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Effects of *Faidherbia albida* on some important soil fertility indicators on agroforestry parklands in the semi-arid zone of Ghana

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A study was conducted in the Guinea and Sudan Savannah zones in the Upper East Region of Ghana to investigate the effects of *Faidherbia albida* on some important soil fertility indicators. Soil sampling and analysis, litter trap, and litter bag techniques were employed to determine the soil's content of major nutrients, the rate of litterfall production and litter decomposition, respectively. Analysis of variance (ANOVA) was performed to determine differences among treatment means, while Tukey's highest significant difference (HSD) was used to perform post hoc tests among means within the same sample set. Soils under *F. albida* tree canopies were found to contain significantly higher organic carbon and total nitrogen than those outside the canopies. Peak leaf litter production occurred during the first three months of the onset of the rainy season. Annual leaf litterfall was 340 g m^{-2} year^{-1} in the Guinea Savannah zone and 264 g m^{-2} year^{-1} in the Sudan Savannah zone. The high leaf litterfall, followed by high decomposition and mineralization at the beginning of the cropping season, the high nutrient content of its leaves, coupled with its nitrogen fixing ability, make *F. albida* a potential candidate for soil improvement and improved productivity of major crops in smallholder farming systems. About 37 and 59 adult *F. albida* trees will be required to supply significant amounts of nitrogen in the Guinea and Sudan Savannah zones, respectively.

Key words: Litter bag technique, litter decomposition, litter fall, litter trap technique, soil organic carbon, soil fertility.

INTRODUCTION

Soil fertility loss is considered as one of the major biophysical causes of declining per capita food production. Soils in the semi-arid zone are typically characterized by their susceptibility to erosion and compaction, low water retention, nutrient mining and multiple nutrient deficiencies (Buresh and Tian, 1997). The low fertility and susceptibility of semi-arid soils has necessitated the need to find sustainable agricultural production methods. One of such sustainable methods has been the intentional integration of trees with field

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crops on farmlands.

One of the main purposes of agroforestry is to maintain or improve upon soil fertility and hence sustain crop productivity. However, due to the importance of subsistence agriculture in most tropical regions, agroforestry is faced with the task of combining the aims of increasing agricultural production and reducing crop yield losses that result from the competition with associated trees (Broadhead, 2015). The higher crop yields obtained nearer to trees in parklands in the semi-arid zones (Vandenbeldt, 1992) or where trees have been recently removed as in the case of conservation and tree fallows (Nye and Greenland, 1960) is a proof of the contribution of trees to soil fertility. Campbell et al. (1994) show that trees have a positive effect on soil fertility. They suggested that the primary mechanism by which trees improve soil fertility is through increased litter and soil organic matter build-up. Nkyi and Acheampong (2013) also identified plant litter decomposition as the major source of nutrients for trees and crops in the tropics. However, excessive demographic pressure and its consequent modern high input, mechanized cultivation practices have collectively threatened the population of trees on parklands. Tree population and diversity on these parklands are therefore reducing at a rate that requires immediate attention (Tom-Dery et al., 2014; Akpalu et al., 2017). The semi-arid zone of Ghana, where this study was carried out, is the area with the most endemic poverty in the country (Cooke et al., 2016), making it difficult for farmers to afford inorganic fertilizers (Morris, 2007).

A parkland is a traditional land-use system in semi-arid zones, that involves the retention and/or introduction of woody perennials, especially trees, in agricultural fields and managing them in combination with crops and livestock (Boffa, 1999), with the main aim of benefitting from the positive ecological and economic interactions that take place between the components (Bayala et al., 2015). Litter accumulation and decomposition under *Faidherbia albida* canopies have been proven by many researchers to be one of the major sources of nutrients and soil organic carbon (SOC) through which soils are improved (Dunham, 1989; Traore et al., 2004; Adamu, 2012). *F. albida* is known for the so-called “albida effect” which refers to better growth of crops or herbaceous plants under its canopy than in an open field. This phenomenon is attributable to a combination of factors including (i) increased nutrient input through nitrogen fixation and manure from litter, and excreta and urine from livestock grazing or ‘camping’ under the tree (Kang and Akinnifesi, 2000), (ii) increased nutrient availability through enhanced soil biological activity and rates of nutrient build-up (Jung, 1970; Felker, 1981), (iii) improved microclimate and soil physical properties (Akpo et al., 2005), and (iv) ability to capture nutrients and moisture from deeper horizons (Broadhead, 2015).

F. albida is widely distributed in Africa, occurring in the tropical and sub-tropical regions of the continent, from Senegal and Gambia in the west to Egypt in the north-east and southwards to South Africa (Barnes and Fagg, 2003). It has a long history of being incorporated into agriculture as a result of population pressures that have necessitated the sedentary use of land in the face of very short or no fallow periods. The leaves and matured fruits (pods) of *F. albida* serve as a source of fodder for livestock in the dry season when herbage is scarce. This has led to the emergence of an agro-pastoral system based on *F. albida*, millet/sorghum, maize and livestock (Barnes and Fagg, 2003). Many authors have demonstrated increased crop yields under *F. albida* (Saka et al., 1994; Payne et al., 1998; Kho et al., 2001; Manjur et al., 2014; Yengwe et al., 2018a). However, *F. albida*-crop-livestock farming system is fast disappearing, leading to deleterious effects on the sustainability of agriculture in the semi-arid zone of Ghana.

A distinct characteristic of *F. albida* is that it sheds its leaves at the onset of the rainy season and is in full leaf during the dry season, a phenomenon referred to as ‘reverse phenology’ (Wickens, 1969). This trait makes it physiologically dormant during the cropping season and therefore, considerably less competitive with field crops. This, coupled with its inability to shade crops, has made it compatible with field crops and acceptable to farmers.

Some studies have however suggested that the anticipated desirable attributes of *F. albida* such as reverse leafing phenology, the deep rooting habit, and extent of nitrogen fixation are sometimes not likely to be attained due to ecological, age and genotypic variations (Wickens, 1969; Chamshama et al., 1994). Furthermore, Sanchez (1995) suggested that the soil improving ability of *F. albida* could diminish and even disappear as one gets closer to the sub humid tropics. Moreover, due to the wide variety of factors that influence the distribution, population and diversity of trees in agroforestry systems, there is the need for farm level research as a follow up to research station, regional or global findings, as a pre-requisite for the introduction of agroforestry technologies (Zomer et al., 2009).

Recent reviews and studies on soil improvement effects of trees have largely concentrated on forest soils while not much attention was given to the relationships between tree-induced soil changes in crop production systems. For instance, only a few studies have attempted to quantify the amount of litterfall in *Faidherbia* agroforestry systems in sub-Saharan Africa and link it with nutrient release for the use of associated crops (Dunham, 1989; Yengwe et al., 2018a).

The aim of this study was to quantify the nutrient yield of *F. albida* and its effects on organic carbon and pH of parkland soils in the semi-arid zone of Ghana. The specific objectives were:

(1) To determine the effects of *F. albida* on the organic carbon, total nitrogen, available phosphorus and

exchangeable potassium content and pH of soils.

