




Towards bamboo agroforestry development in Ghana: evaluation of crop performance, soil properties and economic benefit

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Received: 30 April 2019 / Accepted: 16 April 2020

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Abstract In the quest to promote bamboo agroforestry in the dry semi-deciduous forest zone of Ghana, we evaluated changes in soil properties, crop productivity and the economic potential of a bamboo-based intercropping system. The intercropping system was established from 3-months old sympodial bamboo (*Bambusa balcooa*) seedlings planted at a 5 m × 5 m spacing and intercropped with maize, cassava or cowpea. Separate monocropping fields for maize, cassava, cowpea and bamboo were set up adjacent to the intercropped field. In both the intercropping and monocropping fields, plots were with fertilizer treatments and without. The experiment was laid out in a split plot design with four replicates and studied over three years. Economic analysis was conducted using the financial benefit–

cost ratio method. The results showed that regardless of fertilizer treatments, bamboo agroforestry and monocropped fields had comparable effects on soil properties and crop productivity within two years of establishment. In the third year, however, bamboo agroforestry had significantly ($p < 0.05$) higher soil moisture, pH and crop productivity levels. An intercropping advantage over monocropping was evident for all crops with respective partial land equivalent ratios for fertilized and non-fertilized intercropped systems as follows: cowpea (1.37 and 1.54), maize (1.38 and 1.36), and cassava (1.12 and 1.19). The economic evaluation also indicated marginal profitability of bamboo intercropping over monocropping systems. From the results obtained, there are clear indications that where bamboo is a prioritized woody perennial, integrated systems with crops may be encouraged.

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Keywords Agroecology · Crop productivity · Food security · Soil productivity · Sustainable agriculture

Introduction

In Africa, forests provide important ecosystem services that support the environment and livelihoods. However current deforestation figures point to a dire situation for such important natural resources. FAO (2015, 2016) reports that Africa lost about 3.4

million hectares of forest land between the periods of 2000 to 2010. In Ghana, the closed forest reduced from 2,317,166 hectares to 1,785,802 hectares between 2000 and 2010, depreciating at the rate of 192,648 hectares per 5 years (FAO 2016). Increased deforestation has been linked to some anthropogenic activities with the production of wood fuels considered the most paramount (Chidumayo and Gumbo 2013; Cerutti et al. 2015). Wood fuels are used by about one-third of the world's population (FAO 2017) with future consumption projected to upsurge to 544.8 million m³ for firewood and 46.1 million tonnes for charcoal by 2030 in Africa (Arnold et al. 2003). Detrimental impacts of such increasing demand and consumption of wood fuels on the ecological integrity of forests is inevitable.

In Ghana, about two million tonnes of wood were consumed in 2010 of which 80% was charcoal or firewood (Kemausuor et al. 2011). With an increasing population and the current unreliable supply of electricity in urban areas, the dependence on fuelwood is expected to increase. The excessive dependence on woodfuels in Africa and in Ghana in particular culminate in wanton destruction of vegetation. This situation exacerbates climate change effects. With climate change affecting food production systems and coupled with other biophysical constraints such as declining soil fertility, farmers are unable to obtain the required yield of crops for subsistence and commercial gains (ACET 2017; AGRA 2017). To mitigate this challenge, energy woods plantation is usually recommended despite the risk for competing with food crops production, especially for smallholder farmers (Lobovikov et al. 2012; FAO 2017). Hence the necessity to find alternatives such as the use of woody energy species that can be intercropped to simultaneously address issues of fuelwood scarcity and food insecurity. Government of Ghana's initiatives such as the introduction of the taungya system has seen the establishment of large plantations to curtail deforestation and provide livelihood options for rural households. However, the relatively long rotation periods of some of the species such as teak and acacia have led to renewed interest in the use of bamboo as an additional option.

Bamboo is fast growing and produces high biomass with calorific values comparable to commonly sourced wood biomass such as teak and acacia

(Partey et al. 2017). An initiative named Bamboo and Rattan Development Programme (BARADEP) was launched by Ghana's Ministry of Lands and Natural Resources and approved by the cabinet to promote bamboo use as an alternative to some endangered forest tree species for renewable energy and other domestic and industrial uses (e.g. construction and furniture). Due to bamboo's unique contribution to bio-energy production and other ecological benefits (e.g. soil stabilization and water conservation through fibrous root system), several national economies have established bamboo plantations (Partey et al. 2017). Such bamboo plantations have been reported to have facilitated the reduction in deforestation as it reduces the excessive removal of trees from the natural environment for charcoal and firewood production (Kuehl et al. 2013; Akwada and Akinlabi 2018; Van Khuc et al. 2018). This notwithstanding, monoculture bamboo plantations may pose threats to food security unless such lands are marginal or degraded (Partey et al. 2017). In Asia, productive and economically viable bamboo-based agroforestry systems have been established with reported increased food crop yields and non-food biomass (Mailly et al. 1997; Ahlawat et al. 2008; Nirala et al. 2018).

In Ghana, bamboo-based agroforestry is relatively new with no significant studies that provide information on its agronomic and economic potentials. However, such information is necessary for designing bamboo-based agroforestry systems that meet the needs of farmers (Partey et al. 2017; Akoto et al. 2018). For this reason, bamboo-based intercropping systems with sympodial bamboo (*Bambusa balcooa*), maize, cowpea and cassava were established and studied over three years to determine intercropping advantage over monocropping systems of bamboo, maize, cassava and cowpea in relation to (a) changes in soil properties; (b) crop yields; and (c) economic feasibility.

Materials and methods

Study site

The study was carried out at Jeduako in the Sekyere Central District of Ghana located within Lat 06°55' and 07°30'N and Long 05°00' W (Fig. 1). The district covers a total land area of 1564 km² and has 150

Study Area-Sekyere Central District in Ashanti Region

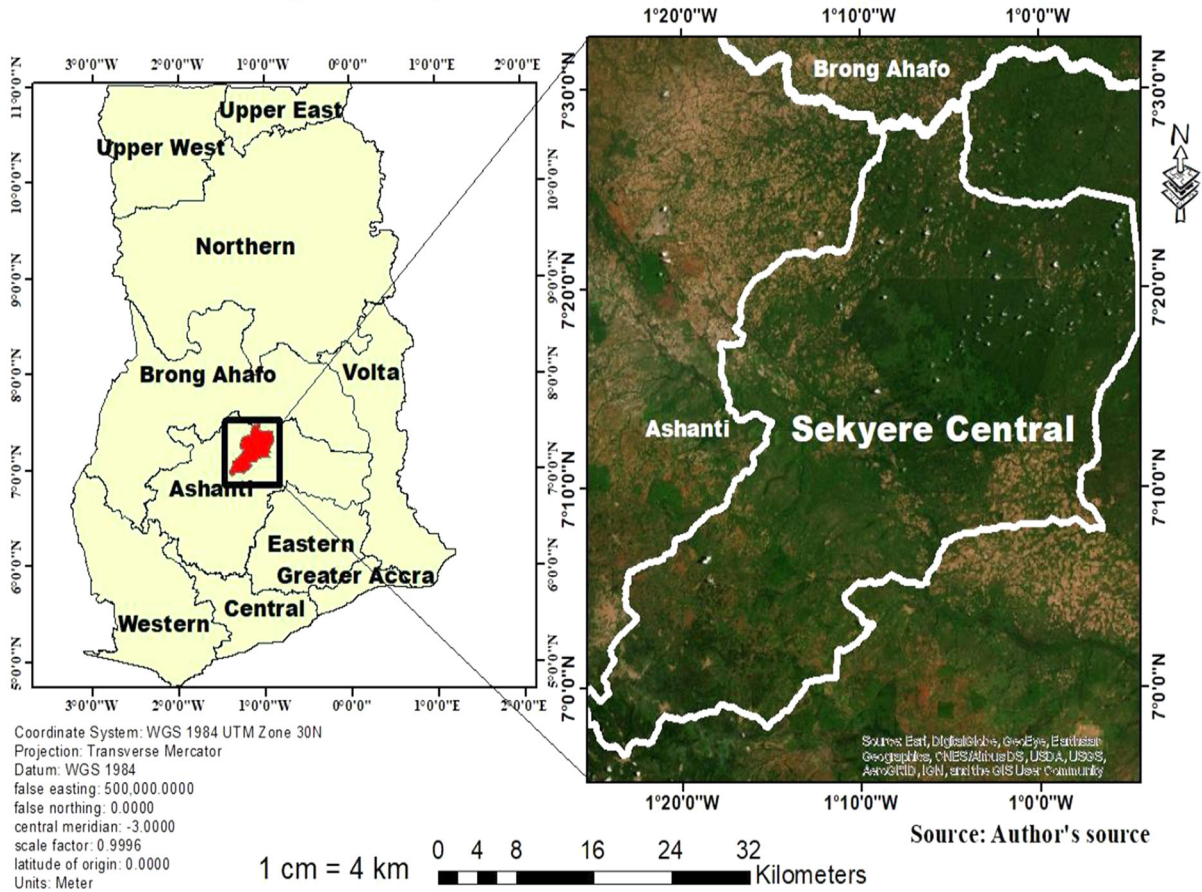


Fig. 1 Sekyere central district in Ghana

settlements with 70% being rural. Total population of the District is 71,232, distributed as 35,225 males (49.5%) and 36,007 females (50.5%) (Ghana Statistical Service 2012). It falls within the dry semi-deciduous forest zone of Ghana and borders the savannah in the north and the forest zone in the south (Damnyag et al. 2011; Tom-Dery et al. 2014). It is characterized by a bimodal rainfall pattern with an average annual rainfall of 1270 mm. The major rainy season starts in March with a main peak in May. There is a slight dip in July and a peak in August, which tapers off in November. December to February is warm and dusty (the driest period). The area has a mean annual temperature of 27 °C with mean monthly temperatures ranging from 22 to 30 °C and a mean annual humidity of 70%. The soil type is sandy loam (Ejura—Denteso Association) and

classified as ferric Acrisol (Tom-Dery et al. 2014; Vigbedor et al. 2015).

This area is a major food basket in Ghana and has high production of fuelwood from natural forest sources. Subsistence agriculture is the major economic activity employing about 65% of the population (Damnyag et al. 2011). Most of the agricultural production is from manually cultivated rainfed crops. Major crops include: maize, cowpea, cassava, yam, and plantain. This site was chosen for this study because of its unique characteristic features which combine those of the forest and savanna zones (Akoto et al. 2018). Furthermore, it is an area in Ghana with a great need for fuelwood. It is also within the zone targeted for the introduction of private and community tree planting for wood energy production (Ghana Forestry Commission 2015).

