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Agronomic Potentials of Rarely Used Agroforestry Species for Smallholder Agriculture in Sub-Saharan Africa: An Exploratory Study

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Despite significant evidence that green manures from agroforestry species can improve soil fertility, green biomasses from many agroforestry species have not been sufficiently explored. In this study, we determined the suitability of green manures of Tithonia diversifolia, Gliricidia sepium, *and* Senna spectabilis *for smallholder agriculture in Africa. Field trials were established to compare them with mineral fertilizer. The results showed that green manures of the three species were of high quality based on their macronutrient compositions. The effect of the green manures (particularly* Tithonia*) on both the biomass and fruit yield of okro were comparable and in some cases greater than fertilizer treatments. Total yield response in* Tithonia *treatment was 61% and 20% greater than the control and fertilizer treatments, respectively. In addition, the okro plants recovered a greater percentage of the nitrogen (N), phosphorus (P), and potassium (K) added as green manure compared to fertilizer-treated plots, which received the greatest N, P, and K inputs.*

Keywords Agroforestry, smallholder agriculture, soil fertility, *Tithonia*

Introduction

Subsistence agriculture remains the major source of food production in sub-Saharan Africa (SSA). This system of agriculture commonly employs more than 70% of the population in one way or the other. Despite the huge participation and the recent slight growth in agriculture during the past three decades, food production has still not kept pace with the high population growth rate (FAO 2001). While factors such as weak markets, high agricultural input prices, and limited access to credit facilities are contributory factors to food insecurity in SSA, the poor state of soil fertility should not be underestimated. With the low level of chemical fertilizer use, decline in soil organic matter, and insufficient attention to crop nutrient studies (Kumwenda et al. 1996) soil fertility decline could be a permanent impediment for sustainable food production in SSA.

FAO (2001) revealed that soils in most of SSA have inherently low fertility and do not receive adequate nutrient replenishment. The 1990s field survey by Stoorvogel and

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his colleagues revealed average losses of 660 kg nitrogen (N) ha^{-1}, 75 kg phosphorus (P) ha^{-1}, and 450 kg potassium (K) ha^{-1} during the past 30 years from about 200 million ha of cultivated land in 37 countries in Africa (Stoorvogel and Smaling 1990; Smaling, Nandwa, and Janssen 1997). Furthermore, FAO (2001) estimated an average annual nutrient loss of 24 kg nutrients ha^{-1} (10 kg N; 4 kg P_2O_5; 10 kg K_2O) in 1990 and 48 kg nutrients/ha in 2000 (i.e., a loss equivalent to 100 kg fertilizers ha^{-1} per year), representing a 100% increase in nutrient loss in a decade. Although the beneficial effects of inorganic fertilizers on soil fertility and crop yields have been realized in most of SSA, the liberalization of trade and introduction of structural adjustment programs have increased fertilizer costs to a level unaffordable to small-scale farmers (Ayuke et al. 2004).

The current unaffordability of inorganic fertilizer use implies that alternative ways of improving and sustaining soil fertility are crucial. One such way is agroforestry. According to Fernandes and Matos (1995), agroforestry practices generally contribute to intensified production that is agroecologically sound and maintains soil fertility. Plant residues applied on soils via agroforestry practices (such as biomass transfer and alley cropping) play critical roles in agroecosystems by improving many soil physicochemical and biological properties associated with soil fertility (Wu et al. 2000; Vanlauwe et al. 2001). Despite significant evidence that biomass application of agroforestry species can improve soil fertility (Beedy et al. 2010; Partey et al. 2011), the beneficial effects of nutrient transfers from biomass of certain agroforestry species to soil are less explored in SSA. Three such underutilized species are Mexican sunflower *Tithonia diversifolia* (hereafter referred to as *Tithonia*), *Gliricidia sepium*, and *Senna spectabilis*. Wide ranges of experiments have shown that green manures from these agroforestry species can increase crop yields from depleted soils. This evidence is comparable to the effects of mineral fertilizers and other sources of soil nutrients on crop yields and soil fertility (Gachengo et al. 1999; Nziguheba et al. 2000; Ikerra, Semu, and Mrema 2006). Because the complex interactions among soil biophysical properties and environmental conditions (e.g., temperature, moisture, and aeration) are keys to the success of any agroforestry system in a given environment (ICRAF 1993; Ayuke et al. 2004), exploring the agronomic potentials of these rarely used nontraditional agroforestry species will make significant contributions to their adoption for smallholder agriculture in Africa. The main objective of this study was to determine the suitability of *Tithonia*, *G. sepium*, and *S. spectabilis* green manures as alternatives to inorganic fertilizers for smallholder agriculture. We hypothesized that the effect of these green manures of agroforestry species on soil properties and crop yields would be comparable to those of inorganic fertilizer treatments.

