volumetric flasks. The flasks were made up to volume with ultra-pure water. Aliquots of 5 mL from each flask were diluted by a factor of two and

analyzed for concentrations of P, K, Ca, Mg and S using the inductively coupled plasma-optical emission spectrometry (ICP-OES).

Standards of multi-element solution (0.5, 1, 50 and 100 mg/L K, Ca, Mg, Mn, Zn, Fe, and Al), sulfur (50 mg/L) and phosphorus (50 mg/L), as well as a blank (0 mg/L) were prepared to contain the same nitric acid concentration as in the digest to calibrate the ICP-OES. The data generated by the ICP-OES were reported in concentrations (μg/L) which, after correcting for the blank reading, was converted to mg/kg dry weight based on the sample weights digested, volume of extract and the dilution factor [45].

2.2.4 Lignin concentration

As outlined in Anderson and Ingram [46], a 1 ± 0.001 g sample of leaf for each tree species was weighed (W1) into 200 mL Berzelius beaker. A 100 mL of acid detergent solution (20 g of cetyltrimethyl ammonium bromide (CTAB) was dissolved in 27.84 mL of sulfuric acid (98% purity) in a 1000 mL volumetric flask and brought to the mark with distilled water and to form a clear solution by heating) was then added and heated to boil for 1 h. The content was filtered hot through a vitreosil crucible (No. 1) of known weights (W2). The residue was washed with 3 × 50 mL aliquots of hot water and then with acetone until no more color was removed. The residue was then oven-dried at 105°C for 2 h, cooled in a desiccator and weighed whilst still in the crucible (W3). The sample remaining expressed as a percentage of the initial weight of the sample, estimated the acid detergent fiber (ADF) content of the sample:

$$\mathrm{ADF}(\%) = \frac{(W3 - W2) \times 100}{W1} \tag{1}$$

A saturated potassium permanganate solution was prepared by dissolving 50 g $KMnO_4$ and 0.05 g Ag_2SO_4 in a 1000 mL volumetric flask and brought to the mark with distilled water. Lignin buffer solution was also prepared by dissolving 6 g $Fe(NO_3)_3{\cdot}9H_2O$ and 0.15 g $AgNO_3$ in water followed by addition of 400 mL methylpropan-2-ol and diluted to 1000 mL with distilled water. A combined solution of the saturated $KMnO_4$ and lignin buffer solution in the ratio of 2:1 was prepared. The crucible containing the ADF was then placed in a shallow enamel containing cold water carefully without wetting the fiber and 25 mL of the combined $KMnO_4$/buffer added. The content was stirred with a glass rod to break up lumps and to wet all the fiber particles in the crucible with the solution and allowed to stand for 3 h. The content in the crucible was then filtered under suction and washed with demineralizing solution (50 g oxalic acid dehydrate dissolved in 700 mL 95% ethanol, followed with addition of 50 mL conc. HCl and diluted to 1000 mL with distilled water) until white. This was filtered and washed thoroughly with ethanol under continuous suction and washed in a similar manner with acetone. The crucible was then oven-dried at 105°C for 2 h, cooled in a desiccator and weighed (W4). The percentage lignin in the sample was then calculated as:

$$\mathit{Lignin}(\%) = \frac{(W3 - W4) \times 100}{W1} \tag{2}$$

2.3 Sample preparation for experimentation

Approximately 100 g each of 2-mm sieved air-dried plant materials (viz. cocoa, *N. laevis* and *P. Americana,* 1:1 (w/w) mixture of cocoa: *N. laevis* and cocoa:

P. americana leaf litters) were weighed into a 500 mL beaker. Water (300 mL) was gradually added to each weighed litter sample with continuous stirring to produce a moist litter treatment that was not saturated [27]. They were kept in a fridge at a temperature of 4°C for 72 h to attain an equilibrated moisture status in all treatments. Three weighed sub samples (6 g) of each treatment were oven-dried at 80°C for 24 h and used to determine a conversion factor to an oven dry basis.

2.4 Leaf decomposition experiment

A known weight (approx. 6 g) of each leaf treatment was transferred into a labeled 15 mL beaker separately. Soil (~5 mg) from the region specific to the leaf treatment was added to the beaker to serve as an inoculant. Each beaker unit was replicated 12 times to give the total of 72 experimental units. These units were weighed and randomly arranged for incubation in a 30°C controlled dark room located in the Soil Chemistry laboratory of the Soil Research Centre, University of Reading, UK. Three (3) replicates of each treatment were retrieved after 0, 20, 50, 80 and 120 days of incubation. The beakers so retrieved following each incubation period, were oven-dried at 80°C for 24 h and weighed. The residual oven-dried litters were appropriately labeled and stored for chemical analysis.

2.5 CO_2-C emission experiment

A sample (3 g) of each litter treatment was transferred into a 250 mL conical flask. As shown in **Figure 1**, the neck of the flask was closed with a rubber bung from which was suspended a vial containing 20 mL of 1 M NaOH solution to trap CO_2 evolved as outlined by Rowell [47]. A similar conical flask was set-up without leaf treatment as a blank. Each flask unit was replicated 3 times to give a total of 21 experimental units comprising 18 litter treatments and 3 blanks. Also, the treated conical flasks were randomly arranged for incubation in a 30°C controlled dark room located in the Soil Chemistry Laboratory of Soil Research Centre, University of Reading, UK. At 0, 3, 5, 11, 16, 28, 43, 60, 75, 90, 103 and 130 days of incubation, the vials were removed, and the NaOH was carefully transferred quantitatively (with rinsing) into an empty 50 mL conical flask for titration. Ten milliliters (10 mL) of 1 M $BaCl_2$ was added to precipitate the carbonate compounds ($NaHCO_3$) formed as a result of reaction between NaOH and CO_2 (**Figure 1**). The vials were thus, removed 12 times and replaced after refilling with fresh NaOH solution before closing the incubation beaker to continue the capture of released CO_2 from the decomposing leaves. The amount of CO_2 captured was determined by titrating the unreacted NaOH in the 50 mL flask with 0.5 M HCl using phenolphthalein as the indicator.

2.6 Data analysis

The data on per cent mass remaining, carbon and nutrient concentrations of pure cocoa leaf and shade species leaf decomposing alone were used to estimate expected data for mixed cocoa and shade litter denoted as predicted mixture, using the simplified form of similar relations used by others as:

$$predicted\,(x) = \frac{Cocoa\,(x) + Shade\,(x)}{2} \tag{3}$$

where x = per cent mass remaining, carbon or nutrient concentration, and C emission of the leaf treatments at each retrieval day [28, 48, 49]. Any significant difference between the estimated predicted mixture value and the actual mixed

Figure 1.
Photograph of CO_2-C emission experiment.

cocoa-shade leaves treatment indicated an interaction in the decomposition of the mixed leaves, either negative or positive [49]. The data on % residual leaf were fitted to the exponential decay Eq. (2) that was proposed first by Olson [50] to describe the decomposition rates of the leaf litter treatments:

$$R_t = R_o * \exp(-k_d t) \tag{4}$$

where R_t = % residual weight at time t, R_o= initial litter per cent at day zero (i.e 100%) and k_d = decomposition rate constant.