Field establishment and experimental procedure

The bamboo-based intercropping system was designed and established in June 2014 with modification from the design recommended by Nath et al. (2009), as an on-station experiment. It was laid out as a split plot design with four replicates (Fig. 2) with cropping/farming system as main plot treatment and fertilizer application as sub-plot treatment. The main plot treatment included: monoculture systems of bamboo, maize, cowpea and cassava; and intercropping systems of bamboo with maize, cowpea and cassava as intercrops. The sub-plot treatment involved fertilizer application or not. The bamboo species used was *Bambusa balcooa* originating from North-Eastern India (Malay et al. 2008). The selection of this species was based on its strong regeneration capacity, ability to grow in dryer soils and high biomass yield (Zhao et al. 2014) for sustainable fuelwood production. It has very low evasive characteristics, and evasiveness can be further controlled through periodic harvesting of culms in coppice management (Malay et al. 2008). The bamboo plants were established from 3-month old seedlings at a 5 m × 5 m spacing (Fig. 2). Crops of different agronomic classifications (tuber, legume

and cereal) were chosen to determine which crop could be most integrative with bamboo. Consequently, different fields were established with maize, cowpea and cassava. The farming systems (bamboo-maize, bamboo-cowpea and bamboo-cassava) were considered as separate experiments. Maize (variety ‘Omankwa’, locally bred) was intercropped within bamboo rows at 0.4 m × 0.8 m spacing by sowing four seeds per hill and thinning to two per hill within two weeks. Cassava (variety ‘Ampong’) was planted at a 1 m × 1 m spacing using cuttings which were 40 cm in length. Cowpea (variety ‘Bengpla’) was planted at 0.2 m × 0.4 m spacing also by sowing four seeds per hill and thinning to two per hill within two weeks. Plots were 5 m × 5 m with the same dimension as the buffer rows between each two plots (Fig. 2). The selection of crops was based on the preference of the community where the experiment was sited during informal interviews and focus group discussions in early 2014.

The field trial was conducted over five continuous planting seasons, i.e. minor rainy season of 2014, major and minor rainy seasons of 2015, and major and minor rainy seasons of 2016. The major rainy season experiments were conducted between June and August, while the minor rainy season

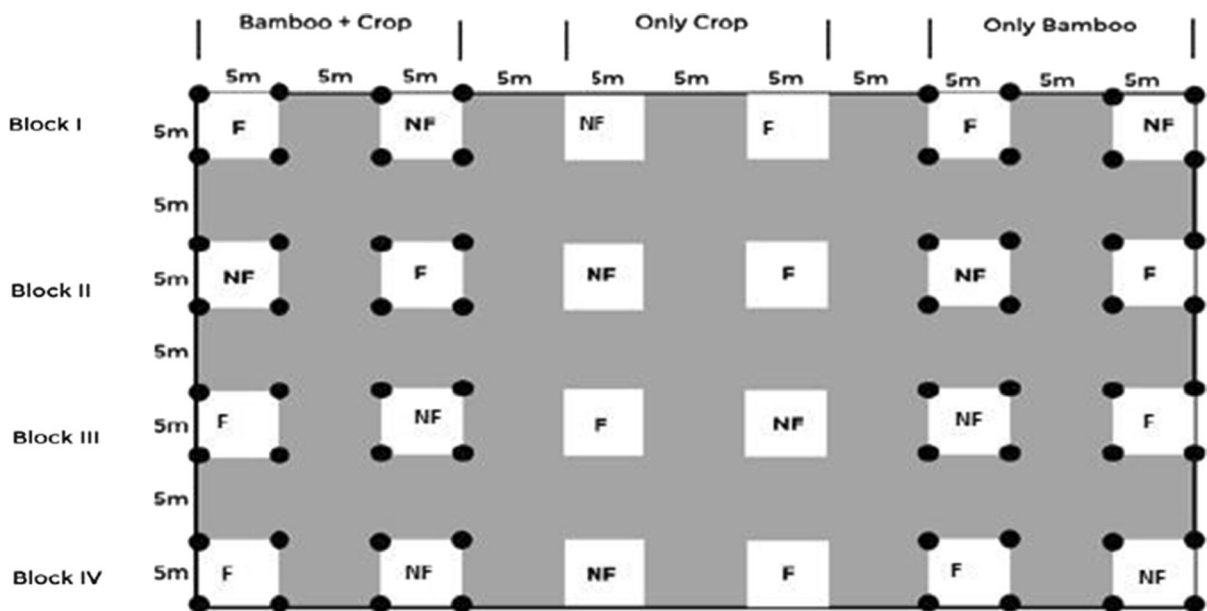


Fig. 2 Layout of bamboo intercropping (bamboo+crop) and monocropping systems (only crop, only bamboo) established at Jeduako in Sekyere Central District of Ghana. Black circles

(slightly oval)=bamboo. Grey area=buffer zone. NF=Non-fertilized plot, F=Fertilized plot.

experiments were conducted between September and November. For maize and cowpea, we present the average yields of two seasons due to lack of significant seasonal effects. Cassava was harvested and yield recorded once a year.

A separate monocropping field for maize, cassava and cowpea was set up adjacent to the intercropping field. In addition, there were three separate fields of bamboo (one adjacent to each crop trial). In both intercropping and monocropping fields, the crops and bamboo were with fertilizer treatment and without. This was done to depict low-input and high-input systems. Fertilizer was applied at the following rates: Maize (90 kg N ha⁻¹, 60 kg P₂O₅ ha⁻¹, 60 kg K₂O ha⁻¹), cassava (68 kg N ha⁻¹, 45 kg P₂O₅ ha⁻¹, 68 kg K₂O ha⁻¹), cowpea (only 60 kg P₂O₅ ha⁻¹) (Partey et al. 2018) and bamboo (90 kg N ha⁻¹, 60 kg P₂O₅ ha⁻¹, 60 kg K₂O ha⁻¹) (Pande et al. 2012). Nitrogen was applied as urea, P as triple superphosphate and K as muriate of potash. The fertilizer was split applied at 7 days after planting (DAP) and 30 DAP using 40% and 60% of the total fertilizer, respectively, according to the local practice. The fertilizer treatments were applied in all five seasons. Weeds were managed by hand weeding after weed emergence, and late emerging weeds were removed by hoeing as and when needed.

Crop productivity was determined as grain and stover yield for maize; tuber and stem biomass yield for cassava; and grain and shoot biomass for cowpea. For cowpea and maize, grain yield was determined by collecting pods and cobs, respectively, into perforated harvesting bags and sun drying over two weeks until the grain reached 12.5% moisture content, which is the acceptable moisture content in most African markets (Kurwakumire et al. 2014). To determine biomass yield, the plants were uprooted from the soil after watering the surface soil. The aboveground biomass (leaf and stem) was separated from the roots and oven dried in the laboratory at 65 °C for 72 h. For cassava, the standing biomass, including the leaves and stem was separated from the root tubers after 10 months of planting and yields expressed on a fresh weight basis.

Soil sampling and analysis

Soil conditions were characterized using a random composite soil sampling approach (Gelderman et al.

2006; Crozier et al. 2010). Each treatment plot of 5 m × 5 m was sampled from three different locations in a zigzag pattern using a stainless-steel auger at 0–20 cm depth. Samples that were taken at the onset of the experiment were composited and homogenized for each block by hand mixing before sending to the laboratory for physicochemical analysis (total n=4). For soil sampling and analysis in the 2014, 2015 and 2016 cropping periods, all 72 treatment plots were sampled every year as described above. Subsequently, for each cropping year, the samples for each of the annual crop plots were homogenised into fertilized and non-fertilized samples across the four blocks, yielding a total of 12 composited samples. The same was done for the bamboo only treatment plots, yielding a total of 6 composited samples. In all, 18 composited samples were collected for laboratory analysis. This was done to monitor soil property changes per treatment per cropping year.

In the laboratory, four replicates of each field soil sample were created. Soil samples were air-dried till constant weight and passed through a 2-mm sieve and analyzed using four replicates. Soil pH was analyzed using a glass electrode with a soil/water ratio of 1:2, total N was determined by dry combustion using a LECO TruSpec™ CN autoanalyzer (LECO Corporation), organic carbon by the dichromate oxidation method (Motsara and Roy 2008), cation exchange capacity (CEC) using ammonium acetate extract (Motsara and Roy 2008), available P by the ammonium molybdate Bray-1 method, available K using ammonium acetate (flame photometer method), moisture content and base saturation (%) using the gravimetric method, and soil texture by the hydrometer method (Motsara and Roy 2008). The initial physicochemical properties of soils at the study site are shown in Table 1.

Bamboo litter accumulation, collection and nutrient analysis

Two litterfall traps per treatment plot were fixed randomly to cover all the 48 treatment plots with bamboo over the entire experimental period. The litter accumulated from each treatment plot of four individual bamboo clumps was composited and average value determined. The same litterfall trap sizes were fixed due to same plant distance except where canopy cover varied. Determination of the

Table 1 Initial physicochemical properties of the top soil (0–20 cm) of the experimental site at Jeduako in Central Ghana

Parameter	Value
pH (H ₂ O)	5.83 (0.30)
Total nitrogen (g kg ⁻¹)	0.50 (0.00)
Organic carbon (g kg ⁻¹)	2.10 (0.10)
Available P (mg kg ⁻¹)	7.81 (0.20)
Available K (mg kg ⁻¹)	82.87 (3.50)
Effective cation exchange capacity (cmol kg ⁻¹)	4.92 (0.10)
Base saturation (%)	90.85 (0.10)
Texture (%)	
Sand	62.04 (0.43)
Clay	15.01 (0.81)
Silt	22.95 (0.79)
Textural class	sandy loam

Values are means of four replicates. Values in parentheses are standard error of means

bamboo litter was performed weekly for the period of collection to ensure uniform results (Breda 2003). *Bambusa balcooa* litter was cleaned and separated into twigs, buds and leaves. However, only leaf litter was sub-sampled for the laboratory analysis. The leaf litter biomass was determined by drying in an oven at 65 °C for 72 h. To determine the initial chemical quality of the leaf litter, 100 g out of the oven-dried matter were ground into a powder and sieved to a 0.5 mm size. Carbon and nitrogen were analyzed using a LECO Carbon–Nitrogen analyzer, calcium and magnesium by the EDTA titration method, phosphorus by the spectrometric vanadium-phosphomolybdate method while potassium was determined by absorption spectrophotometry according to Motsara and Roy (2008). Lignin was determined by the acid detergent fiber method (Eneji et al. 2005). The samples were analyzed in three replicates.

Statistical analysis of field experiment

The partial land equivalent ratio (LER) was used to determine intercropping advantage over monocropping using the relation by Dariush et al. (2006) for agricultural crops. This ratio was used because the focus of the experiments was on the effect of bamboo on the associated crops, and therefore, only agricultural crop yields in the intercropped and monocropped fields were compared using the following equation:

$$\text{Partial LER} = \frac{Y_{pi}}{Y_{mi}} \quad (1)$$

where Y_{pi} =yield of intercrop and Y_{mi} =yield of monocrop.