Materials and Methods

Study Site

The study was conducted at the Agroforestry Research Station of the Faculty of Renewable Natural Resources (FRNR), Kwame Nkrumah University of Science and Technology, Kumasi (KNUST), Ghana, located at 1° 43° N and 1° 36° W. The area falls within the moist semideciduous forest zone of Ghana. It is characterized by a bimodal rainfall pattern, with the major wet season between May and July. This area also experiences a short dry season in August and a long one between December and March. The annual rainfall of the area ranges between 1250 and 1500 mm. The area is characterized by a mean annual temperature of 26.61 °C and a mean annual humidity of 67.6%. Soil type is ferric acrisol with sandy-loam textural class. Climatic data recorded during the study period are reported in Figure 1.

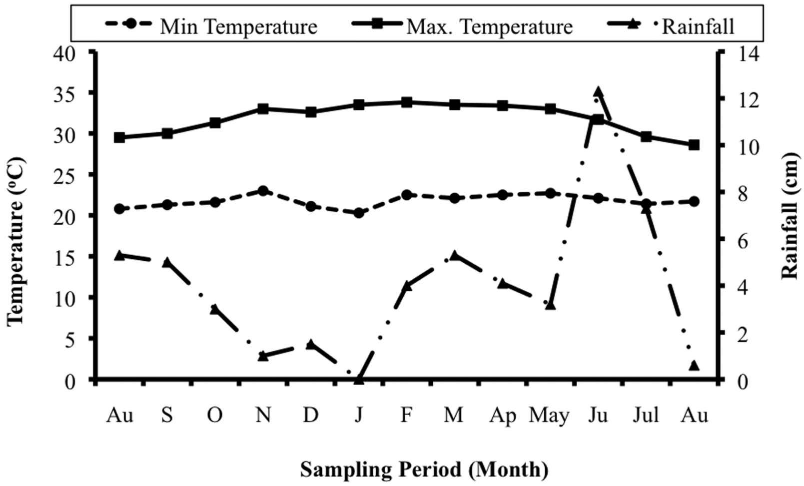

Figure 1. Climatic data at the study site during the experimental period (August 2008–July 2009).

Soil Sampling and Analysis

Prior to setting up the experiment, soil samples were randomly collected at the surface 0–15 cm from 16 locations in a grid format at the experimental site for site characterization. The samples were composited and homogenized into one sample from the 16 subsamples. They were then air dried, passed through a 2-mm sieve, and analyzed for site characterization using five replicated subsamples from the composited sample. The physicochemical properties of the soil top layer (0–20 cm) prior to the experiment are reported in Table 1. At flowering (5 weeks after planting), nine soil samples were collected per plot, prepared as described, and analyzed for soil pH using a pH meter (1:1 H_2O), total N by the Kjeldahl method, organic carbon (C) by the Walkley and Black method (Walkley and Black 1934), cation exchange capacity by flame photometry using ammonium acetate extract (Motsara and Roy 2008), available P by Bray's method 1 (Bray and Kurtz 1945), and available K by flame photometry (Toth and Prince 1949). Furthermore, soil samples were also monitored for soil microbial parameters. Soil microbial biomass (C, N, and P) was measured using the chloroform fumigation–extraction method described by Vance, Brookes, and Jenkinson (1987). All soil analyses were conducted at the Soil Research Institute of Ghana, Kwadaso, Kumasi.

Experimental Design and Treatment Applications

The experiment was conducted during the minor rainy season of 2008 (August–December 2008) and major rainy season of 2009 (March–July 2009) using okro (*Abelmoschus esculentus*) as a test crop. Five treatments were arranged in a randomized complete block design with a plot dimension of 3 m × 3 m, replicated four times. The treatments included a control (no input); green biomass of *Senna spectabilis*, *Gliricidia sepium*, and *Tithonia* (all applied at 4.5 t dry matter ha^{-1}); and mineral fertilizer applied at 150 kg N ha^{-1}, 60 kg P ha^{-1}, and 60 kg K ha^{-1}. Treatments were applied in both cropping seasons. The green biomass of *Tithonia*, *S. spectabilis*, and *G. sepium* including soft stems were surface applied on the soil by hand and hoed a week before planting. At planting, mineral fertilizer in the form of NPK (15:15:15) was basally applied at 250 kg ha^{-1}. After 30 days of planting, plants were side-dressed with 150 kg ha^{-1} of NPK (15:15:15) and subsequently

Table 1
Physicochemical properties of the topsoil (0–15 cm) of the experimental site at the Agroforestry Research Station, Kumasi, Ghana

Parameter	Value
pH (H_2O) (1:1)	4.05
Organic C (g kg^{-1})	22.9
Organic matter (g kg^{-1})	39.5
Total N (g kg^{-1})	2.20
Available P (mg kg^{-1})	5.64
Available K (mg kg^{-1})	251.08
Exchangeable cations ($cmol_c$ kg^{-1})	
Ca	3.74
Mg	2.40
K	0.35
Na	0.08
Exchangeable acidity (Al + H) ($cmol_c$ kg^{-1})	0.55
CEC ($cmol_c$ kg^{-1})	7.12
Base saturation (%)	92.28
Texture (%)	
Sand	60.36
Silt	35.51
Clay	4.13
Textural class	Sandy loam

top-dressed with 90 kg N ha^{-1} (in an equivalent amount of urea) equally split applied at 50 and 70 days after planting. Fertilizers were not applied on green manure plots. During planting, okro seeds were sowed four seeds per hill at 0.6 $\times$ 0.6 m spacing and thinned to two plants per hill 2 weeks after planting. Crop residues from the minor rainy season cropping were totally removed from the field to reduce the confounding effects of organic residues of the okro plants for the subsequent major rainy season cropping.