The data on C emission were fitted to the single exponential rise-to-maximum (growth) model.

$$C_t = C_o * \left[1 - \exp(-k_m t)\right] \tag{5}$$

where C_t = amount of C emitted after time t of the incubation; C_o= amount of C that can be potentially emitted within the period of incubation; and k_m = mineralization rate constant.

The amounts of C accompanying the loss leaves during the decomposition processes were calculated as:

$$[C]_{loss(t)} = \frac{(100 - \%leaf_{remained(t)})}{100} \times [C]_i \tag{6}$$

where $[C]_{\text{loss(t)}}$ is amount of C in the leaf loss (g/kg) at time t (i.e., 0, 20 40, 80 and 120 days), and $[C]_{\text{i}}$ is the initial carbon concentration in the litter (g/kg).

The comparison was carried out statistically using ANOVA to test for significant differences of all data parameters (% residual litter mass, C and nutrient concentrations and release, C emission, C_o, and k_d). Tukey's mean separation procedure at the 0.05 level of significance was used for all data. All figures were produced with SigmaPlot 10.0 using the means of % residual litter mass, C and nutrient concentrations and release and also C emission. Also the fitted model parameters were estimated using the SigmaPlot 10.0 regression analysis module.

3. Results and discussion

3.1 Chemical characteristics of the leaf sample

3.1.1 Eastern region of Ghana

Literature is replete with the important role that litter chemistry plays in decomposition and nutrient release in top soils [14, 26, 51–53]. The initial concentrations of some elemental nutrients of the leaf litter samples are presented in **Table 2**. The leaf litter treatments did not differ significantly ($P > 0.05$) in their C and S concentrations in the Eastern region (ER). The leaf litters generally had low oxidizable carbon concentration by weight with less variability as indicated by the narrow range of 337.0–382.6 g/kg. The cocoa-shade mixture had the highest C and the leaf litter of shade tree contained the least (**Table 2**). Honeycutt et al. [54], Woomer et al. [55], and Kuo et al. [56] noted that plant residues have stable carbon concentration of about 40% by weight. Other studies have used a constant value from 450 to 500 g/kg as the C concentration for all parts of a tree biomass including the leaves [57–60]. Thus, the present C concentrations of the leaf litters from cocoa ecosystems in the ER of Ghana are lower than the commonly used ranges. The C concentration of 357.2 g/kg for the leaf litter of cocoa is lower than that reported by Anglaaere [16] as 413 g/kg for cocoa leaf samples from Atwima District in the same Eastern region of Ghana where the present study was carried out. However, the present litter C ranged confirmed the reported C data of 364 to 400 g/kg on similar cocoa leaf litter by Ofori-Frimpong and Rowell [27].

Among the nutrients that varied significantly between the leaf samples, that of the shade tree *Newbouldia laevis*, had significantly ($P < 0.05$) higher K, Ca and lignin but lower Mg concentration than the cocoa leaf litter (**Table 2**). The N, P and S concentrations in the leaf litters of the cocoa and shade trees did not differ significantly ($P > 0.05$). The predicted mixture contained higher P and Mg concentrations than

Leaf litter	C	N	P	K	Ca	Mg	S	L	C/N
	g/kg								ratio
Eastern region									
Cocoa	357.2a	18.4ab	1.13a	4.58c	12.9c	5.94a	1.89a	215.7c	19.4a
Shade	337.0a	13.8b	1.07a	7.36a	16.3a	3.00d	1.89a	288.0a	25.2a
Coc-shade	382.6a	19.5a	0.99b	5.61b	14.1b	4.12c	1.83a	256.9b	19.6a
Predicted	347.1a	16.1b	1.10a	5.97b	14.6b	4.47b	1.89a	251.8b	22.3a
Western region									
Cocoa	378.7a	17.4a	0.85a	8.57a	11.0a	5.25a	1.65b	220.0c	21.9a
Shade	342.4a	15.2a	0.79a	4.43b	9.1b	2.67b	1.78a	289.1a	23.6a
Coc-shade	360.2a	18.5a	0.85a	6.55c	10.0c	3.96c	1.72ab	265.4b	19.5a
Predicted	360.6a	16.3a	0.82a	6.50b	10.0b	3.96b	1.72ab	254.5b	22.7a

[1]Newbouldia laevis *in Eastern region,* Persea americana *in Western region.*
[2]*Different letters within same region and column indicate significant difference at* P < *0.05 using Tukey's method.*

Table 2.
*Initial chemical composition and lignin (L) content (mean) and nutrient ratios of the leaf litters of cocoa, shade (*Newbouldia laevis, Persea americana*)[1] and mixed cocoa-shade under cocoa ecosystems in eastern and Western regions and the predicted mixed litter in Ghana.[2]*

the analyzed mixture of cocoa-shade leaf litter. The lower P and Mg concentrations in mixed cocoa-shade litter than expected or predicted is an indication of non-additive response or negative interaction when cocoa and shade leaves are mixed together. The other nutrient elements, however, were similar in the mixed cocoa-shade and predicted mixed litters, indicating an additive response for those nutrient elements in mixed litter systems such as shaded or agroforestry systems (**Table 2**).

The initial N concentrations of all the leaf litters were higher than the critical level for cocoa foliage N concentration (9.0 g/kg), below which point net N immobilization would be expected [61]. Thus, with the high N concentration of the leaves, net N mineralization is highly possible during the leaf decomposition. Several researchers have considered the N and/or its ratios such as C/N, lignin/N and polyphenol/N of residues as major factors controlling decomposition processes [14, 34, 52]. The C/N and lignin/N ratios of the leaf litters from ER ranged from 19.4 to 25.2 and 11.7 to 21.8, respectively (**Table 2**). Thus, the C/N ratios of the litters are so close to the critical level of 25 noted for decomposition and N mineralization to occur [62, 63].

Where nutrient ratios are used as indices of nutrient status to microbial growth, Girisha et al. [64] put forward that nutrient retention during decomposition depends on their initial status in the litter. The C-element ratio has been commonly used to explain nutrient status where a nutrient element, *say* R, is said to be limiting when the C/R ratio is above a certain critical level set for microbial growth. In this case, nutrient element R will be retained resulting in immobilization but where C/R ratio is below the critical level, the nutrient element R is released during decomposition of the litter [65]. The C/N ratios were statistically similar in the leaf litter treatments under ER (**Table 2**).