Data on crop yield and soil properties were analysed using the Analysis of Variance (ANOVA) test. Where test results were significant, the Tukey test method was used for mean comparison at a 5% probability level. All statistical analyses were conducted with GenStat 12 software (VSN International).

Estimated bamboo yields

Only bamboo culms were considered for this economic analysis.

It has been recommended that about 33% of the old culms per clump are harvested throughout the life of a bamboo plantation (Pande et al. 2012). For this analysis, bamboo culms were first harvested in the third year of establishment, and subsequently, harvesting was done monthly for sale as culms. Moderate harvesting levels are assumed with an average of 3 culms per clump per month from the bamboo agroforestry plots, and 6 culms per clump per month from the bamboo monocropping plots. Consequently, the number of culms harvested per month from the 220 clumps per ha was $3 \times 220 = 660$ per ha for the bamboo agroforestry plot. For the monocrop bamboo plot, the number of culms harvested per month from the 220 clumps per ha = $6 \times 220 = 1320$ culms per ha (see Table 7).

It is only the main stem of the culm measuring 2 m on average that is considered for sale, and hence, not the cubic volume. There is no standard measure of bamboo culm sale in the study area.

Costs and revenue streams for food and bamboo culm production from bamboo agroforestry

Input and output data over five cropping seasons (only minor season of 2014 and major and minor seasons of 2015 and 2016) were collected from the trial plots. Costs and revenues streams in Ghanaian Cedis (GH¢) (later converted to US Dollars (USD\$)) were estimated at 2017 market rates for the analysis for 5 production cycles over a period of 3 years (“Appendices 1–3”). Bamboo can grow over very long periods (Pande et al. 2012), however, 3 years was adopted as the minimum rotation for the financial analysis. Cost streams in this study included inputs used for establishment of bamboo agroforestry and monocrop stands (land, farm tools/equipment, crop seeds, tree seedlings and labor (for land preparation, planting and herbicides application, weeding/maintenance and harvesting of maize, cassava, cowpea and bamboo culms) estimated per ha (“Appendix 3”). Revenues/benefit streams were determined from the value of crops per unit area, i.e. maize, cassava, and cowpea and bamboo culms harvested per ha. The value of potential carbon sequestered by the agroforestry system was not included in the analysis.

Financial Cost Benefit Analysis

The Financial Cost Benefit Analysis (FCBA) methodology adopted from Gittinger (1982) was used for the comparative economic valuation of the bamboo agroforestry system and monocrop food production in this study. The FCBA is used to assess the desirability of technologies by determining whether the costs of establishment are offset by higher returns from sustained crop yields compared to traditional practices. For the FCBA, the data on cost and revenue for bamboo agroforestry and monocrop food crop trials were analyzed using Microsoft Excel. The cost and revenue streams and cash flows were estimated at 25% (i.e. bank borrowing rate in Ghana for agricultural and forestry investments/projects in 2017) to estimate the profitability of the bamboo agroforestry for culm production compared with the best

alternative use of the land for food crop cultivation for 3 years.

The main assumptions for the financial analysis are:

1. Nominal prices are used for the cost and revenue cash flows; they are not adjusted for inflationary effects over the 3-year period of the financial analysis (Inflationary values were very marginal but occurred very rapidly within the study period distorting the financial analysis; the average of 25% interest rate for agricultural borrowing as given by the Bank of Ghana was therefore adopted).
2. It is also assumed that ecological variables influencing growth will be constant throughout the analysis period.

Comparative estimations of Benefit Cost Ratio

The Benefit Cost Ratio (BCR) was estimated and used to evaluate the profitability of the bamboo agroforestry system with the equation below:

$$\frac{B}{C} \text{Ratio} = \sum_{t=1}^{t-n} \frac{B_t}{(1+i)^t} \div \sum_{t=1}^{t-n} \frac{C_t}{(1+i)^t} \quad (2)$$

where B=benefit, C=cost, t=time in years/production period, i or r =discounted rate, and n=length of production period in years. The trial production systems are profitable if $BCR \geq 1.0$ (Gittinger 1982). Where B_t and C_t are the benefits and costs in year t , r is the discount rate and n is the project life time (i.e. length of a complete production cycle or rotation). Consequently, a technology is attractive for adoption if the B/C ratio is > 1.0 .

Results

Effects of bamboo-based agroforestry on soil properties and agronomic performance of maize

Soil properties under bamboo-maize intercropping system

The combined cropping system and fertilizer application (treatment) had no significant effect on soil moisture, soil pH, CEC, total N, available P and

Table 2 Soil characteristics as influenced by bamboo-based agroforestry and maize monocropping systems from 2014 to 2016

Year and parameters	With fertilizer		Without fertilizer		P value
	Agroforestry	Monocropping	Agroforestry	Monocropping	
<i>2014</i>					
Soil moisture (%)	4.34±0.01 ^a	4.33±0.01 ^a	4.32±0.03 ^a	4.29±0.05 ^a	0.724
CEC (cmolc kg ⁻¹)	5.70±0.04 ^a	5.80±0.08 ^a	5.68±0.08 ^a	5.63±0.09 ^a	0.475
Total N (g kg ⁻¹)	0.39±0.00 ^a	0.44±0.03 ^a	0.39±0.00 ^a	0.39±0.00 ^a	0.100
Available P (mg kg ⁻¹)	4.75±0.03 ^a	4.78±0.03 ^a	4.73±0.03 ^a	4.73±0.03 ^a	0.487
Available K (mg kg ⁻¹)	123.70±1.01 ^a	123.50±0.62 ^a	123.60±0.72 ^a	123.20±0.84 ^a	0.979
pH	5.78±0.03 ^a	5.83±0.04 ^a	5.73±0.03 ^a	5.80±0.04 ^a	0.122
<i>2015</i>					
Soil moisture (%)	4.26±0.03 ^a	4.26±0.02 ^a	4.31±0.03 ^a	4.25±0.03 ^a	0.593
CEC (cmolc kg ⁻¹)	6.05±0.06 ^a	6.03±0.08 ^a	6.00±0.09 ^a	5.95±0.09 ^a	0.767
Total N (g kg ⁻¹)	0.49±0.00 ^a	0.54±0.03 ^a	0.49±0.00 ^a	0.48±0.01 ^a	0.074
Available P (mg kg ⁻¹)	4.55±0.10 ^a	4.50±0.10 ^a	4.58±0.13 ^a	4.40±0.04 ^a	0.539
Available K (mg kg ⁻¹)	127.60±0.30 ^a	127.40±0.22 ^a	127.50±0.30 ^a	127.50±0.29 ^a	0.990
pH	5.83±0.05 ^a	5.84±0.04 ^a	5.80±0.04 ^a	5.78±0.05 ^a	0.769
<i>2016</i>					
Soil moisture (%)	7.13±0.06 ^b	4.27±0.02 ^a	7.01±0.07 ^b	4.25±0.03 ^a	< 0.001
CEC (cmolc kg ⁻¹)	6.65±0.10 ^b	5.93±0.03 ^a	6.68±0.08 ^b	5.85±0.09 ^a	< 0.001
Total N (g kg ⁻¹)	0.48±0.00 ^a	0.53±0.03 ^a	0.48±0.00 ^a	0.48±0.00 ^a	0.092
Available P (mg kg ⁻¹)	4.90±0.11 ^b	4.79±0.20 ^b	4.83±0.21 ^b	4.20±0.04 ^a	0.010
Available K (mg kg ⁻¹)	127.80±0.53 ^a	127.60±0.37 ^a	127.60±0.39 ^a	127.50±0.41 ^a	0.969
pH	5.98±0.09 ^b	5.45±0.09 ^a	6.00±0.11 ^b	5.40±0.17 ^a	0.011

Values are means of 4 replicates±standard error. Values with the same letters in a row are not significantly different according to Tukey test at a 5% significance level.

available K until the third year (2016) of the experiment (Table 2). In 2016, ANOVA and Tukey post-hoc test showed a significant ($p < 0.001$) increase in soil moisture, soil pH and CEC under bamboo agroforestry system with and without fertilizer application. In 2016, soil moisture values under bamboo-based agroforestry with fertilizer were 7.1% on average, while monocropped fields recorded 4.2%. The CEC under agroforestry was about 13% higher than under monocropped fields considering cropping system and fertilizer application (combined treatment effect) with and without fertilizer. Soil pH values were 10% higher on agroforestry fields than on monocropped fields.

Maize yields under bamboo-maize intercropping system

The combined effect of cropping system and fertilizer application (treatments) on the grain and stover yields of maize were significant ($p < 0.05$) throughout the experimental period (2014–2016) (Table 3). In 2014 and 2015, however, grain and stover yields increased only with fertilizer application. No significant differences were observed between fertilized agroforestry and fertilized monocropped fields. Similar observations were recorded for both cropping systems without fertilizer application during the same period. For monocropped fields, grain yield increase with fertilizer was 50% and 164% higher than on non-fertilized fields for 2014 and 2015, respectively. For agroforestry fields, grain yield increase with fertilizer was 74% and 177% higher than on non-fertilized

Table 3 Maize productivity as influenced by bamboo-based agroforestry and monocropping systems

Year and parameter	With fertilizer		Without fertilizer		P value
	Agroforestry	Monocropping	Agroforestry	Monocropping	
<i>2014</i>					
Grain yield (t ha ⁻¹)	1.86±0.02 ^b	1.58±0.09 ^b	1.07±0.15 ^a	1.05±0.06 ^a	< 0.001
Stover yield (t ha ⁻¹)	4.53±0.19 ^b	4.50±0.18 ^b	3.34±0.09 ^a	3.33±0.07 ^a	< 0.001
<i>2015</i>					
Grain yield (t ha ⁻¹)	1.94±0.07 ^b	1.90±0.08 ^b	0.70±0.08 ^a	0.72±0.10 ^a	< 0.001
Stover yield (t ha ⁻¹)	4.75±0.21 ^b	4.71±0.23 ^b	2.96±0.12 ^a	2.89±0.09 ^a	< 0.001
<i>2016</i>					
Grain yield (t ha ⁻¹)	2.75±0.06 ^d	2.00±0.09 ^c	0.79±0.03 ^b	0.58±0.03 ^a	< 0.001
Stover yield (t ha ⁻¹)	6.20±0.17 ^d	5.29±0.17 ^c	3.37±0.10 ^b	2.46±0.05 ^a	< 0.001

Values are the means of 4 replicates ± standard error. Values with the same letters in a row are not significantly different according to Tukey test at a 5% significance level.

fields for 2014 and 2015, respectively. Stover yields were almost two times higher with fertilizer application. In 2016, the grain and stover yields of maize differed significantly ($p < 0.05$) between agroforestry and monocropped fields with or without fertilizer application (Table 3). Compared to fertilized monocropped fields, grain and stover yields were 37.5% and 17.2% higher on fertilized agroforestry plots, respectively. Non-fertilized agroforestry fields also recorded significantly ($p < 0.05$) higher grain and stover yields than non-fertilized monocropped fields. It was evident that cropping system and fertilizer application (treatments), time and their interaction significantly influenced the grain and stover yields of maize (Table 3). For the fertilized agroforestry fields, grain yield of maize in 2016 was 42% and 48% higher than in 2015 and 2014, respectively. The partial LER showed an advantage of intercropping maize with bamboo over monocropping during the third year of the experiment. The partial LER for fertilized and non-fertilized maize intercropping systems was 1.38 and 1.36, respectively.