(2) To determine the trend in leaf litter production from mature *F. albida* trees in the semi-arid zone of Ghana,

(3) To determine the rate at which *F. albida* leaf litter decomposes and releases nutrients to the soil,

(4) To estimate the potential nutrient contribution from *F. albida* leaf litter.

METHODOLOGY

Study area

This study was conducted in the semi-arid zone, Upper East Region of Ghana, West Africa, where both the Sudan and Guinea Savannah vegetation are found. The region is located in the northeastern corner of the country between 00° and 01° West and latitudes 10° 30' North and 11°15' North (EPA, 2002). The land is generally flat with a few hills to the east and southeast. The total land area is about 8,842 km^2, equivalent to about 2.7% of the total land area of the country (GSS, 2012).

The Sudan Savannah zone occupies an area of about 1,900 km^2, and consists of short, drought and fire-resistant deciduous trees interspersed with open savannah grassland. Grass cover is very sparse and in most areas the land is bare and severely eroded especially at the peak of the dry season. Common grasses include *Andropogon, Heteropogon, Aristidia*, and *Loudetia* species (EPA, 2002). Tree cover is very low, with the commonest ones being *Anogeissus leiocarpus, Acacia* species, *Terminalia macroptera, Vitellaria paradoxa, Adansonia digitata, Ceiba pentandra, Faidherbia albida* and *Parkia filicoidea.* These are found in densely settled and cultivated areas (EPA, 2002). The area experiences a unimodal rainfall regime lasting from mid-May to October (5 to 6 months), followed by a long dry season lasting from October to May (6 to 7 months) in a year. Average annual rainfall and temperature are 885 mm and 28.6°C, respectively (EPA, 2002). Most of Northern Ghana falls within the Guinea Savannah ecological zone, covering about 147,900 km^2. Annual rainfall is between 1,000 and 1,300 mm per year. The peak rainfall period is usually in late August or early September with about 60% of the rainfall occurring within 3 months from July to September (Siaw, 2001).

Agroforestry systems developed from the existing vegetation in the Guinea Savannah zone comprise primarily of fruit trees like *A. digitata*, *Ficus* species, *Lannea microcarpa, Parkia biglobosa, Sclerocarya birrea* and *V. paradoxa*, and multipurpose trees such as *Azadirachta indica, Borassus aethiopum, Acacia sieberiana, Ceiba pentandra, F. albida, Senna siamea,* etc., (Michel, 2004).

Litterfall pattern and quantity determination

The litter trap technique (Ssebulime et al., 2018) was used in determining the amounts of litter deposited by a mature *F. albida* tree. The litter traps were made with woven polypropylene sheeting. The mouth which was strengthened with flexible wire measured 30 cm in diameter, 60 cm deep and oval in shape. Ten *F. albida* trees were selected in each of the two ecological zones for litterfall collection. Care was taken to ensure that each selected tree was isolated enough from other trees to avoid litter being mixed up. Heights, diameter at breast height and average canopy width were measured for each selected tree. The canopy area of each sampled *F. albida* tree was determined by measuring crown diameters in two directions at right angles to each other and assuming that the canopy is a perfect circle. The polypropylene litter traps were placed midway under the canopies and supported by three wooden poles at a height of about 1 m from the ground to prevent livestock from tampering with the content of the bags. The traps were emptied monthly but fortnightly during the peak of the rainy season to avoid the rotting of the litter. All collected litter were composited at the end of the month, then subsequently separated into leaves, flowers, pods, branches and bark components and oven dried at 65°C for 4 days to determine their dry weights. The respective components were composited at the end of the study, sub-sampled and analyzed for organic carbon, total nitrogen, phosphorus and potassium content. Annual litter fall was calculated as the total litter collected over the twelve-month period (June 2017 to May 2018). The average amount of litter collected per litter trap was extrapolated to determine litter production on a per hectare basis.

Litter decomposition rate

Litter bag technique was used to determine the decomposition rate of *F. albida* leaf litter. Litter bags were made from 1 mm mesh nylon nets, 25 cm × 20 cm in size and stapled at the edges.

Fifteen grams of leaf litter were gathered from underneath *F. albida* trees, weighed and filled into each of 108 bags, spread evenly in the bags to ensure that the litter had good contact with the soil (Conn and Dighton, 2000). Nine (9) bags were placed at 6 different locations in each of the two ecological zones. Six bags were randomly collected in each ecological zone at each sampling time. Bags were collected on 3, 7, 14, 21, 30, 45, 60, 75 and 105 days after placement. Litter bags were carefully rinsed with tap water to remove any adhering soil particles, dried at 70°C for 48 h and weighed to determine weight loss.

Soil sampling

In each of the two ecological zones, 6 mature *F. albida* trees were selected (2 at each of three sites), for soil sampling. Care was taken to ensure that each selected tree was isolated enough from other trees. Measures of GPS locations, topography, soil texture where the trees were located, as well as height, diameter at breast height (DBH), and average canopy diameter were made. With the sampled tree trunk as the central point, the downslope of the topography was determined and a transect laid in that direction (labeled T1), from which 2 other transects each at 120° from T1 were laid (Takoutsing et al., 2017). With the canopy width determined, soil samples were taken from the center, and edge of the canopy, as well as 5 m from the edge of the canopy along the 3 transects, using a closed soil auger. At each point, soil samples were taken at 0 to 15 cm and 15 to 30 cm depths. The three soil samples collected at a given distance and depth under a tree was composited and sub-sampled for analysis. Soil samples were analyzed for total nitrogen, available phosphorus, exchangeable potassium, organic carbon and soil pH.

Determination of soil total nitrogen, available phosphorus, exchangeable potassium, organic carbon and soil pH

The Kjeldahl's digestion procedure (Nelson and Sommers, 1972) was used for the determination of soil Total Nitrogen (TN) while available phosphorus was determined using Bray's 1 method (Bray and Kurtz, 1945). Ammonium acetate method (Shuman and Duncan, 1990) was used to analyze the exchangeable K in soil samples. Soil pH in $CaCl_2$ solution was determined by a pH meter after calibrating the instrument with a buffer solution and soil organic carbon content was determined using the Walkley & Black method (Walkley and Black, 1934). All samples were analyzed in 6 replicates in the laboratories of the Soil Research Institute of Ghana.

Data analysis

SPSS was used to perform the Shapiro-Wilk test for the normality of all data collected. Where a data set was not normally distributed, the appropriate transformation was used to ensure its normality. Analysis of variance (ANOVA) was then used to analyze the differences in leaf litter produced in the respective months, using GenStat (12th edition) whereas Turkey's Honestly Significant Difference (HSD) test was used to separate means at a significance level of 0.05. Independent t-Test was used to test the hypothesis that difference between the means of litter produced in the two ecological zones was not significantly different from zero.