Table 2 revealed that the P, K and Mg concentrations of all the leaves from the ER were less than the critical range of 2.0 to 2.5 g/kg, 20 and 5 g/kg respectively. As such, P, K and Mg immobilization would be expected during decomposition [61, 66–68]. The Ca concentrations of the litters were higher than the critical 6 g/kg value. The lignin content of the leaf litters from the ER ranged from 220.0 to 289.1 g/kg dry matter (DM). The cocoa leaf litter had significantly ($P < 0.05$) lower lignin status when compared with the shade and the mixed cocoa-shade leaf litters, as well as the predicted mixture (**Table 2**). However, the lignin concentration (215.7 g/kg DM) in the cocoa leaf litter in this study is higher than the data (141–146 g/kg DM) of Dawoe [69] on cocoa leaf lignin status in Ghana. The lignin concentration in mixed cocoa-shade litter was similar to the predicted mixed litters (**Table 2**). Lignin has been considered a determinant of litter quality and a predictor of decomposition by previous researchers [34, 70, 71].

3.1.2 Western region of Ghana

The leaf litters from the Western region (WR) varied considerably in their initial nutrient and lignin concentrations (**Table 2**). The variations in the C, N and P concentrations did not however, differ significantly ($P > 0.05$) among the leaf litter treatments (**Table 2**). The C concentration of cocoa leaves in the present study was lower than the reported data by Anglaaere [16]. This study found the N (1.74%) in leaf litter of cocoa to corroborate previous studies in other parts of Ghana [16, 69]. Anglaaere [16] reported N of 18.5 g/kg for cocoa leaves, whilst Dawoe [69] found an N range of 9.5 to 14.8 g/kg for cocoa leaves from 3 to 30 year old cocoa trees. It thus appears that foliar N concentration for cocoa is highly variable. With the N concentration of all the leaf litters being lower than the critical N level of 20 g/kg, net N immobilization would be expected during decomposition [29, 62, 63].

Differences in total P concentration of the leaf litters from the WR were not significant ($P > 0.05$) and were all low when compared to the leaf litters from ER

(**Table 2**). Anglaaere [16] also found the P to be low, at 1.3 g/kg in Ghanaian cocoa leaf, confirming the low P status of cocoa litters in Ghana found in the two regions by this study. Compared with critical levels of nutrient elements, the cocoa leaf litter in this study is deficient in P, K and Mg concentrations [61]. It is thus expected that during decomposition of the leaf litters from WR, as with ER, the deficient elements would not be released easily resulting in temporal nutrient immobilization [61, 66, 67].

The K, Ca and Mg concentrations in the leaf litter of the WR shade tree *P. americana* were significantly ($P < 0.05$) lower than those in the cocoa litter but higher in lignin concentration (**Table 2**). With respect to K and Mg, the leaf litter of the cocoa in the WR contained approximately twice as much as that in the shade tree litter. Compared with data on cocoa foliar nutrients in Anglaaere [16], the cocoa leaf nutrients from the WR appeared to be similar.

The initial chemical composition of the leaf litter of mixed cocoa-shade was generally similar to that of the predicted mixture treatment with the exception of P and Mg in the ER; and K, Ca and Mg in the WR, suggesting a high predictability of mixed litter nutrients from the single component species nutrient concentrations (**Table 2**). Overall, there were significant variations in the nutrient balance of the leaf litters and also high variability in nutrient ratios as shown in **Table 2**. These nutrient variations were more pronounced in the single litter treatments than the mixed and predicted mixed litters.

3.2 Decomposition trends of the leaf samples

Figure 2a presents the decomposition patterns of leaf litters of cocoa ecosystems in the ER obtained during a 120-day laboratory incubation experiment. During the first 20 days of incubation, the shade litter lost approximately 9% of its initial weight whereas the cocoa leaf litter lost only 2.8% of its weight, indicating a lag phase in the decomposition of the cocoa leaf litter (**Figure 2a**). Anglaaere [16] reported mass loss of 3.45% of cocoa leaf litter within the first one month of initial decomposition. However, the % leaf litter of cocoa and shade trees that remained did not differ significantly during the first 20 days of incubation. Thereafter, significant differences occurred in the per cent mass remaining between the leaf litters of cocoa and shade trees, with the leaf litter of the latter continuously decomposing at a higher rate than the former as incubation time progressed (**Figure 2a**). At the end of the 120 days of incubation, the leaf litter losses were 17.6 and 30.7% in the cocoa and shade litters, respectively. These litter loss percentages compared well with the reported losses between 16 and 33% of cocoa leaf litters within 80 days of incubation by Ofori-Frimpong and Rowell [27].

Overall, the decomposition pattern of the mixed cocoa-shade litter treatment indicated an additive response and thus, appeared predictable from the decomposition patterns of the component litters decomposing alone. Although the litter remains of the mixed cocoa-shade litter could not be separated into the individual components at any stage of the incubation, both the predicted and the actual mixed cocoa-shade litter treatments indicated higher ($P < 0.05$) decomposition rates than the pure cocoa leaf litter treatment (**Figure 2a**); this indicates that mixing leaf litter has the potential to enhance litter decomposition in the cocoa ecosystems in the ER.

The decomposition patterns of the leaf litter gathered from the cocoa farms in the WR is presented in **Figure 2b**. The decomposition pattern of the leaf litter of the shade species (*P. americana*) displayed a lag phase within the first 20 days of incubation where only about 3.6% had undergone decomposition (**Figure 2b**). The leaf litter of cocoa had significantly lower % remaining when compared with the