Plant Sampling and Analysis

Fresh leaves of *Tithonia* used in the experiment were collected from established hedges at Sunyani in the Brong Ahafo Region of Ghana while *S. spectabilis* and *G. sepium* were collected from the research site. The plant materials collected were characterized for quality parameters. Samples of fresh leaves including soft stems collected were oven dried at 65 °C until constant weight, ground to pass through a 0.5-mm sieve, and analyzed for total lignin; polyphenol; N, P, and K; calcium (Ca); magnesium (Mg); and C. Nitrogen was determined by the Kjeldahl method, P by the volumetric ammonium phosphomolybdate method, K by atomic absorption spectrophotometry, C by the gravimetric ash method, and Ca and Mg by the ethylenediaminetetraacetic acid (EDTA) titration method (Motsara and Roy 2008). Lignin was determined according to the acid detergent fiber method (van Soest 1963). Total extractable polyphenols were analyzed from dried material by extraction using 50% aqueous methanol. The plant-to-extractant ratio was 0.1 g / 50 mL, and

Table 2
Chemical characteristics of plant materials used

Species	N (g kg^{-1})	P (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})	C (g kg^{-1})	Lig (%)	Poly (TAE) (%)	C/N	C/P
Ss	30.0	2.6	5.4	6.5	5.1	476.2	8.7	1.6	15.9	183.2
Td	33.3	4.2	6.2	14.0	9.2	453.7	5.8	1.8	13.6	108.0
Gs	29.0	3.0	6.4	8.0	7.0	443.6	23.1	3.1	15.3	147.9

Notes. Ss, *S. spectabilis*; Td, *Tithonia*; Gs, *G. sepium*; Lig, lignin; Poly, polyphenol; and TAE, tannic acid equivalent. $N = 3$.

phenols were analyzed colorimetrically using the Folin–Ciocalteu reagent as described by Constantinides and Fownes (1994). Plant analyses were conducted at the Soil Research Institute of Ghana, Kwadaso, Kumasi. The chemical compositions of the plant materials used in the experiment are reported in Table 2.

Data Collection and Statistical Analysis

For all cropping seasons, data was collected on belowground (BG) and aboveground (AG) biomass and fruit yields of okro. Belowground and AG were determined at flowering using 20 plants per treatment. To determine BG and AG, plants were uprooted from soil after watering the surface soil to minimize root destruction during sampling. Roots were thoroughly washed in distilled water and separated from shoots. Thereafter, the roots and shoots were enveloped and oven dried in the laboratory at 65 °C until constant weight. Fruit yields were measured at each harvest using the fresh weight of fruits collected from 28 plants per plot. Fruit harvesting was done every 4 days after the first harvest until 16 weeks after planting. Yields were expressed on a per hectare basis. To compare the treatment effects of the different seasons, yields were converted to relative increase compared to the control using the relation by Gachengo et al. (1999):

$$\text{Yield increase (\%)} = \frac{(\text{Yield}_{\text{treatment}} - \text{Yield}_{\text{control}})}{\text{Yield}_{\text{control}}} \times 100. \quad (1)$$

Nutrient uptake in the aboveground biomass of okro plants was determined 16 weeks after planting for each cropping season. To determine nutrient uptake, leaf samples were collected from a sample of 15 plants per plot and oven dried at 65 °C to constant weight. Dried material was ground to pass through a 0.5-mm sieve and analyzed for N, P, and K concentrations using the analytical methods mentioned previously. Nutrient uptake was determined by multiplying the dry-matter yields by the various nutrient concentrations. Nutrient uptake was used to determine amount of nutrients recovered using the relation by Gachengo et al. (1999):

$$\text{Nutrient recovery (\%)} = 100 \times \frac{(\text{Nutrient uptake}_{\text{treatment}} - \text{Nutrient uptake}_{\text{control}})}{\text{Amount of nutrient applied to minor crop}_{\text{control}}} \quad (2)$$

For the minor rainy season, all parameters measured were subjected to analysis of variance (ANOVA). However, variables measured in the major rainy season were analyzed using analysis of covariance (ANCOVA) test to remove the residual effects of treatments applied in the minor rainy season experiment. Treatment means were compared using Duncan's multiple range test (DMRT) at a 0.05 probability level. All statistical analyses were conducted using GENSTAT 11 (VSN International 2008).