Leaf litter decomposition rates were determined by finding the difference between the initial mass of litter (15 g) and that at the respective litter bag collection time periods. The annual decay constant (k) was determined using the relation $X/X_0 = e^{-kt}$, where X_0 is the initial dry weight of leaf litter, X is the dry weight remaining at the end of the experiment, and t is the time period (Olson, 1963). ANOVA was used to test for differences among the respective litter collection time periods, while independent t-Test was used to test the null hypothesis that the differences between means in the two ecological zones is equal to zero. Tukey's HSD was employed for post hoc tests among means within the same sample set. ANOVA was used to test for the difference in mass remaining between days of decomposition.

RESULTS

Litterfall pattern and quantity

The pattern of litterfall was similar in both Guinea and Sudan Savannah ecological zones. No litterfall was recorded in the months of September and October. Litterfall comprised leaves, branches and twigs, flowers, and pods (Figures 1 and 2). Matured pods fell between December and April and flowers fell (aborted) in November. The falling of branches did not follow any definite pattern (Table 1). In the Guinea Savannah zone, leaves made up 51.9%, pods 32.3%, dead branches 4.1%, and flowers 11.7% of dry matter produced, whereas in the Sudan Savannah zone leaves 40.3%, pods 34.8%, dead branches 14.2%, and flowers 10.7% of litter produced by the *F. albida* trees.

Leaf litterfall occurred throughout the year, except in September and October, reaching its peaks in June and July in the Guinea Savannah zone and in May to July in the Sudan Savannah zone. The first three months of the raining season (May - July) coincided with high deposition of leaf litter (Figure 3). There were significant differences in the quantity of leaf litter falling from one month to the other (Table 1). Annual leaf fall in the Guinea and Sudan savannah zones were 340.14 and 264 g m^{-2} $year^{-1}$, respectively, while total litter production was 555.86 g m^{-2} $year^{-1}$ in the Guinea Savannah zone and 404.29 g m^{-2} $year^{-1}$ in the Sudan Savannah zone. Pod deposition occurred from December to April in both ecological zones (Table 1).

Leaf litter decomposition

Biomass of buried *F. albida* leaf litter decreased with time in the two ecological zones. Mass loss rates were faster in the earlier stages. From an initial mass of 15 g applied, the biomass remaining were 3.67 g (24.5%) in the Guinea and 2.63 g (17.54%) in the Sudan Savannah zones of Ghana in 105 days after application. Significant differences were observed for leaf litter that decomposed within each ecological zone over the 105 days (Table 2).

The rate of biomass loss followed a similar trend in both ecological zones. Mass loss was faster in the first sixty days, and slowed down afterwards in both ecological zones (Figure 4).

Decomposition constants for leaf litter in the Guinea and Sudan Savannah zones were 0.012 and 0.017, respectively, indicating a higher rate of decomposition in the Sudan Savannah zone than in the Guinea Savannah zone (Figure 5).

Pattern of nutrient release from F. albida leaf litter

Results from the laboratory analysis of leaf litter for nitrogen, phosphorus, and organic carbon contents for various days of decomposition indicate that there were increasing rates of loss/release of organic carbon, total nitrogen and available phosphorus in the first 60 days of decomposition in litter bags (Figure 6a and b). It was estimated that by the 105th day after deposition, with a mean leaf litter deposition of 303 g m^{-2} per year, 9.31, 0.32, 0.43 and 157.30 g m^{-2} of N, P, K, and OC, respectively, were released into soils under matured *F. albida* canopies year. With a mean canopy area of 291.00 and 183.00 m^2 in the Guinea and Sudan Savannah zones, respectively, a mature tree was estimated to release 2.71 kg N, 0.09 kg P, 0.13 kg K and 45.77 kg OC in the Guinea Savannah zone while 1.70 kg N, 0.06 kg P, 0.08 kg K and 28.79 kg OC will be released in the Sudan Savannah zone. Based on these estimates, 37 and 59 trees will be required in the Guinea and Sudan Savannah zones, respectively to release about 100 kg of N into the soil per hectare per year. In addition, 3.45 kg P, 4.63 kg K and 1,698.37 kg OC will also be added per hectare per year.

Effects of *F. albida* on soil NPK, organic matter content and pH

Soil organic carbon content

Soil organic carbon content decreased with increasing distance from the trunk of mature *F. albida* trees and soil depth. Soil organic carbon content in mid-canopy was 0.55%, but decreased to 0.41% at the edge of the canopy, and further decreased to 0.34% 5 m from the edge of the canopy. Soil organic carbon contents did not vary significantly between the two ecological zones under study. In terms of soil depth, soil organic carbon contents reduced sharply with depth. It decreased from 0.51% in

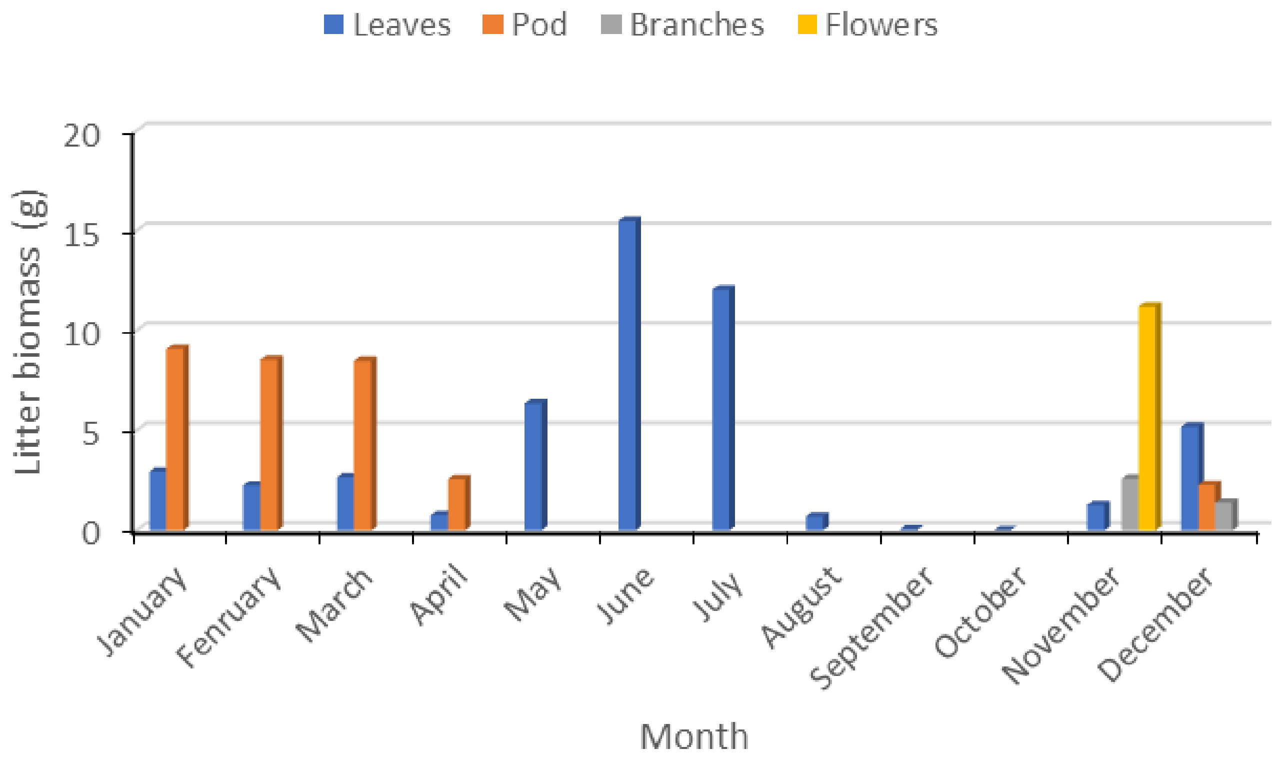


Figure 1. Monthly litterfall in the Guinea Savannah zone of Ghana.