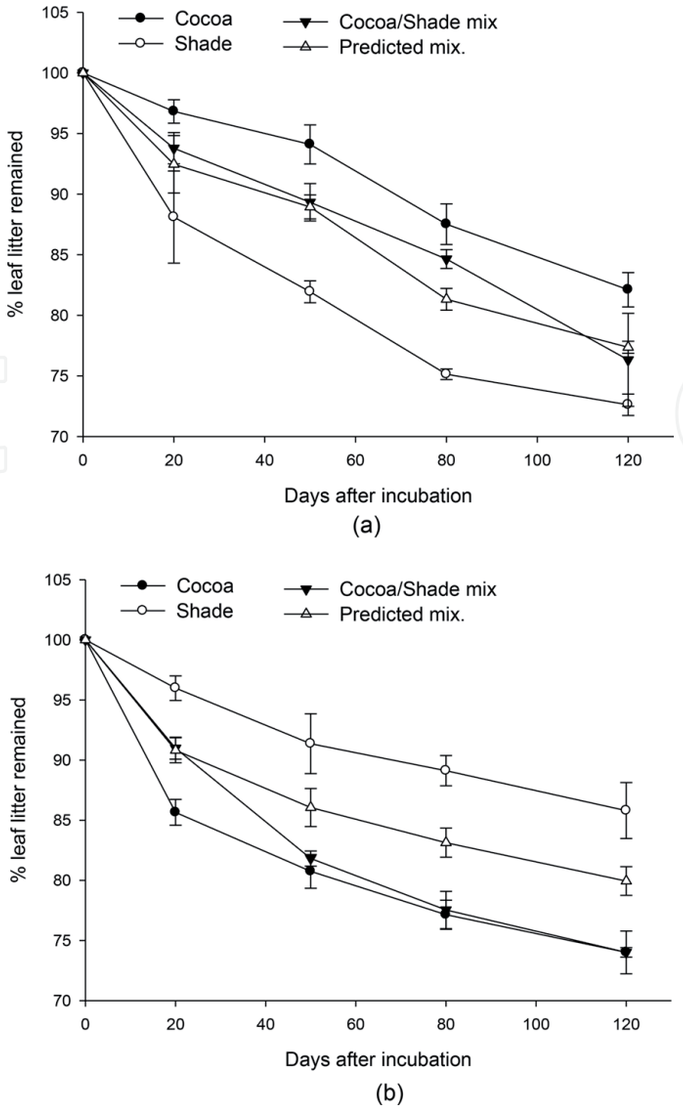

Figure 2.
Decomposition patterns of leaf litters in cocoa ecosystems: (a) Eastern region and (b) Western region. Bars indicate standard error (n = 3).

leaf litter decomposition pattern of the shade species as the incubation progressed. By the end of 120 days of incubation, the mass loss of cocoa was 29.1% of the initial weight whilst the shade litter decomposed by only 15.1% of its initial dry weight (**Figure 2b**). The mass loss of 29.1% for cocoa leaf litter from WR is greater than that (17.6%) from ER and, also, the reported mass loss of 22.35% by the 4th month of incubation of cocoa leaf litter from the Ashanti region of Ghana [16].

Comparison between the decomposition patterns of mixed cocoa-shade and the predicted mixed litter treatments showed no significant ($P > 0.05$) difference up to the first 20 days of incubation. Thereafter, there was a clear difference in the decomposition patterns between them for the next 100 days of incubation with the mixed cocoa-shade litter treatment decomposing at faster rates. As the time for decomposition progressed beyond 50 days, the cocoa-shade mixed litter decomposition pattern tended to behave like the pure cocoa leaf litter (**Figure 2b**). Thus, the mixed cocoa-shade treatment showed a non-additive response with positive interaction after 20 days of incubation and therefore, its decomposition is not predictable from the component species of the mixture. Over the 120-day incubation period, the amounts of leaf litter that decomposed were 26 and 20% for the mixed cocoa-shade litter and predicted mixed litter, respectively. The implication is that shaded

cocoa system in the WR would be more efficient in nutrient cycling than expected. However, decomposition of cocoa leaf litter alone (unshaded system) was similar to that of mixed cocoa-shade litter (shaded systems).

3.2.1 Decay constant

The leaf decomposition patterns shown in **Figure 2a** and **b**, conformed well (R^2 = 0.81–0.99) to the single exponential decay model proposed by Olson [50] for similar mass loss studies. However, the plots of the model were observed not to go through 100% weight remaining at the start (i.e., day zero) of the incubation, indicating some degree of deficiency associated with the model [2]. Notwithstanding, the same model has been used by other researchers in recent times to fit similar litter decomposition data [46, 72–74]. From the fitted model for the % leaf litter remaining, the decomposition rate constants (k_d) of the leaf litter treatments were estimated for a period of 120 days of decomposition and are presented in **Table 3**. The k_d measures the proportion of the material that decays per unit time. Therefore, the lower the k_d of a decomposing organic material, the slower it decomposes.

In the Eastern region (ER), the decomposition rate constants varied considerably and ranged from 1.65 × 10^{-3}/day for the leaf litter of cocoa to 2.72 × 10^{-3}/day for leaf litter of shade tree (**Table 3**). The k_d for the mixed cocoa-shade and predicted mixture treatments were intermediate between that of the cocoa and the shade, in support of their decomposition patterns described earlier (**Figure 2a**). The leaf litter of the shade species had a much higher (P < 0.05) decay rate constant than the cocoa leaf litter treatment. Anim-Kwapong and Osei-Bonsu [75] found a similar high k_d value of 2.51 × 10^{-3}/day (recalculated from authors' half-life value of 9.22 for *N. laevis*) for *N. laevis* also collected from the same ER of Ghana. In respect of the decomposition rate of cocoa leaf litter in the present study, comparable leaf litter decay rates have been reported by Owusu-Sekyere et al. [76] and for some forest tree species [77]. The decomposition rate of the predicted mixed leaves and the actual mixed cocoa-shade treatments (2.14 × 10^{-3}/day) were exactly the same; this agrees with the earlier assertion of additive response for mixed leaf decomposition

Leaf litter treatment	Decomposition constant, k_d/day	Potential C mineralizable, C_o g/kg
Eastern region		
Cocoa litter	0.00165b[2]	107.7b
Shade litter	0.00272a	114.8ab
Mixed cocoa-shade	0.00214ab	118.5a
Predicted mixed litter	0.00214ab	111.2ab
Western region		
Cocoa litter	0.00240a	119.9b
Shade litter	0.00127b	61.10d
Mixed cocoa-shade	0.00259a	209.7a
Predicted mixed litter	0.00187ab	90.40c

[1]Newbouldia laevis *in Eastern region,* Persea americana *in Western region.*
[2]*Different letters within same region and column indicate significant difference at* P < *0.05 using Tukey's method.*

Table 3.
*Decomposition constants and potential mineralizable C (% of initial oxidizable C) of cocoa, shade (*Newbouldia laevis*,* Persea americana*)[1], mixed cocoa-shade and predicted cocoa-shade mixture under cocoa ecosystems in eastern and Western regions of Ghana.*

simulating the litter state of shaded cocoa ecosystems in the ER. Based on the k_d values, the order of the leaf litter decomposition in the ER followed:

Shade > mixed cocoa-shade = predicted mixed litter > cocoa.

The higher rate of decomposition in mixed leaves of cocoa-shade than pure leaves of cocoa suggests that nutrient cycling in cocoa ecosystems of the ER would be favored by shaded cocoa ecosystems. Owusu-Sekyere et al. [76] attributed the slow decomposition rate constant of cocoa to high lignin and polyphenol concentrations in the cocoa leaves. However, in their case the data showed no significant difference between leaves of forest species and cocoa with respect to C/N ratios, yet the forest species exhibited a significantly higher decay rate.