Results

Chemical Properties of Green Manures Used

There were distinct differences in the chemical characteristics of the plant materials used. Among the plant materials, *Tithonia* green manure showed the greatest levels of N, P, Ca, and Mg. The greatest K and C levels were recorded in *G. sepium* and *S. spectabilis* respectively (Table 2). The C/N ratio ranged from 13.6 in *Tithonia* to 15.9 in *S. spectabilis*. The C/P ratio followed the order *Tithonia* < *G. sepium* < *S. spectabilis.* The greatest lignin and polyphenolic concentrations were recorded in *G. sepium* whereas *Tithonia* and *S. spectabilis* recorded the lowest levels of lignin and polyphenol, respectively.

Effects of Treatments on Soil Properties

Chemical Properties. Tables 3 and 4 show the recorded levels of soil chemical properties monitored during the minor and major rainy seasons respectively. In the minor rainy season, ANOVA test revealed significant ($P < 0.05$) effect of treatments on all soil chemical parameters. In contrast with fertilizer treatments, the application of the green manures increased soil pH levels. Soil pH in the minor season was comparable among the green manures but lowest (4.2) in fertilizer treatments. With the exception of *S. spectabilis*, all treatments recorded pH values that differed significantly ($P < 0.05$) from the control and fertilizer treatments. Although total N was comparable among green manures and fertilizer treatments, only *S. spectabilis* treatment differed significantly ($P < 0.05$) from the control (Table 3). Except in *G. sepium*, the application of treatments increased P availability during the minor rainy season. Phosphorus availability was comparable between the following pairs: plots treated with fertilizer and *S. spectabilis* and plots treated with *Tithonia* and *S. spectabilis*. A significant ($P < 0.05$, $r^2 = 0.29$) positive correlation was observed

Table 3

Some chemical properties of the soil at the surface (0–15 cm) as affected by the different treatments during the minor rainy season of 2008

Treatments	pH H_2O (1:1)	Total N (g kg^{-1})	Organic C (g kg^{-1})	Available K (mg kg^{-1})	Available P (mg kg^{-1})	CEC_e ($cmol_c$ kg^{-1})
Control	4.24a	1.5a	13.5a	137.3a	5.94a	6.89ab
Tithonia	4.87b	1.7ab	17.3bc	187.5d	11.05b	8.08b
S. spectabilis	4.56ab	2.1b	19.3c	164.0bc	11.46bc	7.20ab
G. sepium	5.00b	1.8ab	15.1ab	177.4cd	7.93a	7.99b
Mineral fertilizer	4.22a	1.7ab	16.8abc	150.7ab	13.75c	6.46a

Notes. Means with the same letters in a column do not differ significantly according to DMRT (p = 0.05). CEC_e, effective cation exchange capacity. $N = 4$.

Table 4

Some chemical properties of the soil at the surface (0–15 cm) as affected by the different treatments during the major rainy season of 2009

Treatments	pH H_2O (1:1)	Total N (g kg^{-1})	Organic C (g kg^{-1})	Available K (mg kg^{-1})	Available P (mg kg^{-1})	CEC_e ($cmol_c$ kg^{-1})
Control	5.44a	1.2a	12.6ab	73.76c	14.82a	6.21ab
Tithonia	5.50a	1.1a	13.4ab	46.77a	11.88a	6.24ab
S. spectabilis	5.22a	1.4a	15.4c	73.65c	12.09a	6.28ab
G. sepium	5.40a	1.2a	11.9a	63.55b	10.29a	7.81b
Mineral fertilizer	5.19a	1.1a	11.9a	60.32b	12.72a	5.13a

Means with the same letters in a column do not differ significantly according to DMRT ($P = 0.05$). CEC_e, effective cation exchange capacity. $N = 4$.