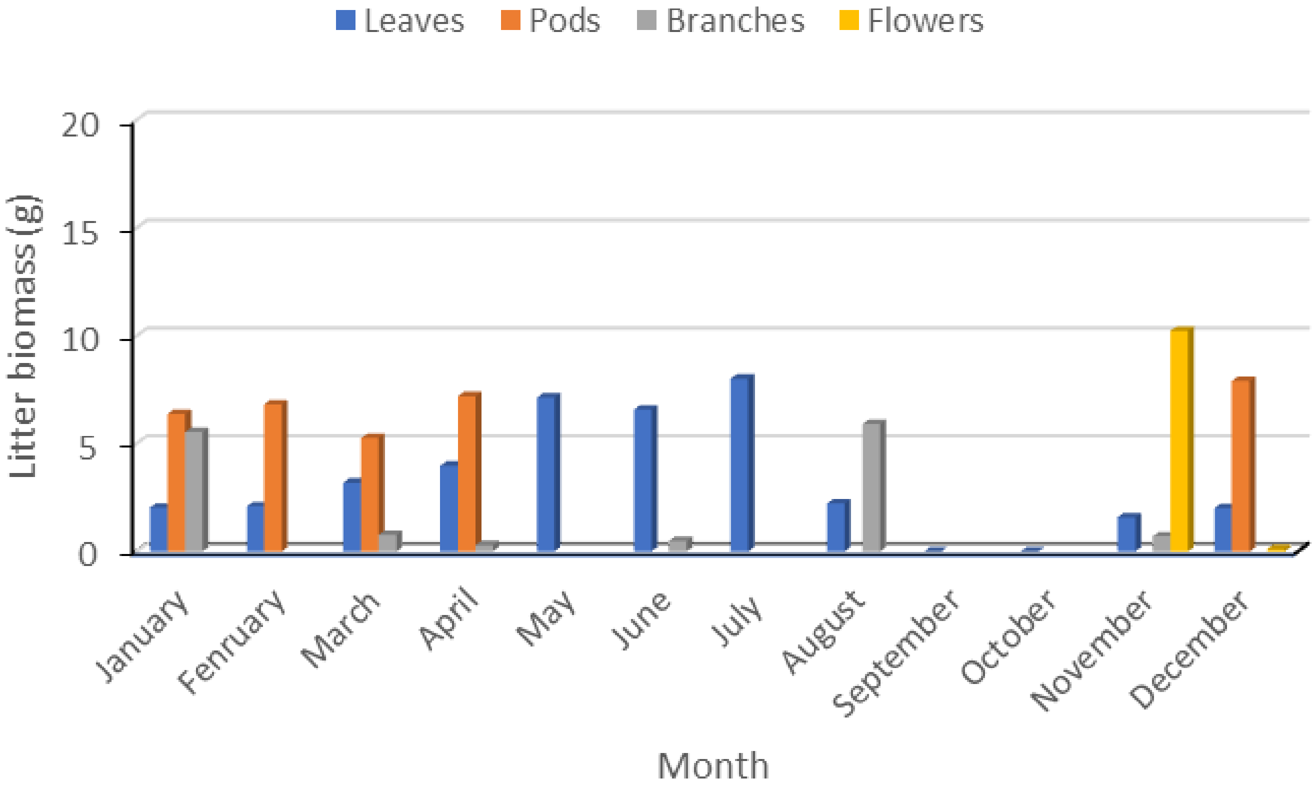


Figure 2. Monthly litterfall in the Sudan Savannah zone of Ghana.

Table 1. Mean total litterfall (leaves, flowers, pods and branches/twigs) and leaf litterfall from *F. albida* trees per litter trap in the Guinea and Sudan Savannah zones of Ghana.

Month	Leaf litterfall (g)		Total litterfall	
	Guinea Savannah	Sudan Savannah	Guinea Savannah	Sudan Savannah
January	1.41^{d} ±0.14	0.98^{cd} ±0.11	3.59^{bcd} ±1.07	2.12^{abc} ±0.64
February	1.08^{de} ±0.14	1.00^{cd} ±0.12	5.17^{abc} ±0.76	1.99^{abc} ±0.49
March	1.27^{de} ±0.12	1.37^{cd} ±0.36	2.90^{cdef} ±0.75	2.71^{abc} ±0.80
April	0.29^{ef} ±0.09	1.91^{bc} ±0.34	0.88^{abcd} ±0.24	2.28^{abc} ±0.39
May	3.05^{c} ±0.20	3.43^{a} ±0.26	3.05^{cde} ±0.20	3.43^{ab} ±0.26
June	7.43^{a} ±0.49	3.15^{ab} ±0.19	7.43^{a} ±0.49	3.22^{ab} ±0.20
July	5.78^{b} ±0.37	3.84^{a} ±0.81	5.78^{abc} ±0.37	3.84^{ab}±0.81
August	0.34^{ef} ±0.08	1.08^{cd} ±0.11	0.34^{ef} ±0.08	1.36^{bc} ±0.22
September	0.02^{f} ±0.01	0.00^{d} ±0.00	0.18^{f} ±0.01	0.00^{c} ±0.00
October	0.00^{f} ±0.00	0.00^{d} ±0.00	0.00^{f} ±0.00	0.00^{c} ±0.00
November	0.61^{def} ±0.11	0.76^{cd} ±0.25	6.61^{ab} ±1.42	4.82^{a} ±1.45
December	2.49^{c} ±0.23	0.96^{cd} ±0.16	2.98^{cdef} ±0.38	1.73^{bc} ±0.67
Total	23.81	18.48	38.91	28.30
P-value	<0.001	<0.001	<0.001	<0.001

*Leaf and total litterfall values (± standard error of mean) for the various ecological zones followed by the same superscript alphabets do not differ significantly between the months they were collected.