Indeed, several works on litter decomposition have reported significant correlation between initial chemical composition of decomposing materials and the decay constants. Some of the litter constituents that have indicated significant correlations with k_d in previous studies included the initial C, N, P, Ca concentrations, lignin, polyphenols and ratios of C/N, lignin/N and polyphenol/N of decomposing organic materials [10–14, 32, 76]. In contrast, the k_d values estimated for the leaf litters from ER did not show significant correlations with C, N, P, S and C/N (**Table 4**). Rather, the k_d values correlated positively ($P < 0.05$) with K, Ca, and negatively ($P < 0.05$) with Mg (**Table 4**). The cations; K, Ca and Mg are known to activate enzymes that promote metabolism [78] implicating their role to driving litter decomposition. Similar correlations between decomposition rates and initial concentrations of K, Ca, and Mg have previously been observed by Briones and Ineson [31]. The lack of correlations between k_d values and N concentration or C/N ratios could partly be due to the narrow ranges of the C and N concentrations of the leaf litters under study and/or partly indicates the insensitivity of the k_d to assess the decomposability of the litters [79–82]. The current study agreed with McTiernan et al. [83] who found a significant correlation between k_d and Ca, and none for k_d and N concentration for a mixture of tree leaf litter during decomposition. Elsewhere, others also found C/P ratios to correlate with litter decomposition [84].

In the Western region (WR), decomposition rate constants of leaf litters under cocoa ecosystems ranged from 0.00127 to 0.00259/day (**Table 3**). The estimated k_d values for cocoa systems are higher than the k_d values ranging from 0.221 to 0.227/y (i.e., 0.00060 to 0.00062/day) in Dawoe [69] for cocoa systems in the Ashanti

Element	Eastern region	Western region
C	0.359	0.362
N	−0.549	0.301
P	−0.390	0.799**
K	0.766**	0.726**
Ca	0.726**	0.689*
Mg	−0.763**	0.715*
S	−0.392	−0.496
L	0.766**	−0.591*
C/N	0.664*	−0.195

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

Table 4.
*Correlation coefficients (*r*) between initial chemical composition and lignin (L) of leaf litter and decay constant (*kd*) from cocoa ecosystems in the Eastern and Western regions of Ghana.*

region of Ghana. The author used data on monthly litter fall to estimate the k_d values using the annual litter-fall over litter-stock formulae, which has a greater source of variability due to seasonal effects on monthly litter-fall. Depending on the season, particularly during wet seasons, less litter fall may be recorded leading to lower estimates for k_d values. Anglaaere [16] reported much lower litter-fall biomass from April to November which coincided with the wet season period in the cocoa cultivation regions of Ghana.

The decomposition of the cocoa leaf treatment was significantly faster than that of the shade species (**Table 3**). The difference in the decomposition rates of leaves from cocoa and the shade species is attributable to the differences in the biochemical composition of their leaf structures as similar attributions have been made by many workers to explain variations in decomposing organic materials [28, 64, 81, 82]. Indeed, the present study found significant ($P < 0.05$) positive correlations between k_d values and K, Ca, and Mg but negative correlations with C and S (**Table 4**). Briones and Ineson [31] also reported significant correlations between k_d and K, Ca, and Mg in decomposition of eucalyptus, ash and birch individually, and as litter mixtures during decomposition. Of the initial concentrations of chemical parameters, the cocoa leaf litter was significantly higher in all the positively correlated parameters and lower in all the negatively correlated parameters than the leaf litter of the shade tree, hence the higher estimate of its decomposition rate constant (**Table 3**).

The decomposition rate appeared faster in leaf litter treatments of mixed cocoa-shade than the predicted mixture from the single decomposition rates of the components, but the difference was not significant ($P > 0.05$, **Table 3**). The observed faster rate of decomposition in the mixed cocoa-shade is an indication of a possible synergistic effect under shaded cocoa systems in the WR during litter decomposition. Compared with the single plant species leaf litter decomposition rate constant, the mixed leaf litter decomposed at a rate similar to leaf litter of pure cocoa, both of which were faster ($P < 0.05$) than the pure leaf litter of the shade tree. The significance of the above finding is that, litter decomposition and nutrient release patterns would not differ between shaded cocoa and unshaded cocoa ecosystems in the WR but will be lower in a forest of only *P. americana* trees.

3.2.2 Carbon release patterns

The carbon and nutrient contents of the residual litters were determined as the product of their concentration and the litter dry mass; this allowed C and nutrient release to be plotted as a percentage of the initial C and nutrient contents of the litters. Similar plots have been provided by other researchers [48, 49]. **Figure 3** presents the C release patterns for the various litters during the course of decomposition. Leaf litters from the ER all released C in the course of the decomposition. The C release patterns were similar and linear except in the mixed cocoa-shade where the pattern was curvilinear with an initial faster C release within the first 20 days, then a gentle release between 20 to 80 days, and a slow release followed thereafter to 120 days (**Figure 3**ER: (C)). However, the amount of carbon released among the litters did not differ significantly ($F_{12, 40} = 0.64$, $P = 0.797$) during the decomposition. Released C during litter decomposition has been attributed to losses of soluble C and mineralization [65]. After 120 days of incubation, the C released from litters of ER varied between 23.3 and 26.8% of the initial litter C contents.

With regard to decomposition of litter from WR, the C release patterns showed significant ($F_{12, 40} = 3.67$, $P < 0.001$) differences among the decomposed litters during the course of the incubation. The C released from mixed cocoa-shade was the slowest and the cocoa litter released the greatest amount of C during the decomposition process (**Figure 3**WR: (C)). However, the % C released from the cocoa