Effects of bamboo-based agroforestry on soil properties and agronomic performance of cowpea

Soil properties under bamboo-cowpea intercropping system

Similar to the results for maize, the ANOVA test showed no significant ($p > 0.05$) combined effect of cropping system and fertilizer application (treatment)

on soil properties (pH, soil moisture, total N, available P, available K and CEC) in the first (2014) and second (2015) year of the experiment. In 2016, significant ($p < 0.05$) effects of cropping system and fertilizer application (treatments) were recorded for soil moisture, CEC, available P and pH. Soil moisture, CEC and pH were significantly ($p < 0.05$) higher on agroforestry fields than on monocropped fields regardless of fertilizer application. Soil moisture, CEC and pH on agroforestry fields were about 169%, 118% and 110%, respectively higher than on monocropped fields. Moreover, available P levels did not differ significantly between agroforestry plots and monocropped plots receiving fertilizer (Tables 4, 5). Particularly for agroforestry plots, values recorded for soil parameters such as CEC, soil moisture and available K were significantly higher in 2016 compared with 2015 and 2014. Data for 2014 and 2015 were generally comparable.

Cowpea yields under bamboo-cowpea intercropping system

The ANOVA showed that combined cropping system and fertilizer application (treatment) significantly ($p < 0.05$) affected the grain and shoot yields of cowpea in all 3 years of the experiment with application of fertilizers. In 2014 and 2015, agroforestry and monocropped fields receiving fertilizer recorded comparable results. Non-fertilized plots in both systems also produced comparable results. In 2016, grain and shoot yields on fertilized and non-fertilized

Table 4 Soil characteristics as influenced by bamboo-based agroforestry and cowpea monocropping systems

Year and parameter	With fertilizer		Without fertilizer		P value
	Agroforestry	Monocropping	Agroforestry	Monocropping	
<i>2014</i>					
Soil moisture (%)	4.04±0.05 ^a	4.01±0.04 ^a	3.97±0.10 ^a	3.89±0.09 ^a	0.150
CEC (cmolc kg ⁻¹)	5.58±0.05 ^a	5.56±0.08 ^a	5.62±0.01 ^a	5.42±0.04 ^a	0.267
Total N (g kg ⁻¹)	0.36±0.03 ^a	0.38±0.04 ^a	0.34±0.04 ^a	0.37±0.04 ^a	0.370
Available P (mg kg ⁻¹)	4.64±0.02 ^a	4.68±0.02 ^a	4.66±0.08 ^a	4.64±0.06 ^a	0.776
Available K (mg kg ⁻¹)	123.9±0.83 ^a	123.50±0.58 ^a	124.00±0.50 ^a	122.10±0.28 ^a	0.200
pH	5.75±0.04 ^a	5.68±0.03 ^a	5.68±0.03 ^a	5.69±0.03 ^a	0.601
<i>2015</i>					
Soil moisture (%)	4.26±0.19 ^a	4.27±0.12 ^a	4.25±0.12 ^a	4.15±0.06 ^a	0.655
CEC (cmolc kg ⁻¹)	5.98±0.05 ^a	6.04±0.06 ^a	6.06±0.06 ^a	5.93±0.03 ^a	0.092
Total N (g kg ⁻¹)	0.40±0.02 ^a	0.41±0.01 ^a	0.39±0.01 ^a	0.39±0.01 ^a	0.379
Available P (mg kg ⁻¹)	4.57±0.08 ^a	4.56±0.07 ^a	4.67±0.07 ^a	4.51±0.10 ^a	0.436
Available K (mg kg ⁻¹)	127.50±0.11 ^a	127.40±0.16 ^a	127.60±0.23 ^a	127.30±0.12 ^a	0.497
pH	5.72±0.03 ^a	5.73±0.06 ^a	5.70±0.03 ^a	5.70±0.04 ^a	0.811
<i>2016</i>					
Soil moisture (%)	7.06±0.05 ^b	4.13±0.04 ^a	7.03±0.05 ^b	4.22±0.11 ^a	< 0.001
CEC (cmolc kg ⁻¹)	6.64±0.13 ^b	5.71±0.07 ^a	6.71±0.07 ^b	5.65±0.08 ^a	< 0.001
Total N (g kg ⁻¹)	0.41±0.06 ^a	0.42±0.01 ^a	0.41±0.06 ^a	0.40±0.06 ^a	0.983
Available P (mg kg ⁻¹)	4.96±0.07 ^b	4.82±0.18 ^b	4.73±0.16 ^b	4.14±0.06 ^a	0.002
Available K (mg kg ⁻¹)	128.00±0.40	127.60±0.34	127.70±0.29	127.00±0.12	0.205
pH	5.94±0.09 ^b	5.36±0.12 ^a	5.88±0.10 ^b	5.41±0.09 ^a	0.003

Values are means of 4 replicates±standard error. Values with the same letters in a row are not significantly different according to Tukey test at a 5% significance level.

Table 5 Cowpea productivity as influenced by bamboo-based agroforestry and monocropping systems

Year and parameter	With fertilizer		Without fertilizer		P value
	Agroforestry	Monocropping	Agroforestry	Monocropping	
<i>2014</i>					
Grain yield (t ha ⁻¹)	1.58±0.06 ^b	1.61±0.05 ^b	1.40±0.07 ^a	1.42±0.03 ^a	0.007
Shoot yield (t ha ⁻¹)	3.86±0.16 ^b	3.91±0.18 ^b	3.37±0.06 ^a	3.42±0.05 ^a	0.003
<i>2015</i>					
Grain yield (t ha ⁻¹)	1.52±0.02 ^b	1.53±0.04 ^b	1.41±0.02 ^a	1.37±0.06 ^a	0.017
Shoot yield (t ha ⁻¹)	4.07±0.11 ^b	4.05±0.16 ^b	3.80±0.18 ^a	3.91±0.17 ^a	0.002
<i>2016</i>					
Grain yield (t ha ⁻¹)	2.62±0.10 ^d	1.92±0.13 ^b	2.03±0.13 ^c	1.32±0.10 ^a	< 0.001
Shoot yield (t ha ⁻¹)	4.78±0.11 ^c	4.38±0.21 ^b	4.32±0.24 ^b	3.26±0.29 ^a	< 0.001

Values are the means of 4 replicates±standard error. Values with the same letters in a row are not significantly different according to Tukey test at a 5% significance level.

agroforestry plots were significantly ($p < 0.05$) higher than on monocropped fields. Compared to fertilized monocropped fields, grain and shoot yields in fertilized agroforestry fields were 136% and 109% higher, respectively. Moreover, the results show that grain yield on non-fertilized agroforestry fields was higher than on both fertilized and non-fertilized monocropped fields. Especially on agroforestry fields, there was a general increase in grain and shoot yields with time, with the highest value recorded in 2016. For fertilized agroforestry fields, grain and shoot yields in 2016 were 172% and 165% higher compared to 2015 and 2014, respectively. The partial LER showed an advantage of intercropping cowpea with bamboo over monocropping during the third year of the experiment. The value for fertilized and non-fertilized cowpea intercropping systems was 1.37 and 1.54, respectively.

Effects of bamboo-based agroforestry on soil properties and agronomic performance of cassava

Soil properties under bamboo-cassava intercropping system

Similar to maize and cowpea, there was no significant ($p > 0.05$) combined effect of cropping system and fertilizer application (treatment) on soil properties in 2014 and 2015. However, in 2016, soil moisture and soil pH were significantly ($p < 0.05$) affected. Soil moisture on agroforestry plots was significantly ($p < 0.05$) higher than on monocropped fields (Table 6) indicating the sole effect of bamboo on soil properties.

Soil moisture on agroforestry fields was about 166% higher than on monocropping fields. The pH values on agroforestry fields were significantly higher than on monocropping fields regardless of fertilizer

Table 6 Soil characteristics as influenced by bamboo-based agroforestry and cassava monocropping systems

Year and parameter	With fertilizer		Without fertilizer		P value
	Agroforestry	Monocropping	Agroforestry	Monocropping	
<i>2014</i>					
Soil moisture (%)	4.18±0.02 ^a	4.17±0.06 ^a	4.20±0.01 ^a	4.12±0.04 ^a	0.493
CEC (cmolc kg ⁻¹)	5.58±0.03 ^a	5.65±0.03 ^a	5.58±0.12 ^a	5.54±0.02 ^a	0.503
Total N (g kg ⁻¹)	0.46±0.00 ^a	0.45±0.01 ^a	0.45±0.00 ^a	0.44±0.01 ^a	0.452
Available P (mg kg ⁻¹)	4.68±0.02 ^a	4.68±0.02 ^a	4.64±0.02 ^a	4.65±0.02 ^a	0.549
Available K (mg kg ⁻¹)	121.60±0.43 ^a	121.10±0.63 ^a	121.10±0.73 ^a	120.30±0.53 ^a	0.605
pH	5.76±0.004 ^a	5.77±0.03 ^a	5.76±0.003 ^a	5.75±0.05 ^a	0.992
<i>2015</i>					
Soil moisture (%)	4.32±0.04 ^a	4.31±0.00 ^a	4.30±0.02 ^a	4.26±0.02 ^a	0.433
CEC (cmolc kg ⁻¹)	5.40±0.09 ^a	5.50±0.11 ^a	5.50±0.09 ^a	5.27±0.03 ^a	0.289
Total N (g kg ⁻¹)	0.43±0.01 ^a	0.44±0.00 ^a	0.44±0.00 ^a	0.43±0.01 ^a	0.544
Available P (mg kg ⁻¹)	4.61±0.11 ^a	4.49±0.09 ^a	4.50±0.11 ^a	4.46±0.11 ^a	0.144
Available K (mg kg ⁻¹)	118.90±0.61 ^a	118.90±0.87 ^a	119.10±0.77 ^a	118.50±0.68 ^a	0.922
pH	5.44±0.12 ^a	5.47±0.10 ^a	5.49±0.07 ^a	5.48±0.06 ^a	0.916
<i>2016</i>					
Soil moisture (%)	7.05±0.07 ^b	4.21±0.03 ^a	7.03±0.07 ^b	4.26±0.03 ^a	< 0.001
CEC (cmolc kg ⁻¹)	5.34±0.10 ^a	5.56±0.06 ^a	5.54±0.17 ^a	5.24±0.08 ^a	0.185
Total N (g kg ⁻¹)	0.45±0.01 ^a	0.43±0.01 ^a	0.45±0.01 ^a	0.43±0.01 ^a	0.170
Available P (mg kg ⁻¹)	4.33±0.17 ^a	4.73±0.27 ^a	4.63±0.15 ^a	4.38±0.28 ^a	0.581
Available K (mg kg ⁻¹)	121.30±0.45 ^a	120.90±0.45 ^a	121.00±0.51 ^a	121.80±1.28 ^a	0.884
pH	6.10±0.07 ^b	5.88±0.03 ^a	6.11±0.01 ^b	5.95±0.03 ^a	0.006