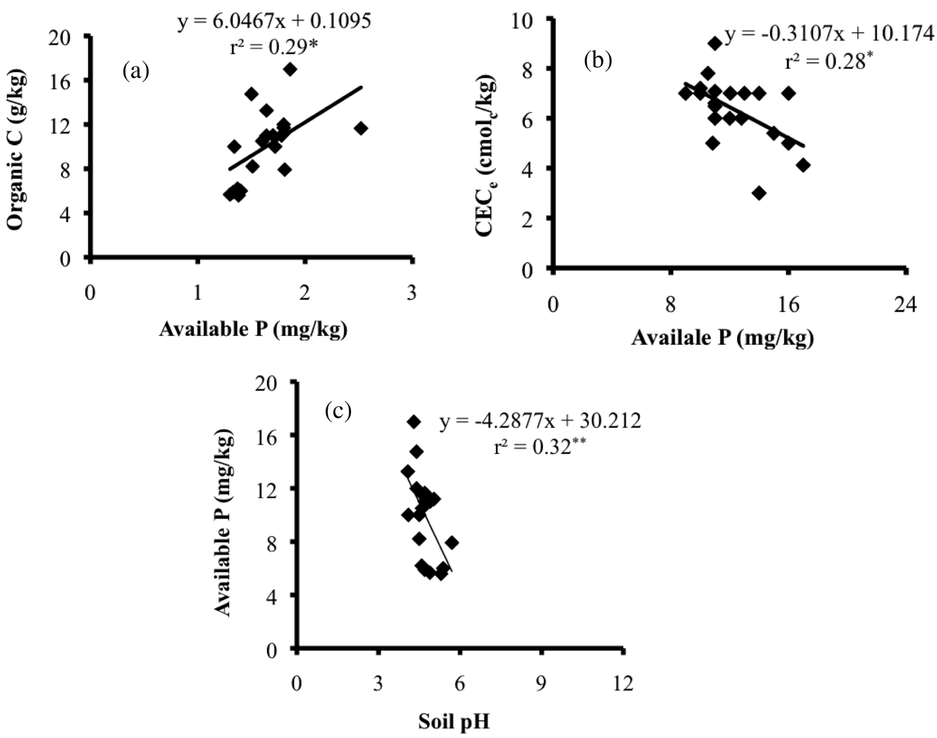

Figure 2. Relationship between available P and organic C (a), CEC_e (b), and pH (c). Asterisks (*, **) denote significance at 5% and 1% probability levels, respectively.

between available P and soil organic C (SOC) (Figure 2a). Similarly, available P recorded a significant ($P = 0.01$, $r^2 = 0.32$) negative correlation with CEC_e (Figure 2b) and soil pH (Figure 2c). Furthermore, the application of treatments increased K availability except in fertilizer-treated plots. *Tithonia* recorded the greatest availability of K, which, although comparable to *G. sepium* treatments, differed significantly ($P < 0.05$) from *S. spectabilis* and fertilizer treatments.

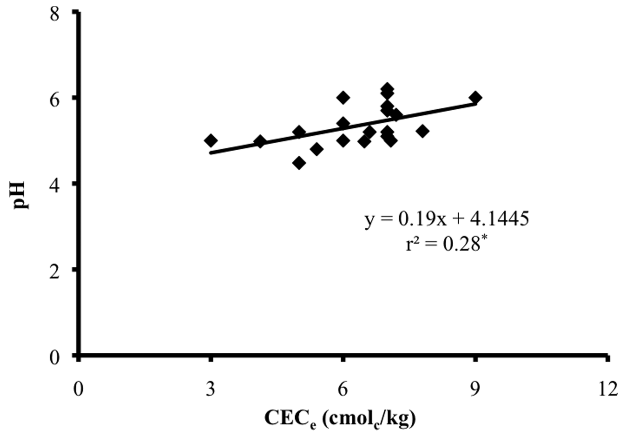

Figure 3. Relationship between soil pH and CEC_e. Asterisk (*) denotes significant at the 5% probability level.

In the major rainy season, ANCOVA test revealed significant ($P < 0.05$) effect of treatments on only SOC, available K, and CEC_e. A significant ($P < 0.05$, $r^2 = 0.28$) positive correlation was observed between soil pH and CEC_e (Figure 3). Consistently, both cropping seasons recorded a significantly greatest SOC levels in *S. spectabilis* treatments. Potassium availability between seasons was contrasting in some of the treatments. In the minor season, available K was significantly greatest in *Tithonia* and *G. sepium* treatments but tended to be lowest during the major season experiment. Observations made in *S. spectabilis* plots in relation to available K were also contrasting (Tables 3 and 4). During the major season, the control and *S. spectabilis* treatments recorded comparable available K levels that differed significantly ($P < 0.05$) from the other treatments.

Microbial Properties. Except in fertilizer-treated plots, the application of treatments increased the soil microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) during the minor cropping season (Table 5). In the major rainy season, only *S. spectabilis* and *G. sepium* significantly ($P < 0.05$) increased MBC and MBN, respectively. Meanwhile, the effect of treatments on microbial biomass phosphorus (MBP) was only significant ($P < 0.05$) in the major rainy season. Consistently, *G. sepium* recorded the lowest MBC/MBN ratio in both cropping seasons. Some significant relationships were observed between the soil microbial properties and chemical properties (Table 6).

Effects of Treatments on Agronomic Characteristics of Okro Plants

Biomass Production. The effects of treatments on the above- and belowground biomass of the okro plants were recorded at flowering during both cropping seasons. Treatments had significant ($P < 0.001$) effect on both above- and belowground biomass in both seasons. In most cases, the effect of the green manures on the biomass production of the okro plants was comparable to inorganic fertilizer treatment (Table 7).