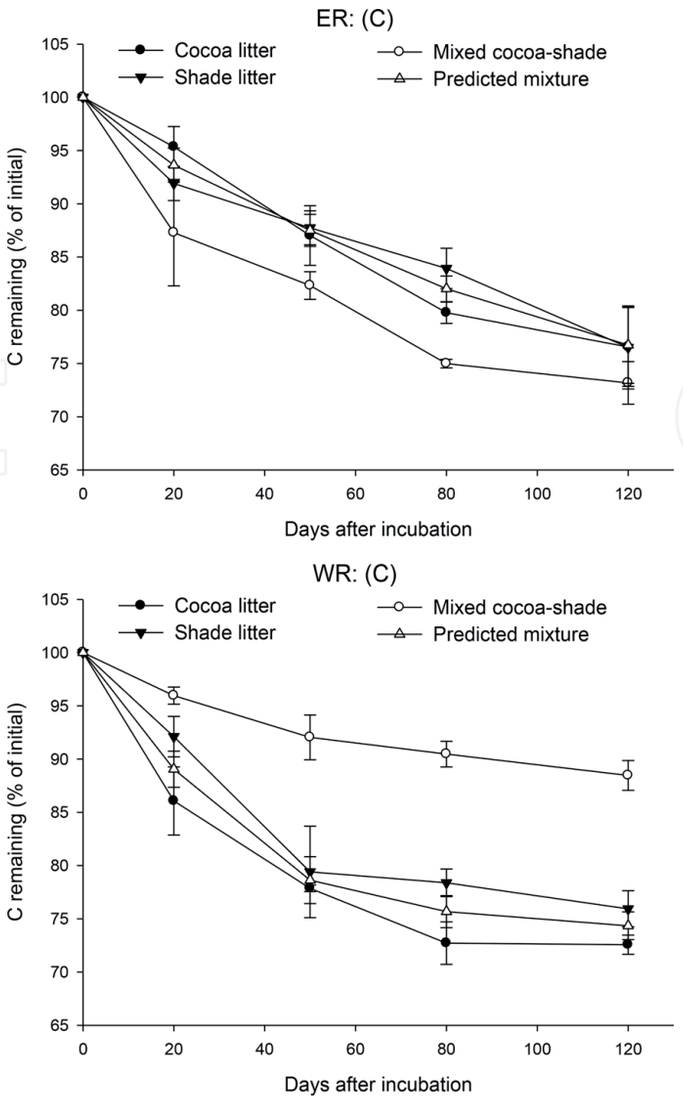

Figure 3.
Carbon released patterns (% of initial C) during a 120-day decomposition of leaf litters from cocoa ecosystems at various stages.

litters were not significantly ($P > 0.05$) different from those of shade and predicted mixture. The % carbon emitted after the 120 days of incubation varied from 11.5% in the mixed cocoa-shade litter to 27.4% in cocoa leaf litters. The implication of the slower C releasing rate of mixed litter than the expected is that, nutrient cycling through decomposition under shaded cocoa system would lead to nutrient limitation and, most likely, could cause nutrient deficiency for growing crops.

3.3 Carbon emission patterns during leaf decomposition

Decomposition processes in agro-ecosystems have been implicated as enriching the atmosphere with carbon dioxide (CO_2). During leaf litter decomposition, the decomposing litter is accompanied with losses of carbon. Although the amount of litter decomposed would be expected to be proportional to the C loss, considerable variations do occur due to different biochemical composition of different plant species [83]. There have not been many studies to monitor the fate of the C loss through the decomposed litter. This requires a method that will capture the C released as litter undergoes decomposition. If C loss data from such a method tends to be comparable to those from the litterbag technique, then the problem of having to retrieve decomposing litter is overcome.

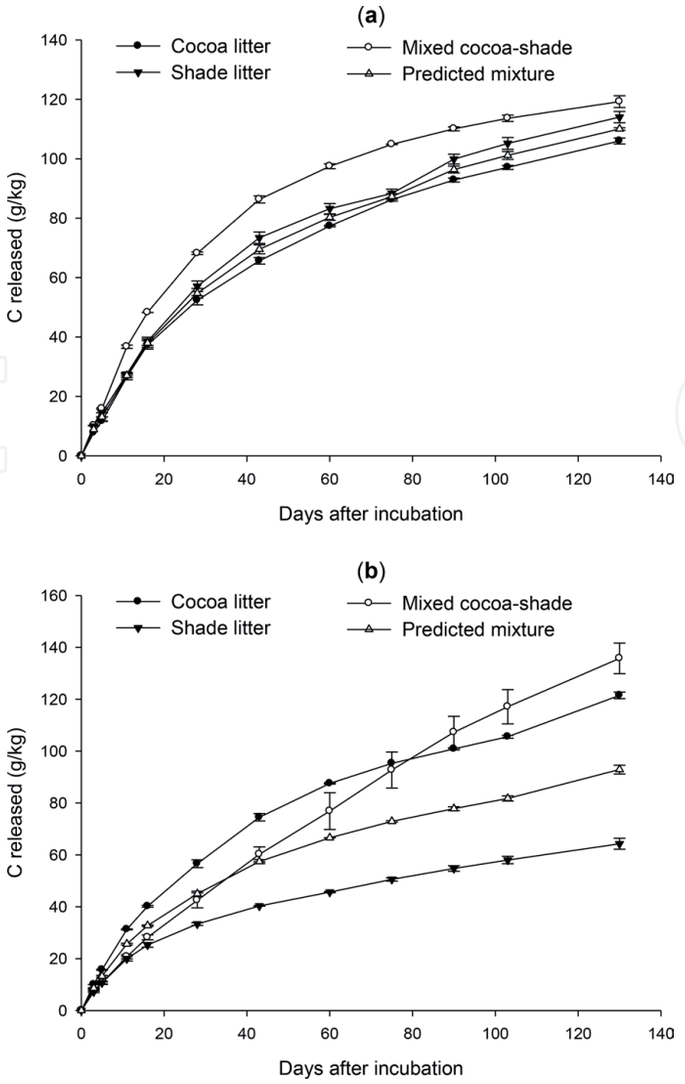

Figure 4.
Carbon mineralization patterns of leaf litters in cocoa ecosystems: (a) Eastern region and (b) Western region. Bars indicate standard error (n = 3).

As a response to the above concern, **Figure 4a** and **b** present the patterns and cumulative amounts of CO_2-C emissions measured during the decomposition of leaf litters collected under cocoa ecosystems of ER and WR of Ghana. The patterns of C emitted from the decomposing leaf litter were somewhat similar. Overall, C emissions increased rapidly during the first 16 days followed by a relatively slow rate as time progressed (**Figure 4a** and **b**). Previous works have also shown double-phase patterns for CO_2-C emissions during soil organic carbon mineralization [82, 85–88]. Even though the C emission patterns were similar, the litter treatments differed significantly ($P < 0.05$) in the amounts of C released at all times during the incubation.

Among the litter treatments from the ER, the mixed cocoa-shade consistently released significantly more C than the other treatments which did not differ in their C emissions (**Figure 4a**). Thus, whilst there was no difference between the pure cocoa and shade treatments, the C emission of their mixture was higher than expected and could not be predicted from the separate litter treatments as indicated by the significantly ($P < 0.05$) lower C emission pattern of the predicted mixture. At 130 days of incubation, the amounts of C emitted from the litter treatments ranged from 106.0 to 119.2 g/kg for cocoa and mixed cocoa-shade treatments, respectively (**Figure 4a**). The higher C mineralization in mixed cocoa-shade appeared to be the effect of P which is the only nutrient element that differed between the mixed cocoa-shade and the other samples from ER (**Table 2**).

Leaf treatments from the WR exhibited similar C release patterns as earlier stated; each showing a double phase comprising of an initial rapid rate and a subsequent decreasing rate as the incubation advanced (**Figure 4b**). However, in the case of the litter treatments from WR, the cocoa leaf treatment emitted significantly ($P < 0.05$) more C than the other treatments until 43 days of incubation when there was no longer significant difference from the C emissions of mixed cocoa-shade treatment (**Figure 4b**). The lowest C emission pattern was observed from the treatment with shade leaf litter. The C emission patterns of the mixed cocoa-shade and predicted mixture treatments exhibited fluctuations such that higher C emission was estimated by the predicted mixture from 5 to 16 days. The C emitted from both did not differ between 28 and 75 days, and thereafter, the C emissions of the mixed cocoa-shade treatment exceeded the predicted emissions towards the end of the observation (**Figure 4b**).