Values are means of 4 replicates±standard error. Values with the same letters in a row are not significantly different according to Tukey test at a 5% significance level

Table 7 Cassava productivity as influenced by bamboo-based agroforestry and monocropping systems

Parameter	With fertilizer		Without fertilizer		P value
	Agroforestry	Monocropping	Agroforestry	Monocropping	
<i>2014</i>					
Root tuber yield (t ha ⁻¹)	11.49±0.48 ^b	11.52±0.11 ^b	10.33±0.07 ^a	10.26±0.14 ^a	< 0.001
Biomass yield (t ha ⁻¹)	36.26±0.16 ^b	35.92±0.64 ^b	31.42±0.76 ^a	31.53±0.46 ^a	< 0.001
<i>2015</i>					
Root tuber yield (t ha ⁻¹)	12.15±0.33 ^b	11.92±0.08 ^b	10.09±0.08 ^a	9.99±0.10 ^a	< 0.001
Biomass yield (t ha ⁻¹)	36.31±0.07 ^b	36.41±0.24 ^b	31.48±0.31 ^a	31.44±0.29 ^a	< 0.001
<i>2016</i>					
Root tuber yield (t ha ⁻¹)	13.09±0.19 ^d	11.74±0.24 ^b	12.65±0.11 ^c	10.67±0.07 ^a	< 0.001
Leaf and stem biomass yield (t ha ⁻¹)	40.30±0.51 ^d	35.69±0.89 ^b	38.34±0.45 ^c	33.30±0.52 ^a	< 0.001

Values are means of 4 replicates±standard error. Values with the same letters in a row are not significantly different according to Tukey test at a 5% significance level.

application. Moreover, the results show that total N, CEC, available K, soil moisture and soil pH significantly ($p < 0.05$) increased with time. This was particularly evident on agroforestry plots where the highest values were recorded in 2016 (Table 6).

Cassava yields under bamboo-cassava intercropping system

Combined effect of cropping system and fertilizer application (treatment) significantly ($p < 0.05$) affected the root tuber and leaf and stem yields of cassava (Table 7). The increased cassava yield was mainly due to the application of fertilizer. Regardless of fertilizer application, there were no significant differences between agroforestry and monocropped fields until 2016. In that year, agroforestry plots, both with and without fertilizer application recorded significantly ($p < 0.05$) higher yields for root tuber and leaf and stem. Differences in root tuber yield between fertilized agroforestry and fertilized monocropped fields were about 1.35 t ha⁻¹ and 4.61 t ha⁻¹ for leaf and stem yield. For non-fertilized plots, root tuber yield was about 119% higher on agroforestry plots compared to monocropped plots. Consistent with the soil properties, increases in yields with time were particularly evident on agroforestry fields. The partial LER showed an advantage of intercropping cassava with bamboo over monocropping during the third year of the experiment. The partial LER for

fertilized and non-fertilized cassava intercropping systems was 1.12 and 1.19, respectively.

Bamboo growth and litter accumulation under bamboo-crops intercropping system

The cropping system had a significant ($p=0.014$) effect on bamboo growth only when bamboo was 3 months old (Table 8). Among the crops, bamboo seemed to integrate better with maize and cowpea than with cassava during the initial establishment stages. However, no significant growth effects were observed after 6 months. On average, there was a higher number of stems/culms per clump per ha in the monocrop bamboo (40–50 culms per clump and about 1100 culms/ha) than in the agroforestry system (30 culms per clump and 660 culms/ha) although there was an equal number of seedlings of bamboo per ha planted in both monocropped and agroforestry plots.

Due to the role of bamboo litter on soil properties, we monitored litter accumulation after the first incidence of litter fall, which occurred during the second year of the experiment. The mean litter accumulation during the experimental period increased from 0.22 t DM ha⁻¹ in the second year to 1.83 t DM ha⁻¹ in the third year (DM=dry matter content). Data are the means of 6 replicates (six bamboo clumps) per ha. We also monitored bamboo litter quality in the system. The composited oven

Table 8 Height (m) of bamboo when grown as a monocrop and in combination with maize, cowpea and cassava over 36 months under field conditions

Cropping system	Age (months)					
	6	12	18	24	30	36
Bamboo monocropping	3.74±0.10 ^b	7.77±0.09 ^a	9.67±0.09 ^a	14.68±0.23 ^a	10.53±0.17 ^a	12.57±0.18 ^a
Bamboo+maize agroforestry(intercropping)	3.59±0.06 ^b	7.17±0.12 ^a	9.28±0.20 ^a	10.18±0.22 ^a	11.98±0.26 ^a	14.64±0.25 ^a
Bamboo+cowpea agroforestry(intercropping)	3.73±0.03 ^b	7.45±0.06 ^a	9.45±0.07 ^a	10.43±0.06 ^a	12.40±0.08 ^a	14.65±0.26 ^a
Bamboo+cassava agroforestry(intercropping)	3.41±0.08 ^a	7.41±0.22 ^a	9.55±0.12 ^a	10.15±0.21 ^a	12.45±0.19 ^a	14.57±0.22 ^a
SED	0.090	0.220	0.190	0.210	0.290	0.100
P-value	0.014	0.128	0.292	0.276	0.253	0.792

Values are means of 4 replicates ± standard error. Values with the same letters in a column are not significantly different according to Tukey test at a 5% significance level. Values are combined data for both fertilized and non-fertilized plots from 24 plots

SED standard error of difference

dried and ground *Bambusa balcooa* leaf litter was characterized in the laboratory for N (1.99%), P (0.36%), K (0.60%), Mg (0.17%), C (125.1%), Ca (0.59%), Lignin (91.9%) C/N (12.6) and Lignin/N (46.2) as recommended by Palm et al. (2001). The results showed comparatively low macro and micro nutrients as against high lignin content.

Economic evaluation of bamboo agroforestry and monocropping systems: costs and benefits from agroforestry and monocropping systems

The summary cash flow from producing bamboo and food crops from the agroforestry (intercropping) and monocropping systems is presented in “Appendices 1 and 2”. All the tested combinations proved to be profitable as indicated by the positive net cash flows ranging from the highest value for the fertilized monocrop bamboo (GH¢ 87,758.50/US\$ 20,649.06) to the lowest value (GH¢ 6732/US\$ 1584) for the non-fertilized monocrop food production systems over a period of 3 years (“Appendix 1”). Bamboo cultivated in an agroforestry system with or without fertilizer contributed up to 70% of total income due to the proliferation of culms that can frequently be harvested throughout the year as compared to the seasonal income from food crops under rain-fed conditions. Results from the bio-physical aspects of the experiment show higher food crop yields with application of NPK 15–15–15 in the sub-plots over those without fertilizer. Clump productivity was almost the same with and without fertilizer in the agroforestry system, hence, incomes were almost

similar in these systems. Bamboo-cowpea intercropping system had the highest FBCR of 1.24 (“Appendix 2”).

Discussion

Soil properties under bamboo agroforestry systems and monocrop fields

Soil properties such as CEC, soil moisture, pH and in some cases available P increased in the agroforestry fields compared with the monocropped plots (Table 2, 4 and 6). This can be attributed to increased litter accumulation from the bamboo during the third year of the experiment (Shanmughavel et al. 2000). Bamboo litter has been shown to improve soil properties. According to Nath et al. (2009) and Shanmughavel et al. (2000), bamboo litter can act as an input–output system of nutrients which regulates energy flow and improves soil properties. Moreover, the ability of bamboo to grow in wider variety of soils allows its use for soil rehabilitation (Nath et al. 2008). This has been alluded to the rich litter content of bamboo, and could thus help in maintaining and improving soil physical, chemical and biological properties as it returns substantial amounts of N P K, Ca and Mg to the soil (Shanmughavel et al. 2000). For instance, the potassium content in bamboo litter has been reported to be crucial in bamboo agroforestry systems as it acts as a soil amendment catalyst (Ahmad et al. 2007). Considerable amounts of nutrients are returned to the soil through litterfall,

which plays an important role in the biogeochemical cycling of nutrients (Mahmood et al. 2011). A similar observation of higher carbon deposition and greater nutrient return, especially N and P, in litterfall components of bamboo has been reported (Borisade and Odiwe 2018). Therefore, on the agroforestry fields, the increase in pH may have resulted from the displacement of hydroxyl ions from sesquioxide surfaces of the soil due to the presence of organic anions in the bamboo litter (Nalivata et al. 2017). Soil pH levels on agroforestry fields during the third year were higher than in the initial data (Table 1), which implies bamboo litter may have had a liming effect on the soil. This was consistent for all crops. Moreover, increased soil CEC in the presence of organic matter such as plant litter has been reported, and it is shown to be an indication of an increased nutrient holding capacity of soil (Oorts et al. 2003). The increased CEC within the bamboo agroforestry systems implies its potential to remediate low-acidity clay soils within tropical agro-ecological zones, which are characterized by inherently low soil fertility due to low levels of organic matter (Zingore et al. 2015; Tully et al. 2015; Nalivata et al. 2017). For soil moisture, bamboo litter may have provided a mulching effect reducing the evaporation of soil water. The litter from bamboo adds nutrient and plays an important role in maintaining soil fertility (Bellingham et al. 2013) and improvement of the nutrient status of the soil (Kleinhenz et al. 2001). Although our current study showed a relatively low bamboo leaf litter quality, the leaf litter may have served as mulch, providing moisture conditioning effect which is crucial for agricultural crop growth as it serves as a catalyst for other soil chemical dynamics as reported by Gogoi and Bhuyan (2016).

Bamboo rehabilitates over-burdened soils by conserving soil and managing water flow with large biomass accumulation and abundant litterfall (Fu et al. 2000). Similar observations were reported by Gogoi and Bhuyan (2016), who confirmed that bamboo litter improved soil moisture for horticulture crops and tubers in India. The significant soil water conservation effect of bamboo litter has also been reported as it retains 80–100% of rainfall (Pande et al. 2012).

The ecological role of bamboo has been well studied and reported. For instance, Nath et al. (2008) indicated the contribution of the dense bamboo root system to soil aeration and porosity and potential role in soil nutrient fast re-cycling and improvements through root

decay. Thus, the ecological benefits of bamboo in climate change mitigation and its ability to restore marginal lands add to the growing interest for its use in agroforestry (Patel et al. 2017; Sharma et al. 2018).