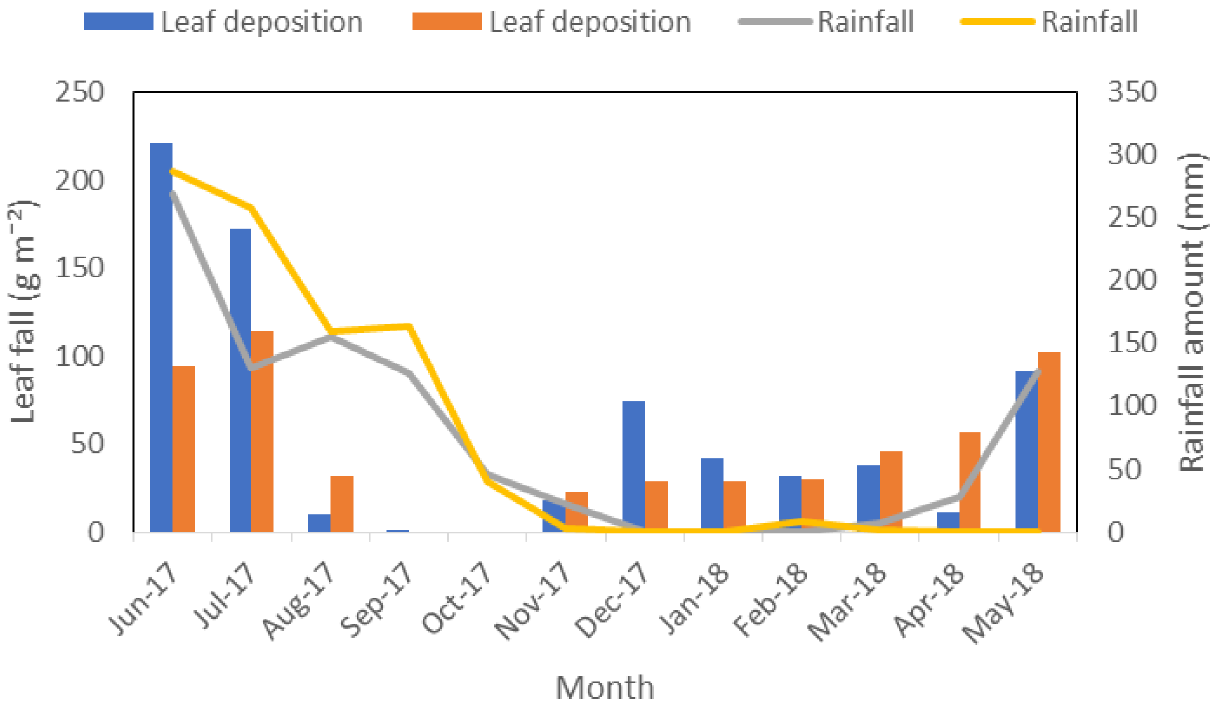


Figure 3. Leaf-fall pattern and rainfall in the Guinea and Sudan Savannah zones.

the topsoil to 0.36% in the subsoil (Table 3).

Soil total nitrogen content

Like organic matter and carbon content, total nitrogen content decreased significantly as one moved from mid-canopy to open field. Total N content was 0.058% in mid-canopy while it decreased to 0.046% at the edge of the canopy, and 0.039% in the open field. Total N content was also significantly higher in the topsoil (0.054%) than in the subsoil (0.041%). No significant differences were

Table 2. Mass remaining from an initial leaf litter 15 g in two ecological zones.

Day	Mass remaining (g)	
	Guinea Savannah	Sudan Savannah
3	12.73^{a} ±0.15	11.51^{a} ±0.12
7	11.53^{a} ±0.18	10.91^{ab} ±0.18
14	9.91^{b} ±0.30	8.91^{bc} ±0.51
21	7.79^{c} ±0.27	7.94^{c} ±0.32
30	7.15^{cd} ±0.23	7.64^{c} ±0.23
45	6.54^{cd} ±0.28	6.84^{cd} ±0.47
60	6.10^{d} ±0.22	4.87^{de} ±0.68
75	4.73^{e} ±0.40	3.87^{ef} ±0.60
105	3.67^{e} ±0.34	2.63^{f} ±0.56
P-value	<0.001	<0.001

Differences between collection period means in the same column bearing different superscripts are significant according to Tukey's HSD post hoc test (± standard errors of the means).

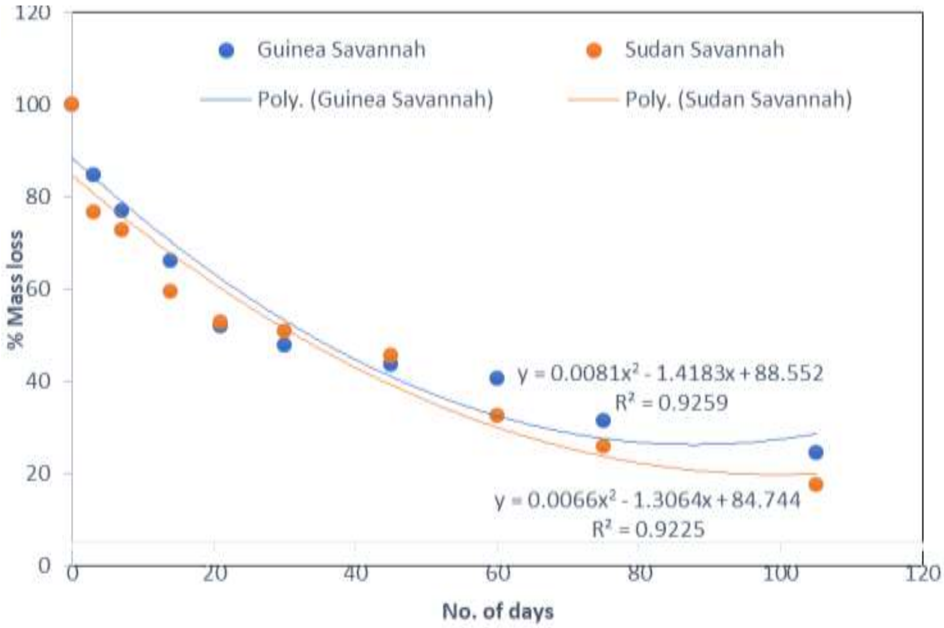


Figure 4. Percentage mass of litter remaining (decomposition) in litter bags with time in Guinea and Sudan Savannah zones of Ghana.

observed between the two ecological zones with respect to total nitrogen (Table 3).

Phosphorus and potassium

There were no significant differences in available phosphorous between soils under *F. albida* canopy and open field. However, phosphorous content in the topsoil (15.11 ppm) was significantly higher than that in the subsoil (9.40 ppm). Soils in the Guinea Savannah zone were richer in phosphorous than those in the Sudan Savannah zone (Table 3). No significant differences were observed in potassium content with respect to all the factors (distance from *F. albida* trunk, soil depth and ecological zone) considered in this study (Table 3).