Nutrient Uptake and Recovery. Nitrogen, P, and K recoveries were greatest in *G. sepium*–treated plots among all treatments. The percentage of N, P, and K recovered ranged from 28 in *S. spectabilis* to 88 in *G. sepium*, 12 in fertilizer to 65 in *G. sepium,* and 1 in

Table 5
Soil microbial biomass C, N, P (mg kg^{-1}), and MBC/MBN ratio in soil as affected by different nutrient sources during the minor and major rainy seasons of 2008 and 2009 respectively

	Minor season				Major season			
Treatments	MBC	MBN	MBP	MBC/ MBN	MBC	MBN	MBP	MBC/ MBN
Control	850a	79a	9.6a	10.8bc	1100ab	100a	9.0a	11.0b
Tithonia	1160c	130b	9.2a	8.9ab	1260bc	100a	19.7c	12.6bc
S. spectabilis	1090b	120b	8.9a	9.1abc	1410c	100a	14.6b	14.1c
G. sepium	1130bc	140b	9.9a	8.1a	1100ab	200b	16.2b	5.5a
Mineral fertilizer	910a	80a	8.9a	11.4c	1000a	100a	14.0b	10.0b
CV (%)	4.1	16.2	13.7	16.7	8.5	17.7	13.4	17.6

Notes. Means with the same letters in a column do not differ significantly according to DMRT ($P = 0.05$). MBC, microbial biomass carbon; MBN, microbial biomass N; and MBP, microbial biomass phosphorus. $N = 4$.

Table 6
Pearson correlation coefficients (r) for the relationships between soil microbial biomass (C, N, and P) and soil chemical properties

	MBC	MBN	MBC/MBN	MBP
MBC	1			
MBN	0.83***	1		
MBC/MBN	0.57**	−0.92***	1	
MBP	0.35^{ns}	0.45*	−0.54*	1
Organic C	0.78***	0.27^{ns}	0.47*	0.08^{ns}
CEC_e	0.44*	0.65**	−0.39^{ns}	0.15^{ns}
Total N	0.33^{ns}	0.01^{ns}	0.45*	−0.56**
Available P	−0.29^{ns}	−0.39^{ns}	0.10^{ns}	0.51*
Available K	0.75***	0.78***	−0.67***	−0.68***

Notes. MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; MBP, microbial biomass phosphorus; CEC_e, effective cation exchange capacity; and ns, not significant.
*$P \leq 0.05$.
**$P \leq 0.01$.
***$P \leq 0.001$.

fertilizer to 23 in *G. sepium* respectively. Phosphorus and K recovered in the aboveground biomass of the okro plants were lowest in mineral fertilizer–treated plots among treatments (Table 8).

Yield. In all cropping seasons, yield of okro increased with the application of the soil amendments as yields recorded for treatments differed significantly ($P < 0.001$) from the control. In most treatments, yields were as much as twice that of the control. Total yield from both seasons was significantly ($P < 0.05$) greatest in *Tithonia* and *G. sepium*

Table 7
Aboveground (AG) and belowground (BG) biomass of okro plants as influenced by treatments during the minor and major rainy seasons of 2008 and 2009, respectively

	Minor season			Major season	
Treatments	AG	BG	kg dry matter ha^{-1}	AG[a]	BG[a]
Control	192.6a	41.11a		146.8a	54.2a
Tithonia	465.4c	95.50c		1240.6c	171.3d
S. spectabilis	326.4b	71.78b		770.2b	142.0cd
G. sepium	474.7c	88.44bc		1106.7bc	132.7bc
Mineral fertilizer	400.8bc	81.56bc		901.4bc	107.6b
CV (%)	13.9	14.9		16.1	10.7

[a]Analyzed using aboveground and belowground data of minor cropping season as covariates. Means with the same letters do no differ significantly according to DMRT ($P = 0.05$).

Notes. CV, coefficient of variation. $N = 4$.

Table 8
Nutrient uptake and recovery in total aboveground biomass of okro plants at flowering as affected by the different treatments during the minor season

	Nutrients added (kg ha^{-1})			Nutrient uptake (kg ha^{-1})			Nutrient recovery (%)		
Treatment	N	P	K	N	P	K	N	P	K
Control	0	0	0	60.7	6.4	4.8	NA	NA	NA
Tithonia	150	18.9	27.9	144.6	15.4	10.7	56	47	21
S. spectabilis	135	11.7	24.3	98.8	9.1	6.9	28	23	8
G. sepium	131	13.5	28.8	176.5	15.2	11.5	88	65	23
Mineral fertilizer	150	100	100	154.1	18.2	5.6	62	12	1
SED				17.5	1.8	1.1	12	4.9	4.28

Notes. NA, not applicable; SED, standard error of difference. $N = 4$.

treatments (Table 9). The greatest (200%) and lowest (150%) relative yield increments were recorded in *S. spectabilis* and mineral fertilizer during the minor season. During the major season the trend was different: the greatest (130%) and lowest (50%) relative yield increments were recorded in *Tithonia* and *S. spectabilis* respectively (Figure 4).