Yields of crops under agroforestry and monoculture systems

The first two years of establishing bamboo with the crops showed no significant differences between crop yields in monocropped and agroforestry plots. Within tree-based intercropping systems, competitive and complementary interactions can be expected, but this is dependent on farm management practices and physiological stages of components (Atangana et al. 2014; Ong et al. 2015). From the results obtained, there are clear indications that maize, cowpea and cassava could be planted with *B. balcooa* albeit without crop productivity enhancement or reduction at least within the first two years of establishment. Although the height of 6-month old bamboo was comparatively lower (Table 8) due to potential competition with cassava, its recovery over the subsequent periods shows both components can be combined. Moreover, the results in the third year of the experiment provide evidence that planting crops within bamboo rows may increase crop productivity. This finding is supported by the observation of Seshadri (1985), who studied the bamboo agroforestry (*Dendrocalamus strictus*) with soybean, and observed that sowing soybean as an intercrop of bamboo during the first six years was technically feasible and economically viable, and recommended that the period of intercropping can be extended further in wider spacing of the bamboo clumps and judicious manipulation of the bamboo canopy. The study again confirms the feasible integration of bamboo into cropping systems as was observed by Khilesh (2012) in a study which found a highly significant yield performance of wheat (*Triticum aestivum*) under a bamboo-based agroforestry system in four years. The rainfall data of the study site (Fig. 3) indicates relatively low rainfall in the major cropping season in the third year, and rather than declining, crop yield increased significantly in the bamboo agroforestry plots compared to the monocropping system. This could have resulted from the mulching effect of the bamboo litterfall as asserted by Nath et al. (2009).

In terms of crop yields, most of the similar studies were carried out in India or Asia rather than in Africa.

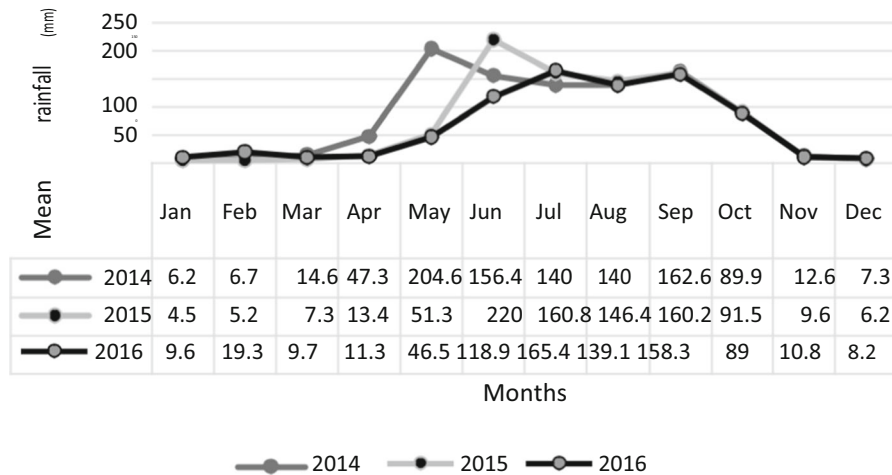


Fig. 3 Mean monthly rainfall distribution recorded during the experimental periods in 2014, 2015 and 2016. Data points are the means of three replicates. Data were obtained from the Ghana Meteorological Station at Mampong- Ashanti Region

However, our results provide evidence that instead of competitive interactions, planting cowpea, maize and cassava within the rows of a 3-year old bamboo may improve the productivity of the associated crop. Yet not all such studies arrive at the same conclusions. For example, lower yield was recorded for bamboo intercropping with Kharif crops compared to monocropping of same crop (Rahangdale et al. 2014). It has also been documented that bamboo and tree species gradually become more competitive with age and progressively reduce crop yield (Handa et al. 1995; Bihari 2001; Shanmughavel and Francis 2001; Ahlawat et al. 2008). Eyini et al. (1989) reported reduction in groundnut growth and yield, which may have resulted from the allelopathic effect of bamboo leaves (which contain phenolic acids) and shade under an agroforestry system. Nevertheless, there are a good number of studies that corroborate our findings that intercropping allows more efficient use of available resources such as sunlight, moisture and soil nutrients leading to higher crop productivity (Poodineh et al. 2014; Wang et al. 2014; Karasu et al. 2015). Judicious manipulations of bamboo clumps and good cultural practices as in adopting appropriate spacing, mulching and root extension control could enhance bamboo intercropping with the tested crops (Pande et al. 2012).

We found partial LER > 1.0 for both fertilized and non-fertilized systems, which demonstrates the advantage of combining crops with bamboo in an integrated

(for the study site) and validated at the Earth Observation Research and Innovation Center (EORIC)- University of Energy and Natural Resources- Sunyani, Ghana

manner. Shanmughavel and Francis (2001, 2002) recommended intercropping of pigeon pea, soybean and turmeric in bamboo (*B. bambos*) plantations based on comparative growth and yield, where the LER for the bamboo-turmeric system was 1.2. There is adequate evidence from the current study that integrated systems of maize, cowpea or cassava with bamboo may be encouraged in the study region. However, the results of this study should not be generalized.

Cost and benefit analysis of bamboo agroforestry and monocrop systems

Based on the partial LER analysis and the results from the comparative economic assessment of the bamboo agroforestry vs. monocropped bamboo, it seems that integrating bamboo into smallholder agricultural intercropping systems can contribute to food security, diversification of income sources and sustainable bio-energy production. There are numerous studies indicating declining yields under intensive cropping even on some good lands, e.g. the Indo-Gangetic plains (ILEIA 2000; FAO 2011; Vira et al. 2015). Tropical agroforestry systems have been proposed as a mechanism for sustaining both biodiversity and its associated ecosystem services in food production areas to forestall rapid deforestation and land degradation (Schroth et al. 2004; Steffan Dewenter et al. 2007). While the biodiversity effect

of bamboo agroforestry has yet to be assessed, it can be assumed that bamboo agroforestry helps to avoid land degradation and to maintain certain ecosystem services that would be lost from intensive farming systems.

Most economic analyses of bamboo intercropping systems have proven to be economically viable. For instance, the economic return, especially net present value, internal rate of return, benefit–cost ratio, return-to-land and return-to-labor of intercropped bamboo agroforestry have been found to be much higher than those of seasonal agricultural systems in many locations (Elevitch and Wilkinson 2000; Alavalapati and Mercer 2004; Rasul and Thapa 2006; Rahman et al. 2007, 2008; Roshetko et al. 2013). The benefit–cost ratios in the current study indicate that production under all six tested scenarios is profitable albeit marginal.

In bamboo agroforestry, the woody bamboo culms are noted to produce important products, such as fuelwood, other wood products, fodder etc., which provide extra income to farmers and could contribute to poverty reduction (McNeely and Schroth 2006; Snelder and Lasco 2008; Tscharrntke et al. 2011). This is particularly true for marginal farmlands where agricultural crop production is no longer biophysically or economically viable (Roshetko et al. 2008), and may become incompatible with the sustainable development aspirations (Snelder and Lasco 2008). This bamboo attribute is important in sustaining the system for long-term productivity and for sustainable economic and ecological/environmental stability. The sustained soil quality and maintained crop productivity under bamboo agroforestry in the present study is an indication of the potential of bamboo agroforestry to support the ecosystem in the study region for environmental quality and sustained food production. The importance of agroforestry systems in ensuring ecosystem services such as enhanced food production, carbon sequestration, watershed functions (stabilization of stream flow, minimization of sediment load) and soil protection has been reported (Alavalapati et al. 2004; Roshetko et al. 2007; Jose 2009; Idol et al. 2011; Lasco et al. 2014). Although labour intensive, the bamboo-food crop intercropping system can promote intensification and hence contribute to reducing deforestation.

Conclusions

The results revealed a greater advantage of growing crops with bamboo over monocropping systems. This underpins the benefits of establishing bamboo agroforestry systems, especially in areas where bamboos have been identified as priority species by other initiatives, such as the Ghana Energy Commission's Bioenergy Initiative and the Ghana BARADEP areas. The economic analysis indicates that once bamboo clumps mature, culms can be harvested throughout the year. Monocrop bamboo cultivation may be suitable for restoring degraded lands and beneficial to large-scale charcoal producers, or where farmers have enough land to permit its establishment. Small-scale farmers however, could benefit from bamboo intercropping systems through increased system productivity, diversified income streams and environmental sustainability at least for a period of three years. Ghana Forestry Commission may adopt this bamboo-agroforestry model in their quest to using bamboo for reforestation of degraded forests in Ghana. Moreover, the Ghana Ministry of Food and Agriculture may use the results of this study to underpin the current government's flagship programme of planting for food, jobs and environmental quality. It may also facilitate the reinvigoration of the 1986 Ghana National Agroforestry policy by introducing bamboo as a key multipurpose woody species. Farmers could then diversify income streams, increase resilience against climate change effects, sustain cropping system productivity, and improve environmental quality. Finally, this study can provide useful land-use management inputs for other African countries particularly Ethiopia, Kenya and South Africa, which are strongly pursuing the bamboo agroforestry concept and other developing countries which are equally faced with food and bio-energy security threats. Further studies could investigate component interactions within bamboo-based intercropping systems beyond 3 years with different bamboo species, planting spacing, use of coppice-system and root pruning to control possible invasiveness of bamboo. Also, economic sensitivity analysis with inflationary borrowing rates are necessary for a robust economic assessment. We recommend a careful choice of appropriate bamboo species for different cropping systems. We again, anticipate a biodiversity trade-off

in using exotic species against using native species; which could be looked into in future studies complementing this study to develop a comprehensive outlook for upscaling bamboo agroforestry in Ghana.

Acknowledgements Open Access funding provided by Projekt DEAL. This paper was produced as an activity of BiomassWeb (grant no. 031A258A), a project funded by the German Federal Ministry of Education and Research (BMBF) in the context of the initiative GlobE ‘‘Securing the Global Food Supply’’. BiomassWeb is managed by the Center for Development Research (ZEF), University of Bonn, Germany. Authors are also very grateful to Dr. Obiri-Darko (Principal Scientist- Forestry Research Institute of Ghana, (FORIG)/ CSIR-Ghana) and International Bamboo and Rattan Organization (INBAR) for the consultancy work on the economic analysis.

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Appendix 1

See Table 9.