Soil pH

Soil pH was unaffected by the presence of *F. albida* and therefore did not exhibit any significant difference under

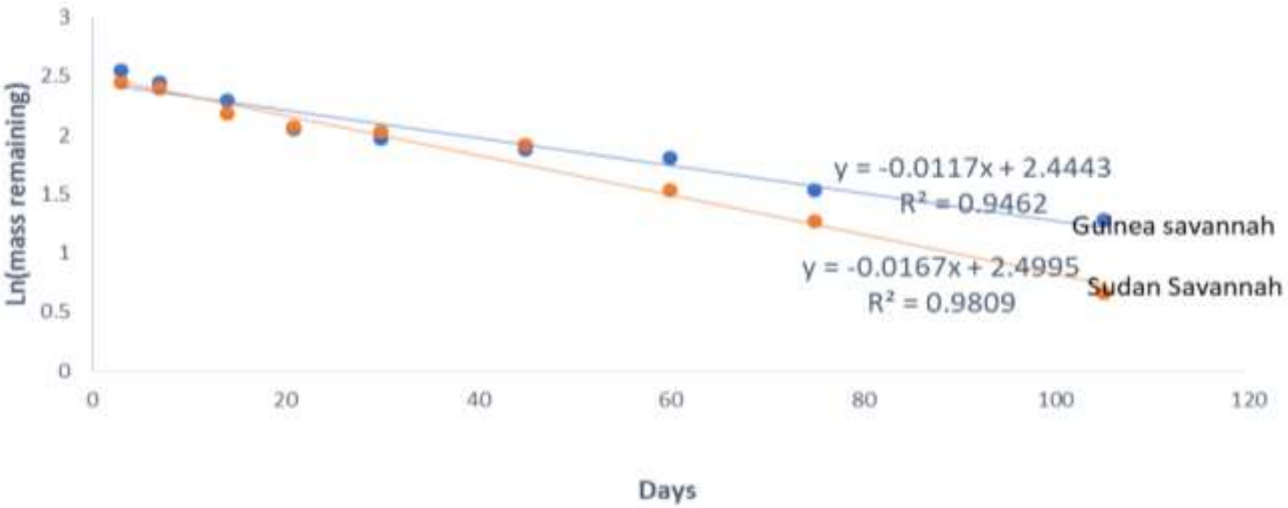
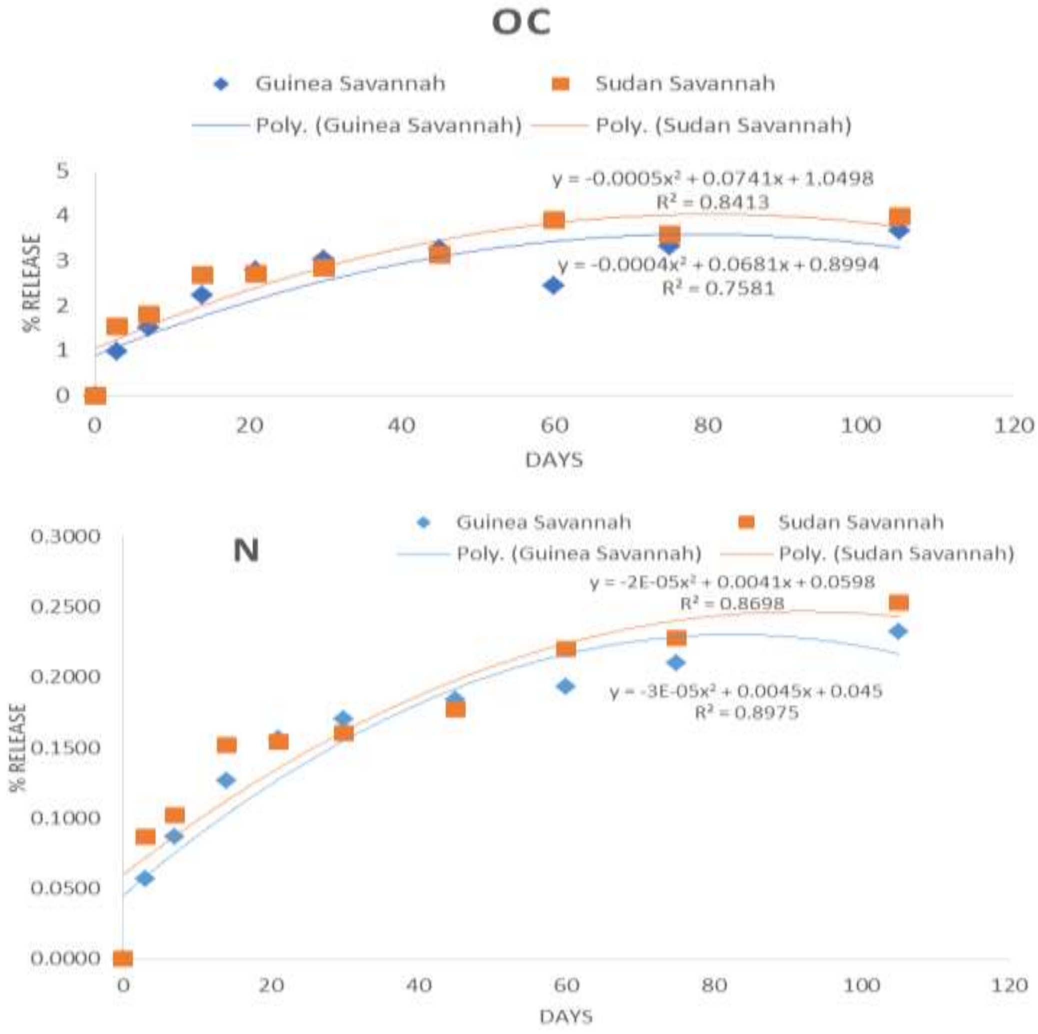


Figure 5. Model for the determination of decomposition rate constant in the Guinea and Sudan Savannah zones of Ghana.



a

b

Figure 6. (a) Rate of Organic Carbon loss from *F. albida* leaf litter in the Guinea and Sudan Savannah Zones of Ghana. (b) Rate of Total Nitrogen loss from *F. albida* leaf litter in the Guinea and Sudan Savannah zones of Ghana.

Table 3. Soil major nutrients, organic carbon content and pH of soils under *F. albida* trees in the Guinea and Sudan savannah zones of Ghana.