At 130 days, the range of C emitted from the treatment with leaf litters from WR was 64.3 to 135.8 g/kg for the shade and mixed cocoa-shade treated litters. Previous works on soil carbon mineralization reported that the initial biochemical composition plays a major role in driving the process and C/N ratio of decomposing organic material is said to be a good indicator of its mineralization potential [89]. However, the findings herein are unable to confirm or deny the importance of C/N ratio since the litters did not differ significantly and were all less than the critical C/N ratio of 25 below which mineralization would be expected [62, 63].

3.3.1 Potential mineralizable C for 130 days incubation

The potential mineralizable C pools from the leaf litters at the end of 130 days of incubation were estimated by fitting the C emission patterns (**Figure 4**) to a single exponential rise-to-maximum (growth) model (Eq. (6)). The same model has been used previously on similar data by others [82, 87, 90]. The data on emitted C conformed well to the model (R^2 = 98.0–99.9) and the estimated parameters provided estimates of potential mineralizable C and the mineralization rate constants of the litter treatments as presented in **Table 3**.

The potential mineralizable C (C_o) estimated for the litters from ER during the 130-day incubation had a narrow range of 107.7–118.5 g/kg for cocoa and mixed cocoa-shade treatments, respectively (**Table 3**). The estimated potential mineralizable C represents approximately 26.4–29.6% of the oxidizable C in leaf litters of cocoa and mixed cocoa-shade, respectively. This indicates that the leaf litters had close potential for releasing similar amounts of C. However, these estimated mineralizable carbon values differed significantly ($F_{3, 4} = 11.50$, $P = 0.020$) according to the litter treatments. The differences in amount of estimated mineralizable C appear to reflect the quality of the oxidizable carbon source. Indeed, a correlation analysis indicated the presence of significant relationships between the estimated mineralizable C of leaf litters from ER and some initial chemical properties of the litter treatment as follows: N ($r = 0.713$, $P = 0.047$), P ($r = -0.784$, $P = 0.021$), and C/N ($r = -0.883$, $P = 0.004$). However, other researchers found high mineralizable C from decomposing *Mucuna* litter and attributed this to its low lignin content rather than its C/N ratio [85, 87]. This means that the amount of potential mineralizable C from decomposing organic material is partly controlled by its biochemical quality.

There were considerable variations in the estimated mineralizable C among the leaf litter obtained from the WR (**Table 3**). The results indicated a wider range of mineralizable C pools of 61.10–209.70 g/kg respectively for the shade and mixed cocoa-shade litter treatments. The estimated potential mineralizable C range for the WR litters represented a potential C loss range of 13.4–49.6% of the

initial oxidizable C content of the litters within 130 days of incubation. The present estimate for C loss relative to the period is much higher when compared with Saffigna et al. [91] who reported a decline in mineralizable C by 29% when sorghum residues were removed for 6 years from a hitherto amended soil. However the lower C loss associated with sorghum residue partly reflects its lower oxidizable carbon content relative to cocoa litter. The cocoa litter contained approximately twice as much mineralizable C as contained in the shade litter, but the mixed cocoa-shade contained more than twice as much potential mineralizable C as expected by the predicted mixture capacity (**Table 3**).

There were no significant correlations between the estimated mineralizable C pools from the WR leaf litter treatments and the biochemical composition of the decomposing litter although there were indications of moderate relationship with each one of the following: C ($r = -0.672$, $P = 0.068$), N ($r = -0.564$, $P = 0.145$), and P ($r = 0.530$, $P = 0.176$). It thus confirms that the amount of potential mineralizable C estimated from the litter incubation partly reflected the initial chemical composition and the amount of oxidizable C in the decomposing litter.

3.4 Comparison of C from leaf weight loss and CO_2-C evolution methods

Although leaf decomposition is generally measured by weight loss, it is also measured by carbon dioxide release in numerous studies [24, 25]. These methods have several sources of variations as mentioned in the introductory section that potentially could confound the results and cause deviations from litter decomposition under natural vegetation types. Comparison of methods is an option through which interference from the methods with the results can be isolated.

Table 5 presents the measured amounts of C released from cocoa systems in ER and WR during leaf litter decomposition averaged over the incubation period (120 days) by the weight loss and carbon dioxide evolution methods. Under the cocoa systems in the Eastern region, the C released measured by the CO_2 evolution method was significantly higher than measured by the weight loss method in cocoa leaf ($F_{1,3} = 38.1$, $P = 0.009$), mixed litter ($F_{1,3} = 23.5$, $P = 0.017$) and predicted mixed litter ($F_{1,3} = 18.4$, $P = 0.023$) decomposition but their difference was not significant ($F_{1,3} = 0.07$, $P = 0.810$) with respect to shade tree leaf decomposition (**Table 5**). These higher amounts of C from the released CO_2 measurements are usually unexpected under natural unconfined environments since the release of CO_2

Region	Litter			
	Cocoa leaf litter	Shade leaf litter	Mixed leaf litter	Predicted mixed litter
Eastern region				
Loss litter C	167.7b	329.0a	230.8b	248.4b
Evolved CO_2-C	304.0a	326.4a	371.1a	315.2a
Western region				
Loss litter C	371.3a	153.8b	324.7a	262.5a
Evolved CO_2-C	338.3a	185.1a	326.9a	261.8a

[1]*Different letters within same region and column indicate significant difference at* $P < 0.05$ *using Tukey's method.*

Table 5.
Cumulative C released (g/kg) over 120 days during litter decomposition under cocoa systems in Eastern and Western regions as measured by the weight loss and CO_2-C evolution methods.[1]

during litter decomposition is but one of several ways including fragmentation and organic matter leaching that contributes to the weight loss of buried litter [24, 25].

However, the confinement of the current experiment as described earlier meant that weight losses through fragmentation and leaching of organic matter were disallowed. Therefore, the litter weight loss solely depended on the release amounts of CO_2-C during the period. Thus, the expected weight loss from decomposing litters must at most, be equivalent to the amounts of CO_2 released in the absence of leaching of other organic material. The many steps such as initial total C determination of the decomposing litter, weighing litter remains that have not been dried well or have attached soil particles to determine weight loss and the use of larger time intervals are all sources of variations associated with the determination of C release by the weight loss method. These steps have the potential of being over estimated and might explain the lower amounts C losses by the weight loss method when compared to the CO_2-C evolution method. On the other hand, the short time intervals of the CO_2-C evolution methods with regard to the frequent replacement of the adsorbent creates room for atmospheric CO_2-C to interfere with the decomposition and consequently leads to over estimation of release C from the litter decomposition alone.