Table 9 Summary cash flow of bamboo agroforestry, monocrop bamboo and monocrop food production from 2014–2016

Input output	Cash flow/ha (GH¢)					
	No fertilizer bamboo agroforestry (food /culms)	Fertilizer bamboo Agroforestry (food/culms)	Fertilizer monocrop/ bamboo (culms)	No fertilizer monocrop bamboo (culms)	No fertilizer monocrop (food)	Fertilizer Monocrop (food)
<i>Revenue</i>						
Food crops	37,752	51,168	0	0	34,632	48,204
Bamboo	87,120	87,120	154,800	122,400	0	0
<i>Culms</i>						
Total revenue	124,872 (\$29,381.65)	138,288 (\$32,538.35)	154,800 (\$36,423.53)	122,400 (\$28,800.00)	34,632 (\$8,148.71)	48,204 (\$11,342.12)
<i>Cost</i>						
<i>Land and other</i>						
Material inputs	7690	10,093	6130.00	5620.00	4390	8293
Tools/equip	1830	1830	939.00	939.00	1830	1830
Labor	69,350	70,100	59,722.50	55,680.00	21,680	22,430
Transport	250	250	250.00	250.00	0	0
Total cost	79,120.00 (\$18,616.47)	82,273 (\$19,358.35)	67,041.50 (\$15,774.47)	62,489 (\$14,703.29)	27,900 (\$6,564.71)	32,553 (\$7,659.53)
Net cash flow	45,752.00 (\$10,765.18)	56,015 (\$13,180.00)	87,758.50 (\$20,649.06)	59,911 (\$14,096.71)	6732 (\$1,584.00)	15,651 (\$3,682.59)
% of labor	88	85	89	87	78	69
BCR	1.2	1.2	1.23	1.2	1.1	1.1

Dollar/Cedi exchange rate: US\$ 1=GH¢ 4.25 (2017 bank base exchange rate). Cost variables: Material inputs = planting material, herbicides, fertilizer, storage, boots, packaging sacks. Tools/equipment = cutlass/machete, hoe, chisel, rake. Labour inputs = plot establishment, maintenance, harvesting processing and storage of food crops, harvesting and processing bamboo culms). Transport = seedlings for planting. Marketing = products purchased by middlemen at farm gate. Values of crops are averages of the 3 years per ha of each cropping system. Bamboo values are the average values for products in the third year and afterwards.

Appendix 2

See Table 10.

Table 10 Estimates of cash flow of individual bamboo agroforestry, monocrop bamboo and monocrop food production systems from 2014–2016

	Cash flow									
	No fertilizer					Fertilizer				
	Bamboo agroforestry (food crops)		No fertilizer			Bamboo agroforestry (food crops)		Fertilizer		
	Cowpea	Cassava	Maize	Cowpea	Cassava	Maize	Cowpea	Cassava	Maize	Cowpea
Revenue										
Food crops	12,052	8000	17,700	20,100	1000	30,068	10,030	9002	15,600	18,000
Bamboo culms	31,100	29,000	27,020	30,100	30,000	27,020	0	0	0	0
Total revenue cost	43,152 (\$10,153)	37,000 (\$8706)	44,720 (\$10,522)	50,200 (\$11,812)	31,000 (\$7294)	57,088 (\$13,432)	10,030 (\$2360)	9002	(\$2118)	15,600 (\$3671)
20,200 (\$ 4753)										18,000 (\$4235)
Land and other material inputs	2090	2000	3600	4000	2000	4093	1090	1000	2300	1200
Tools/equipment	530	500	800	530	500	800	530	500	800	500
Labor	24,050	20,000	25,300	30,000	10,000	30,100	7,080	6,600	8,000	7,430
Transport	80	70	100	80	70	100	0	0	0	0
Total cost	26,750 (\$6294)	22,570 (\$5311)	29,800 (\$7012)	34,610 (\$8144)	12,570 (\$2958)	35,093 (\$8257)	8,700 (\$2047)	8,100	(\$1906)	11,100 (\$2612)
12,803 (\$3012)										11,050 (\$2600)
Net cash flow	16,402 (\$3859)	14,430 (\$3395)	14,920 (\$3511)	15,590 (\$3668)	18,430 (\$4336)	21,995 (\$5175)	1330 (\$313)	902 (\$212)	4500 (\$1059)	6950 (\$1635)
% of labor	86	79	89	88	88	90	80	78	69	82
BCR	1.2	1.2	1.2	1.2	1.24	1.2	1.1	1.11	1.14	1.2

Dollar/Cedi exchange rate: US\$ 1 = GH¢ 4.25 (2017 bank base exchange rate). Cost variables: Material inputs=planting material, herbicides, fertilizer, storage, boots, packaging sacks. Tools/equipment=cutlass/machete, hoe, chisel, rake. Labour inputs=plot establishment, maintenance, harvesting processing and storage of food crops, harvesting and processing bamboo culms). Transport=seedlings for planting. Marketing=products purchased by middlemen at farm gate. Values of crops are averages of the 3 years per ha of each cropping system. Bamboo values are the average values for products in the third year and afterwards

Appendix 3

See Table 11.

Table 11 Data used in estimating cost and returns in agroforestry and mono crop systems

Description	Cost	Return	Quantity
No. of bamboo culms/ha (Agroforestry)			660
No. of bamboo culms/ha (Monocrop bamboo)			1320
Mortality replacement (30%)			
Initial fertilizer (50 kg bag/ha)			3
Cost of fertilizer GH¢/50 kg bag	89		
Bamboo seedling price GH¢/seedling	6		
Labor wages (GH¢/man-day) (2016)	15		
No. of harvestable culms per clump (Agroforestry plots)		3	
No. of harvestable culms per clump (Monocrop plots)		6	
Initial harvest in third year (culms/ha)		3	
Third year, maize yield (t/ha)			
Bamboo agroforestry (Fertilized) (t/ha)		2.75	
Bamboo agroforestry (Not fertilized) (t/ha)		0.79	
Monocrop maize (Fertilized) (t/ha)		2	
Monocrop maize (Not fertilized) (t/ha)		0.58	
Third year, cowpea yield (t/ha)			
Bamboo agroforestry (Fertilized) (t/ha)		2.62	
Bamboo agroforestry (Not fertilized) (t/ha)		2.03	
Monocrop cowpea (Fertilized) (t/ha)		1.92	
Monocrop cowpea (Not fertilized) (t/ha)		1.32	
Third year, cassava yield (t/ha)			
Bamboo agroforestry (Fertilized) (t/ha)		13.09	
Bamboo agroforestry (Not fertilized) (t/ha)		12.65	
Monocrop cassava (Fertilized) (t/ha)		11.74	
Monocrop cassava (Not fertilized) (t/ha)		10.67	

Values of crops are averages per ha of the first three years of each cropping system establishment; Bamboo values are the average values for products in the third year and afterwards, monthly for only one year

References

- African Center for Economic Transformation (ACET) (2017) Agriculture, powering Africa's economic transformation. African transformation report. ACET Online Magazine, Washington, D.C, pp 10–19
- Alliance for a Green Revolution in Africa (AGRA) (2017) Africa agriculture status report: the business of small-holder agriculture in Sub-Saharan Africa (Issue 5). Alliance for a Green Revolution in Africa (AGRA), Nairobi, Kenya, pp 24–34
- Ahlawat SP, Kumar RV, Gupta VK, Dhyani SK (2008) Scope of bamboo-based agroforestry system in India. In: Proceedings of national conference of "Bamboo management, conservation, value addition and promotion" Tropical Forest Research Institute, Jabalpur, India, 89
- Ahmad R, Sher MS, Khalid A, Arshad M, Muhammad SH (2007) Growth and yield response of Wheat (*Triticum aestivum* L) and Maize (*Zea mays* L.) to nitrogen and tryptophan enriched compost. *Pakistan J Bot* 39(2):541–549

- Alavalapati JRR, Mercer DV (2004) Agroforestry development: an environmental economic perspective. *Agroforest Syst* 61:299–310
- Akoto SD, Denich M, Partey ST, Frith O, Kwaku M, Mensah A, Borgemeister C (2018) Socioeconomic indicators of bamboo use for agroforestry development in the dry semi-deciduous forest zone of Ghana. *Sust* 10(7):2324
- Akwada DR, Akinlabi ET (2018) Bamboo an alternative wood to reducing tropical deforestation in Ghana. In: DII-2018 Conference On Infrastructure Development And Investment Strategies for Africa, pp 1–12
- Arnold M, Kohlin G, Persson R, Shepherd G (2003) Fuelwood revisited: what has changed in the last decade? CIFOR Occasional Paper No 39 Bogor, CIFOR, Indonesia
- Atangana AR, Khasa PD, Chang S, Degrande A (2014) Ecological interactions and productivity in agroforestry systems. In: Atangana AR, Khasa PD, Chang S, Degrande A (eds) *Tropical agroforestry*. Springer, New York, pp 151–172
- Bellingham PJ, Morse CW, Buxton RP, Bonner KI, Mason NWH, Wardle DA (2013) Litterfall, nutrient concentrations and decomposability of litter in a New Zealand temperate montane rain forest. *The New Zealand J Ecol* 37(2):162–171
- Bihari B (2001) *Agroforestry model of bamboo cultivation on degraded agricultural land*. Ph.D thesis. Guru Ghasidas University, Bilaspur, India, pp 67–83
- Borisade TV, Odiwe AI (2018) Nutrient input in litter and soil of *Bambusa vulgaris* stands in a secondary rainforest, Ile-Ife. *Nigeria Trop For Sci* 30(2):195–206
- Cerutti PO, Sola P, Chenevoy A, Iiyama M, Yila J, Zhou W, Kuehl Y (2015) The socioeconomic and environmental impacts of wood energy value chains in Sub-Saharan Africa: a systematic map protocol. *Environ Evid* 4(1):12
- Chidumayo EN, Gumbo DJ (2013) The environmental impacts of charcoal production in tropical ecosystems of the world: a synthesis. *Energy Sustain Devs* 17(2):86–94
- Crozier CR, Hardy DH, Kissel DE, Mitchell CC, Oldham JL, Phillips S, Sonon L (2010) Research-based soil testing and recommendations for cotton on coastal plains soils. *Southern Cooperative Series Bulletin*. <https://www.clemson.edu/sera6/sera6cotton%20pub.pdf>. Accessed 29 January 2019
- Damnyag L, Saastamoinen O, Pappinen A, Tynelä T, Appiah M (2011) Economic cost of deforestation in semi-deciduous forest—a case of two forest districts in Ghana. *J Eco Econ* 70:2503–2510
- Dariush M, Ahad M, Meysam O (2006) Assessing the land equivalent ratio (LER) of two corn [*Zea mays* L] varieties intercropping at various nitrogen levels in Karaj. *Iran. Cent Eur Agric* 7(2):359–364
- Elevitch CR, Wilkinson KM (2000) Economics of farm forestry: financial evaluation for landowners *Agroforestry guides for pacific islands*. Permanent Agriculture Resources, Honolulu
- Eyini M, Jayakumar H, Panniselvam S (1989) Allelopathic effect of bamboo leaf extract on the seedlings of groundnut. *Trop Eco* 30:138–141
- FAO (2011) *Save and grow: a policy makers guide to the sustainable intensification of crop production*. FAO, Rome, pp 16–21
- FAO (2015) *Global forest resource assessment 2015*. Food and Agriculture Organization of the United Nations, Rome, pp 1–62
- FAO (2016) *State of the world's forest 2016*. Food and Agriculture Organization of the United Nations, Rome, p 6
- FAO (2017) *The charcoal transition: greening the charcoal value chain to mitigate climate change and improve local livelihoods*. Food and Agriculture Organization of the United Nations, Rome
- Fu M, Xiao J, Lou Y (2000) *Cultivation and utilization on bamboo*. China Forestry Publishing House, Beijing, pp 34–39
- Gelderman R, Gerwing J, Reitsma K (2006) Recommended soil sampling methods for South Dakota. College of Agriculture and Biological Life Sciences, South Dakota State University, U.S.A., pp 76–79
- Ghana Forestry Commission (2015) *National forest plantation development programme annual report*. Forestry Commission, Accra, pp 23–26
- Ghana Statistical Service (2012) *2010 population and housing census summary report of final results*. Accra. pp 99
- Gittinger JP (1982) *Economic analysis of agricultural projects*, 2nd edn. John Hopkins University Press, Maryland, pp 65–70
- Gogoi B, Bhuyan TC (2016) Physico-chemical properties and microbial biomass carbon of bamboo growing soils: a comparative study. *Ind For* 142(8):739–744
- Handa AK, Roy P, Solanky KR, Chouhan SPS, Khare N (1995) Role of bamboo in agroforestry under rain-fed condition. National Research Center for Agroforestry, Jhansi, p 36
- Idol T, Haggard J, Cox L (2011) Ecosystem services from smallholder forestry and agroforestry in the tropics. Integrating agriculture, conservation and ecotourism: examples from the field. Springer, Dordrechts, pp 209–270
- ILEIA (2000) *Monocultures towards Sustainability*. <https://www.agriculturesnetwork.org/magazines/global/monocultures-towards-sustainability/monocultures-towards-sustainability-editorial>. Accessed 25th May 2018
- Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. *Agroforest Syst* 76(1):1–10
- Karasu A, Kuscü H, Mehmet ÖZ, Bayram G (2015) The effect of different irrigation water levels on grain yield, yield components and some quality parameters of silage maize (*Zea mays indentata* sturt). *Notulae Botanicae Horti Agrobotan Cluj-Napoca* 43(1):138–145
- Kemausuor F, Obeng GY, Brew-Hammond A, Duker A (2011) A review of trends, policies and plans for increasing energy access in Ghana. *Renew Sust Ener Revi* 15(9):5143–5154
- Khilish KD (2012) Performance of wheat (*Triticum aestivum*) under bamboo (*Dendrocalamus strictus*) based agroforestry system in Chhattisgarh. *Master's Thesis*, Inira Grandhi Agricultural University, Raipur, India. 12–16
- Kleinhenz V, Midmore DJ (2001) Aspects of bamboo agronomy. *Advan Agron* 74:99–153
- Kuehl Y, Li Y, Henley G (2013) Impacts of selective harvest on the carbon sequestration potential in Moso bamboo (*Phyllostachys pubescens*) plantations. *For Trees Liveli* 22(1):1–18