Discussion and Conclusion

Differential effects of the various treatments on soil properties and the agronomic characteristics of okro reflected the apparent differences in the qualities of the soil amendments applied. Among the green manures, *Tithonia* showed the greatest levels of N, P, Ca, and Mg. Although reasons behind high nutrient accumulation in *Tithonia* biomass are largely unknown (George et al. 2001) observations made in this research are similar to those reported in previous studies (Gachengo et al. 1999; Jama et al. 2000; Ikerra, Semu, and Mrema 2006; Partey et al. 2011). Meanwhile, the biochemical characteristics of the green

Table 9
Effects of soil amendments on fruit yield of okro

	Yield (t ha^{-1})		
Treatment	Minor season	Major season[a]	Total[a]
Control	0.6a	1.0a	1.6a
Tithonia	1.7c	2.3b	4.1c
S. spectabilis	1.8c	1.5ab	3.3b
G. sepium	1.6bc	2.1b	3.7c
Mineral fertilizer	1.5b	1.8ab	3.3b
CV	10.4	12.9	8.6

[a]Analyzed using yield in minor season as covariate.
Notes. Means with the same letters do no differ significantly according to DMRT ($P = 0.05$). CV, coefficient of variation. N = 28.

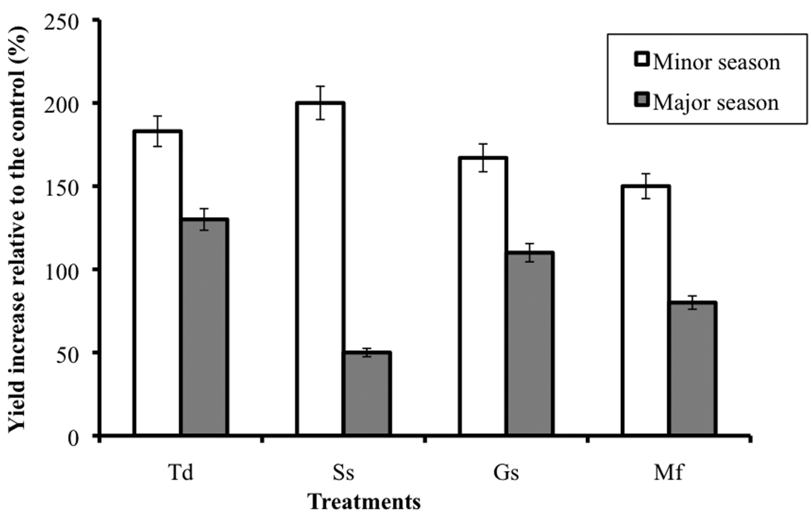

Figure 4. Okro yields expressed as a percentage of yield increase relative to the control for the minor and major rainy seasons of 2008 and 2009 respectively. Data points are the means of four replicates. Error bars represent standard error of means.

manures confirmed their suitability for fertilizer technology (Palm et al. 2001; Partey et al. 2011).

Generally, the green manures from the agroforestry species resulted in improved soil properties and agronomic characteristics of okro in all cropping seasons. These effects were comparable to inorganic fertilizer treatments. In contrast with fertilizer treatments, the application of green manures increased soil pH during the minor rainy season. Significant increase in soil pH with the application of plant residues or green manure is similarly reported (Mucheru-Muna et al. 2007; Eghball 2002). While the application of mineral fertilizers might result in decrease in pH because of the addition of H^+ ions to the cation exchange complex of soils, the presence of organic anions in organic amendments reportedly displaces hydroxyls from sesquioxide surfaces (Parffit 1978; Ikerra 2004) thereby resulting in increase in pH. This displacement reaction may have resulted in the increased pH levels recorded in plots amended with the green manures (particularly in the minor season). Soil pH levels recorded at the end of the experiment was a significant increase from the initial, which makes application of plant residues promising for many acidic soils in SSA. The application of the organic materials significantly increased the effective cation exchange capacity of the soils, which in most cases is attributed to the increase in organic matter (Oorts, Vanlauwe, and Merckx 2003). This enhancement in CEC_e is crucial in many areas of the humid and subhumid tropics dominated by soils of low cation exchange capacity, the so-called low-acidity clay soils that may quickly lose their fertility if fallow periods, or some analog to fallow conditions, are not imposed (Kang 1991). The significant positive correlation observed between CEC_e and pH is consistent with studies by Oorts, Vanlauwe, and Merckx (2003). This relationship is also consistent with earlier reports by Charman (2007) that CEC_e has an important bearing on soil pH because both parameters have influence on soil nutrient availability (Troeh and Thompson 2005). The influence of pH and CEC_e on nutrient availability was reflected in their significant correlation with available P (Figure 3). Although P availability was greatest in fertilizer treatments, it was comparable to *S. spectabilis* and *Tithonia* treatments. The suitability of these species for P fertilization has been previously confirmed (Gachengo et al. 1999; Nziguheba et al. 2000; Phan Thi 2000; Cong and Merckx 2005; Ikerra, Semu, and Mrema 2006), which is consistent with the observations made in this research.