Factors/treatments	SOC (%)	TN (%)	P (mg/kg)	K (Cmol/kg)	pH
			Distance from tree trunk		
Mid canopy	0.554^{a} (0.274)	0.058^{a} (0.235)	13.110^{a} (11.210)	0.337^{a} (0.169)	6.10^{a} (0.53)
Canopy edge	0.412^{ab} (0.270)	0.046^{ab} (0.232)	12.640^{a} (12.130)	0.352^{a} (0.683)	6.03^{a} (0.64)
Out of canopy	0.339^{b} (0.231)	0.039^{b} (0.200)	11.070^{a} (9.550)	0.177^{a} (0.141)	5.93^{a} (0.63)
LSD	0.145	0.013	6.230	0.240	0.351
Fpr	0.014	0.014	0.792	0.278	0.615
			Soil depth		
0 - 15 cm	0.509^{a} (0.285)	0.054^{a} (0.025)	15.110^{a} (11.54)	0.265^{a} (0.199)	6.06^{a} (0.53)
15 - 30 cm	0.361^{b} (0.236)	0.041^{b} (0.020)	9.400^{b} (9.44)	0.313^{a} (0.557)	5.98^{a} (0.66)
LSD	0.119	0.010	5.090	0.200	0.287
P-value	0.015	0.015	0.030	0.626	0.609
			Ecological zone		
Guinea savannah	0.456^{a} (0.32)	0.049^{a} (0.03)	18.00^{a} (12.34)	0.342^{a} (0.15)	6.370^{a} (0.41)
Sudan savannah	0.414^{a} (0.23)	0.046^{a} (0.02)	6.00^{b} (4.73)	0.236^{a} (0.57)	5.670^{b} (0.54)
LSD	0.128	0.011	4.39	0.195	0.227
P-value	0.516	0.516	<0.001	0.280	<0.001

Mean values in the same column for the same factor with the same superscript are not significantly different at $P < 0.05$ level using Tukey's HSD. Standard deviations are in parenthesis.

and outside canopies, and in the different soil depths. However, soils in the Sudan Savannah zone were found to be significantly more acidic (5.7) than those in the Guinea Savannah zone (6.4) (Table 3).

DISCUSSION

Litterfall pattern and litter quantity

The litter deposition pattern found in this study corroborated the findings of several authors (Fagg and Roshetko, 1995; Fagg, 1995; Roupsard et al., 1999; Barnes and Fagg, 2003; Hadgu et al., 2009; Adamu, 2012; Wahl and Bland, 2013; Broadhead, 2015; Yengwe et al., 2018a) that, *F. albida* exhibits reverse leafing phenology. Leaf litter deposition occurred mainly between May and July, which coincides with the onset of rains and hence the beginning of the cropping season. The beginning of leaf-fall about a month into the raining season agrees with what Roupsard et al. (1999), found in other West African arid zones. About 60% of the total annual leaf litter deposited by the tree produced during this period is likely to contribute to the improved nutrient levels, as leaves are considered to contain most of the litter bound nutrients (Yang et al., 2004). Leaves falling almost throughout the year in this study corroborates the report by Dunham (1989) in Zimbabwe, but conflicted that of Jung (1970) in Bombay Senegal, who observed that 94% of leaves fell during four months of the rainy season. This could be due to the fact that the study area in Senegal experiences two rainy seasons in a year while this study area and that of Dunham (1989) experiences a single rainy season in a year.

In Chisama, Zambia, the peak of leaf litter deposition occurs between August and December (Yengwe et al., 2018a), while occurring between May and July in the semi-arid zone of Ghana suggests that leaf fall is influenced by climatic conditions, especially rainfall.

The maximum daily leaf litter deposition of 7.4 g m^{-2} day^{-1} (in June) in the Guinea Savannah (with annual rainfall of 911.5 mm) and 3.8 g m^{-2} day^{-1} in the Sudan Savannah zone (in July), with annual rainfall of 921.1 mm, was generally higher than the 1.6 g m^{-2} day^{-1} determined by Dunham (1989) in the woodlands of Mona, Zimbabwe, where mean annual rainfall was 757 mm.

Flower deposition occurring in only one month (November) and pod deposition following immediately from December is an indication that reproductive growth leading to pod production and maturity occurs within a short period.

Pod production occurs between December and April of the succeeding year. This period coincides with the dry season when fodder is scarce in the communities, compelling farmers to sell off their animals at cheap prices (Adzitey, 2013). The pollarding of *F. albida* branches and leaves to feed livestock however reduces the amount of litter added to the soil directly by livestock, which continuously camp under the tree to feed on falling pods from the tree. Moreover, in areas where livestock cannot have access to the trees, farmers gather the pods for sale in the local market while leaf litter, the main source of above ground organic matter are left under the tree to enrich the soil.

Leaf litter decomposition

Leaf litter is considered to be the main source of nitrogen and organic carbon in soils in *Faidherbia*-farming systems in the semi-arid zones (Barnes and Fagg, 2003). Decomposition rate (mass loss) was faster in the initial days (first 60 days) of placement in both ecological zones than in the latter days. This might be due to the higher nitrogen content (lower C-N ratio) of leaves which could serve as substrate for microbes (Gnankambary et al., 2008), and slowing down later as the lignin and polyphenol contents increased relative to nitrogen (Couteaux et al., 1995). A similar result was also observed by Swift et al. (1979) who pointed out that some of the labile litter, upon being deposited on the soil, decompose very rapidly in a matter of days or weeks whereas the more recalcitrant components could remain in the soil for several months or even years, leaving more and more resistant compounds to build up with time. Estimated decomposition constants for the Guinea (0.012) and Sudan (0.017) Savannah zones were however lower than what Gnankambary et al. (2008) obtained at Boni village in Burkina Faso (0.077). It is probably due to differences in, and interaction of the various regulatory factors such as physical environmental conditions (especially annual mean temperature and moisture), organisms (made up of fauna and micro-organisms), and litter quality, usually defined by lignin, nitrogen, and condensed and soluble polyphenol concentrations (Zhang et al., 2008). However, according to Silver and Miya (2001), leaf litter decomposition is more strongly influenced by climate (particularly temperature) than substrate quality.

Pattern of *F. albida* leaf litter nutrient release with time

The result from the laboratory analysis of leaf litter from *F. albida* agrees with the observation that leaf litter is a major source of nutrients and organic carbon in soils in agroforestry parklands (Vitousek, 1982; Aerts, 1996). This suggests that substantial amounts of nutrients from *F. albida* leaf litter could be released on time for use by field crops. The reduced rates of nitrogen and phosphorus released after the initial 60 days was also observed by Ribeiro et al. (2002). They noted that the higher the nitrogen and phosphorus concentration in the litter, the more rapidly those nutrients were released during decomposition. The amounts of N estimated to be released from *F. albida* leaf litter, were about 6.20 kg ha^{-1} year^{-1} in the Guinea Savannah zone and 1.86 kg ha^{-1}year^{-1} in the Sudan Savannah zone of Ghana, is less than the 25 kg N ha^{-1} as determined by Raghubanshi et al. (1990) in the dry tropical region of India, as a result of the relatively lower *F. albida* population densities on farmlands in this study. Retaining or planting about 37 to 59 *F. albida* trees per hectare to supply significant quantities of nitrogen (about 100 kg ha^{-1}) for field crops would drastically reduce the cost of procuring inorganic fertilizer as is being experienced in most of the semi-arid regions of Africa including Niger and Zambia (Garrity et al., 2010; Garrity and Bayala, 2019).