Apparently, the above sources of deviations associated with the two methods were minimal under the litter treatments of WR cocoa systems. Hence, the expectation of equality between litter weight loss C and CO_2-C released was confirmed in all but the shade tree leaf litter decomposition. Differences between released C estimated from litter weight loss and CO_2-C evolution measurement methods were not statistically significant under decomposing cocoa litter ($F_{1, 3}$ = 3.9, P = 0.143), mixed litter ($F_{1, 3}$ = 0.008, P = 0.933) and predicted litter ($F_{1, 3}$ = 0.008, P = 0.934) in the WR (**Table 5**). In contrast, the shade tree leaf litter decomposition from WR released significantly ($F_{1, 3}$ = 11.5, P = 0.043) different amounts of C, where the measured C by CO_2-C evolved was higher than that in loss litter (**Table 5**).

Although the measured differences varied between regions, regression analysis of pooled data from the two regions indicated the existence of a strong relationship between weight loss of litter C and the CO_2-C evolution during litter decomposition (**Figure 5**). The line of best fit to the scatter suggests that CO_2-C emission is proportional to litter decomposition in the cocoa ecosystems. Quantitatively, litter decomposition accounts for 70.9% of the variations in measured CO_2-C emissions from the cocoa ecosystems (**Figure 5**). Other researchers have also found strong agreements between the two methods with respect to measuring the C released during decomposition [27, 31, 32].

3.5 Mitigation of CO_2 emissions

The quantity of carbon released from the decomposition of dead materials into the atmosphere contributes significantly to the global carbon budget. It is estimated that about 70% total annual carbon flux (this is equivalent to 68 Pg C/y) derives from the decomposition of plant materials [92]. Forests are recognized as an important component for climate mitigation and adaptation. Conceivably, promoting agroforestry practices such as cocoa ecosystems in the tropics on cleared lands would mitigate the atmospheric CO_2 loads through photosynthesis and C storage in their tissues. The amount of C stored is proportional to the biomass of the tree components and consequently the amount of CO_2 removed from the atmosphere.

In comparing the C stored in cocoa systems with annual crops, many studies have reported higher C storage in the cocoa systems [22, 93, 94]. Lavelle and Pashanasi [95] noted that forest ecosystems and pastures contain more biomass C than cropland. On a vertisol in Ethiopia, Lulu and Insam [96] observed positive

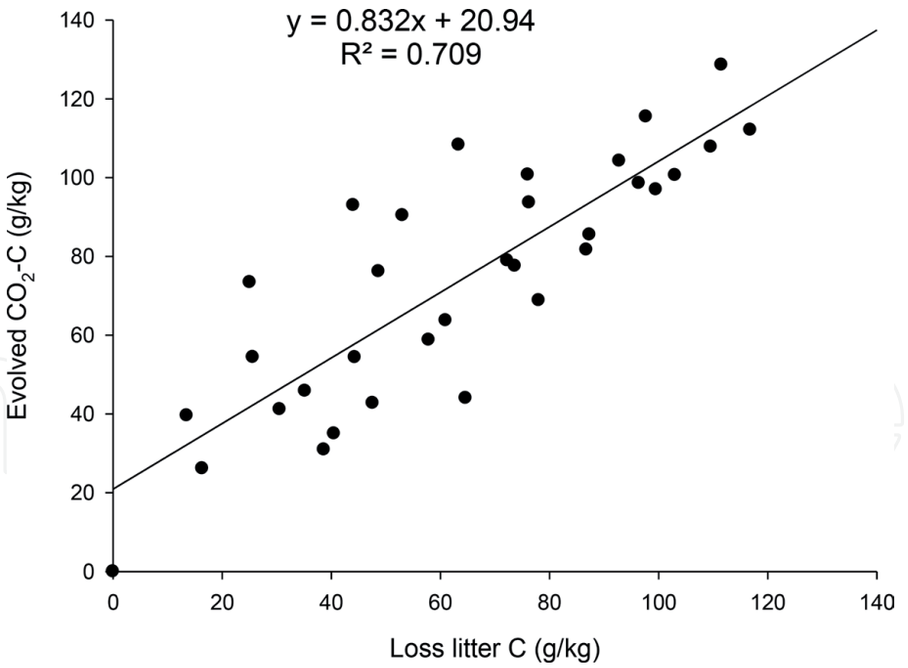

Figure 5.
Relationship between measurements of C released during litter decomposition by the litter weight loss and the CO_2-C evolution methods.

effects of agroforestry practice with Sesbania on soil organic carbon (SOC) pool. Dowuona et al. [97] reported a 25.6 g/kg SOC on a ferric acrisol under *Leucaena leucocephala* woodlot in Ghana compared to the 15.6 g/kg SOC for its *Chromolaena odorata* native fallow adjacent soil.

The recognition of the potential of sequestering carbon in plantations has attracted the attention of many researchers on C sequestration projects. These researchers have predicted a potential market for C in developing nations as a result of the investments from companies and governments wishing to offset their emissions of greenhouse gases as directed by the Kyoto Protocol's Clean Development Mechanism [98, 99].

Whether the soil acts as a source or sink of carbon gases depends greatly on the type and intensity of activities of human management on the land. Soil management practices have been documented to have tremendous effects on soil organic matter (SOM) storage. In a study from adjacent forested and cultivated soils in eight agro-ecosystems from the Ethiopian highlands and Nigerian lowlands, SOM content was two to four times higher in the forested than in the cultivated soils [100]. In an 11-year experiment to assess the potential of different cropping systems to sequester C in the soils, Bostick et al. [101] noted significant reductions of soil organic carbon from a continuous fallow of 0.53% C to 0.46, 0.37, 0.35 and 0.33% C for sorghum-fallow, continuous cotton, continuous sorghum and cotton-maize-sorghum rotations, respectively, in Burkina Faso. Haynes and Francis [102] have reported high amounts of C under pasture relative to cultivated soils. Pichot et al. [103] observed that average soil C increased between 116 and 377 kg/ha/y in a 10-year study in Burkina Faso when soils were amended with low and high levels of inorganic and organic fertilizer, respectively.

4. Conclusions

Litter decomposition helps to replenish soil nutrient pools. Therefore, plant litter decomposition plays a key role in biogeochemical nutrient cycling, the rate of which

determines the productivity of natural and in part agro ecosystems. The findings of this study have contributed to our understanding of litter decomposition and C dynamics in cocoa ecosystems of Ghana.

Trends of leaf litter decomposition and C mineralization indicated that mixed cocoa-shade litter treatments decomposed faster than the cocoa leaf litter alone; this suggests that litter mixing has a positive interaction effect in cocoa ecosystems. The management implication of this finding is that if the release of nutrients into the soil is a consequence of litter decomposition, then the mixed litter systems as in shaded cocoa ecosystems would be more effective in releasing plant nutrients than the single tree species litter systems.

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