Generally, K availability was low in all treatments during the major season compared with the minor season. There were also contrasting observations between seasons in *Tithonia* and *S. spectabilis* treatments. Results may be attributed to differences in biomass quality and the response of the plant materials to biophysical factors (such as rainfall) that affect decomposition and nutrient-release patterns of green manures. Furthermore, results from the experiment demonstrated that difference in both quantity and quality of C inputs could significantly affect microbial biomass. Throughout the experimental period, organic amendments generally increased MBC and MBN compared to the control and mineral fertilizer–treated plots. Increased microbial biomass by organic C inputs is well documented (Goyal et al. 1999; Zaman, Di, and Cameron 1999; Chowdhury et al. 2000; García-Gil et al. 2000; Peacock et al. 2001). Varying effects of organic substrates on soil microbial C, N, and P are reported in this research, and it is consistent with soil ecological claims that substrate composition has profound influences on microbial utilization of C and nutrients in the substrate (Cheshire and Chapman 1996; Martens 2000; Tu et al. 2006). In addition, the significance of C inputs for increased soil microbial biomass was confirmed in the results of this study as per the significant correlation observed between MBC and organic C (Table 6). This significant interaction explains why the effects of mineral fertilizer on microbial biomass (C and N) were less significant, obviously because extractable C inputs were nil although N, P, and K inputs were high in the fertilizer applied. Further, because the application of easily decomposable organic materials with a significantly low total C/N ratio is associated with enhanced soil microbial biomass in cropping systems (Smith and Paul 1990), the greatest MBC and a comparable MBN and MBP were observed in *Tithonia*-treated plots. It is reported that soil microbial biomass under different organic amendments may have implications for nutrient availability to crops. This is because high microbial biomass often leads to high nutrient availability to crops through enhancing both the microbial biomass turnover and the degradation of nonmicrobial organic materials (Zaman, Di, and Cameron 1999; Tu et al. 2006; Wang, Smith, and Chen 2004). This assertion is confirmed by the significant relationship obtained between soil microbial biomass parameters and CEC_e, available K, available P, and total N (Table 6).

In most of SSA, declining food production is attributed to potential N and P losses (Ikerra, Semu, and Mrema 2006; Jama et al. 2000; Smaling, Nandwa, and Janssen 1997) through leaching, nutrient mining, and continuous cropping. In the present study we emphasized N supply through green manuring or inorganic fertilizer application as N decline is the major constraint to crop production at the study location (Partey et al. 2011). The quantities of green manures applied were chosen to balance N rates between 130 and 150 kg ha^{-1} as required for okro production at the study site. The green manure rates were feasible for agronomic practices as quantities beyond 5 t/ha could potentially increase the labor cost for green manure harvesting (Mucheru-Muna et al. 2007). From the chemical analysis, we found N supply to be comparable among the green manures but slightly lower than that supplied through the inorganic fertilizer. Fertilizer rates were made slightly greater to compensate for potential losses (through leaching) in the early growth stages of the okro. From the study, the effect of the green manures on the biomass production and fruit yield of okro was comparable to the effect of fertilizer treatments in both seasons. Total fruit yield from both seasons tended to be significantly greater in plots treated with the green manures than fertilizer and the control. Although the results do not dispute the applicability or use of inorganic fertilizers as soil fertility amendments, they add to evidence in support of the suitability of the green manures for smallholder agriculture (especially in places where inorganic fertilizers are limited). Earlier experiments confirmed that the application of *Tithonia*, *S. spectabilis*, and *G. sepium* green manures increase crop yields even on depleted soils (Gachengo et al. 1999; Nziguheba et al. 2000; Ikerra, Semu, and Mrema 2006; Makumba et al. 2006), which is consistent with the observations made here. The okro plants recovered a greater percentage of the N, P, and K added from *G. sepium* green manure than the other treatments. Nutrient recovered from *Tithonia* followed closely to *G. sepium* and was greater than fertilizer-treated plots, which received the greatest N, P, and K inputs. This observation supports the idea that the quality of the organic input, not just the amount of nutrients added, affects nutrient availability patterns and crop growth (Gachengo et al. 1999). The lower recovery of nutrients, particularly P and K, from fertilizer treatments may be a result of leaching losses, which may have resulted in a lack of synchrony between crop nutrient demand and supply by the soil.

We conclude from this study that the application of green manures from agroforestry species can increase crop yields and improve soil fertility indicators. As observed, the application of the green manures (particularly in *Tithonia*) increased crop yields to twice the control yield in both cropping seasons. Generally, okro fruit yield recorded for the green manures were comparable and in some cases greater than fertilizer treatments. Total yield responses in *Tithonia* treatments, for instance, were 61% and 20% greater than the control and fertilizer treatments respectively. Significant results obtained from this study confirm that green manures of the three rarely used agroforestry species are potential soil nutrient sources and could help boost crop productivity levels on smallholder farms in SSA.

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