Effect of *F. albida's* effects on soil organic carbon, N, P, K content and pH

Effects of distance from tree trunk on nutrient content

The significant differences observed in the soil organic carbon and total nitrogen contents between soils under *F. albida* canopies and those in open field is an indication that *F. albida* has the potential for improving the fertility status of parkland soils as reported by several other authors (Alexander, 1989; Brouwer et al., 1992; Ayuba and Murya, 2000; Kho et al., 2001; Adamu, 2012; Wahl and Bland, 2013; Yengwe et al., 2018b). The relatively improved soil fertility status of soils under *F. albida* canopies could not be attributed mainly to deposition of dung and urine by livestock, as suggested by some authors. This suggestion was disproved by Charreau and Vidal (1965) cited in Wickens (1969), when they worked on sites where livestock were absent for such a long time that the effects of animal dung and urine on the soil could be discounted.

Values for organic carbon and nutrient elements obtained from this study were generally lower than those found elsewhere. For instance, whereas this study found soil organic carbon (SOC) to be 0.554%, total N, 0.058%, available P, 13.11 mg/kg, exchangeable K, 0.337 cmol. kg^{-1} and pH to be 6.1 under *F. albida* canopies, Adamu (2012) obtained 1.84% for SOC, 0.19% total N, 43.75 mg kg^{-1} for available P, 0.32 cmol.kg^{-1} for exchangeable K, and soil pH of 6.6 in the Gezewa region of Nigeria. In the woodlands of Mana Pools National Park in Zambia, Dunham (1991) obtained 1.16% for SOC, 0.148% for total N, 51 mg kg^{-1} for available P, 0.84 cmol.kg^{-1} for exchangeable K, and soil pH of 5.3. Sileshi (2016), in a review of studies to quantify the effects of *F. albida* on some soil nutrients observed consistent and significantly higher N, P, and K values under canopies than outside the canopies. The relatively lower nutrient levels observed in this study could be due to the low leaf litter deposition rates due to site and management practice differences, as suggested by Marriott and Wander (2006). Moreover, in this study, soil samples were collected from continuously cropped farms as compared to these other areas where the lands were relatively under fallow. Cultivated soils tend to contain less total N and other nutrients than undisturbed soils (Urioste et al., 2006). Anthropogenic factors like frequent thrash burning, pollarding for feeding livestock and direct livestock browsing could also account for these relatively lower values. Kho et al. (2001), also asserted that since the fertility improvement and competitive effects of the same agroforestry technology would differ under different conditions, it will be unrealistic to attempt to extrapolate from one location or condition to another. These results also seem to corroborate the suggestion made by Sanchez (1995) that, the soil improving ability of *F. albida* could diminish and even tend to disappear as one gets closer to the sub humid tropics.

Changes in some soil fertility indicators with soil depth under F. albida canopies

This study found that SOC, total N, and available P contents significantly decreased at lower soil depth (15 - 30 cm) as compared with the topsoil (0 - 15 cm). This trend affirms the observation of Kho et al. (2001), who determined the effects of *F. albida* on soils in a millet production system in Niger. They observed that the levels SOC, total N and exchangeable K were higher in the 0 - 15 cm depth of the soil but decreased in lower depths. A similar trend was observed by Pandey et al. (2000), who recorded maximum levels of total N and SOC in the 0 - 10 cm depths, but declined sharply with depth under *Acacia nilotica* canopies in a predominantly rice-based cropping system in Madhya Pradesh, India. Decreasing levels of SOC, total N and available P with increasing soil depth most probably due to the relative higher abundance of litter deposited on the top soil, coupled with the higher microbial/biological activity in the upper horizon than in the lower horizons.

Effects of F. albida on some soil properties in different ecological zones.

Significant differences were observed in available P content and soil pH in the two ecological zones studied. Whereas the other parameters such as SOC, total N and exchangeable P did not exhibit any significant differences across these two ecological zones, available P levels were three times higher in the Guinea Savannah zone than in the Sudan Savannah zone. This could be due to geological differences (Manning, 2010), and/or the management of crop residues, and other cultural practices (Hedley et al., 1982).

Soil pH is one of the most important indicators of key chemical properties of the soil (McLean, 1982) as it directly or indirectly influences soil nutrient availability, cation solubility, SOC characteristics and soil moisture regime (Lauber et al., 2009). This study found that soils in the drier Sudan Savannah zone were more acidic than those in the Guinea Savannah zone. It was noted by McLean (1982) that salt accumulation as a result of limited rainfall or inadequate drainage conditions could increase soil acidity.

CONCLUSION AND RECOMMENDATIONS

Though leaf litter was deposited almost throughout the year (except in October and November) about 60% of the total annual leaf litter was deposited during the first three months after the onset of the raining season.

The rate of leaf litter decomposition increased steadily up to about 60 days after deposition. These high leaf litter decomposition and nutrient release rates during the first 60 days of the cropping season could contribute to the supply of nutrients for use by major field crops like sorghum, millet, maize, etc. Since leaf biomass of trees usually contains higher N/P ratio than that required by crops, P could become deficient in an attempt to supply N through *F. albida* leaf litter application. It would, therefore, be economically prudent to integrate an inorganic phosphorus source with the organic materials (Jama et al., 1997). A possible source of P could be soft rock phosphate which is a colloidal phosphate containing 18% P, and is easier for plants to assimilate (Rajan, 1987; Szilas et al., 2007).

At the current population densities of 2.3 and 1.1 trees per hectare, *F. albida* leaf litter can add only about 6.20, 0.21 0.29 and 104.82 kg of N, P, K, and OC per hectare per year in the Guinea Savannah Zone. In the Sudan Savannah zone, *F. albida* leaf litter will add about 1.86, 0.06, 0.09 and 31.38 kg of N, P, K, and OC per hectare per year. These amounts are insignificant in relation to the requirements for the production of major annual crops like maize, millet, sorghum, vegetables etc.

For the full potentials of *F. albida* in soil fertility improvement to be realized among these resource-poor farming communities, there is the need for efforts to increase its current population density of 2.29 and 1.09 trees per hectare to on parklands in the Guinea and Sudan Savannah zones, respectively to 37 and 59 trees per hectare. At this population density, mature *F. albida* has the potential of adding about 100 kg N, 3.45 kg P, 4.63 kg K and 1,698.37 kg OC to the soil annually. The shortfall in the amounts of P and K supplied by *F. albida* could be supplemented through inorganic sources. This could be achieved through awareness creation among farmers on the enrichment planting and management of *F. albida* seedlings, with a better understanding of its ecological requirements and growth habits.

The agroforestry significance of *F. albida* was partly demonstrated by its significant influence on two very important soil macro nutrients, carbon and nitrogen. Nitrogen is the most important element especially for economic reasons especially among resource-poor, smallholder farming communities found in the semi-arid zone of Ghana. It is the nutrient that is required in the largest amounts and its availability in soils is directly proportional to crop yields and is the most likely to be deficient. Soil organic carbon (or organic matter) has direct and indirect effects on nutrient use efficiency and crop production systems.

Increasing the population density of *F. albida* from one or two trees to 37 or 59 trees per hectare on parklands requires very pragmatic action among all stakeholders including policy makers, agricultural extension agents and farmers, since its success has effects on the cost of importing and distributing inorganic fertilizers.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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