- Kurwakumire N, Chikowo R, Mtambanengwe F, Mapfumo P, Snapp S, Johnston A, Zingore S (2014) Maize productivity and nutrient and water use efficiencies across soil fertility domains on smallholder farms in Zimbabwe. *J Field Crop Resear* 164:136–147
- Lasco RD, Delfino RJP, Espaldon MLO (2014) Agroforestry systems: helping smallholders adapt to climate risks while mitigating climate change. *WIREs Clim Chan* 5:825–833
- Lobovikov M, Schoene D, Yping L (2012) Bamboo in climate change and rural livelihoods. *Mitig Adapt Strat Glob Chan* 17(3):261–276
- Mahmood H, Siddique MRH, Rahman MS, Hossain MZ, Hasan MM (2011) Nutrient dynamics associated with leaf litter decomposition of three agro-forestry tree species (*Azadirachta indica*, *Dalbergia sissoo* and *Melia azadirachta*) of Bangladesh. *For Res* 22:577–582
- Mailly D, Christanty L, Kimmins JP (1997) ‘Without bamboo, the land dies’: nutrient cycling and biogeochemistry of a Javanese bamboo talun-kebun system. *For Ecol Man* 91(2–3):155–173
- Malay D, Bhattacharya S, Singh P, Filgueiras TS, Pal A (2008) Bamboo taxonomy and diversity in the era of molecular markets. *Adv Bot Res* 47:225–268
- McNeely J, Schroth G (2006) Agroforestry and biodiversity conservation—traditional practices present dynamics, and lessons for the future. *Biod Conser* 15:549–554
- Motsara MR, Roy RN (2008) Guide to laboratory establishment for plant nutrient analysis. *Food Agric Org U. N. Rome* 19:43–47
- Nalivata P, Kibunja C, Mutegi J, Tetteh F, Tarfa B, Dicko MK, Ouattara K, Cyamweshi RA, Nouri MK, Bayu W, Wortmann CS (2017) Integrated soil fertility management in Sub-Saharan Africa. *Fertilizer use optimization in sub-Saharan Africa*, 113–124
- Nath S, Das R, Chandra R, Sinha A (2009) Bamboo based agroforestry for marginal lands with special reference to productivity, market trend and economy. *Agroforestry in Jharkhand*, *Envis Jharkhand News*, pp 80–96
- Nath V, Pal RS, Banerjee SK (2008) Bamboo: Its distribution, production, habitat and agroforestry potential. *Ind Forest* 134(3):387–439
- Nirala DP, Kumar J, Ahmad MS, Kumari P (2018) Bamboo based agroforestry system for livelihood and ecological security in North Chhotanagpur division of Jharkhand. *Pharm Phytochem* 1:1996–1999
- Ong CK, Black C, Wilson J (eds) (2015) *Tree–crop Interactions: agroforestry in a changing climate*. CABI, Wallingford, pp 33–40
- Oorts K, Vaniauwe B, Merckx R (2003) Cation exchange capacity of soil organic matter fractions in a fercic lxisol with different organic matter inputs. *Agric Ecosyst Environ* 100:161–171
- Pande VC, Kurothe RS, Rao BK, Kumar G, Parandiyal AK, Kumar A, Singh AK (2012) Economic analysis of bamboo plantation in three major ravine systems of India. *Agric Econ Res* 25(1):49–59
- Partey ST, Sarfo DA, Frith O, Kwaku M, Thevathasan NV (2017) Potentials of bamboo-based agroforestry for sustainable development in Sub-Saharan Africa: a review. *Agric Res* 6:22–32
- Partey ST, Thevathasan NV, Zougmore RB, Preziosi RF (2018) Improving maize production through nitrogen supply from ten rarely-used organic resources in Ghana. *Agrofor Syst* 92(2):375–387
- Patel B, Gami B, Patel P (2017) Carbon sequestration by bamboo farming on marginal land and sustainable use of wood waste for bioenergy: case studies from abellon clean energy. *Wood is Good*. Springer, Singapore, pp 451–467
- Poodineh O, Keighobadi M, Dehghan S, Raoofi MM (2014) Evaluation of intercropping system on weed management, forage quality, available of nitrogen and resource use. *Int J Agric Crop Sci* 7:1298–1303
- Rahangdale CP, Pathak NN, Koshta LD (2014) Impact of bamboo species on growth and yield attributes of Kharif crops under agroforestry system in wasteland condition of the Central India. *Int J Agroforest Silvi* 1(3):031–036
- Rahman SA, Rahman MF, Codilan AL, Farhana KM (2007) Analysis of the economic benefits from systematic improvements to shifting cultivation and its evolution towards stable continuous agroforestry in the upland of Eastern Bangladesh. *Int For Rev* 9(1):536–547
- Rahman SA, De Groot WT, Snelder DJ (2008) Exploring the agroforestry adoption gap: financial and socioeconomic of litchi-based agroforestry by smallholders in Rajshahi (Bangladesh). *Smallholder tree growing for rural development and environmental services*. Springer, Dordrecht, pp 227–243
- Rasul G, Thapa GB (2006) Financial and economic suitability of agroforestry as an alternative to shifting cultivation: the case of the Chittagong hill tracts, Bangladesh. *Agric Syst* 91:29–50
- Roshetko JM, Lasco RD, Angeles MSD (2007) Smallholder agroforestry systems for carbon storage. *Mitig Adap Stra Glob Chan* 12(2):219–242
- Roshetko JM, Snelder DJ, Lasco RD, Van-Noordwijk M (2008) Future challenge: a paradigm shift in the forestry sector. *Smallholder tree growing for rural development and environmental services*. Springer, Dordrecht, pp 453–485
- Roshetko JM, Rohadi D, Perdana A, Sabastian G, Nuryartono N, Pramono AA, Widyani N, Manalu P, Fauzi MA, Sumardanto P, Kusumowardhani N (2013) Teak agroforestry systems for livelihood enhancement, industrial timber production, and environmental rehabilitation. *J Trees Liveli* 22:251–256
- Schroth G, de Fonseca GAB, Harvey CA, Gascon C, Vasconcelos HL, Izac AMN (2004) *Agroforestry and biodiversity conservation in tropical landscapes*. Island Press, Washington, DC, pp 40–46
- Seshadri P (1985) *Intercropping of Bamboo (Dendrocalamus strictus) with Soybean—an agroforestry study*. Ph. D. Thesis. Tamil Nadu Agricultural University. Coimbatore, India. 480
- Shanmughavel P, Francis K (2001) Intercropping trials of four crops in Bamboo plantations. *Bamb Ratt* 1(1):3–9
- Shanmughavel P, Francis K (2002) *Bambusa bambos—An afforestation trial*. In: 12th World Forestry Congress, FAO, Quebec City, Canada. 23–29
- Shanmughavel P, Peddappaiah RS, Muthukuma T (2000) Litter production and nutrient return in *Bambusa bambos* plantation. *Sustain For* 11(3):71–82

- Sharma R, Wahono J, Baral H (2018) Bamboo as an alternative bioenergy crop and powerful ally for land restoration in Indonesia. *Sust* 10:4361–4367
- Snelder DJ, Lasco RD (eds) (2008) Smallholder tree growing for rural development and environmental services: Lessons from Asia (Vol 5). Springer Science and Business Media, London, pp 12–19
- Steffan-Dewenter I, Kessler M, Barkmann J, Bos MM, Buchori D, Erasmi S, Guhardja E (2007) Tradeoffs between income, biodiversity, and ecosystem functioning during tropical rainforest conversion and agroforestry intensification. *Proc Nat Acad Sci* 104(12):4973–4978
- Tom-Dery D, Schroeder J, Struwe J (2014) Regeneration potential and stand structure of a proposed plantation site in the transition zone of Ghana. *Int J Biod Conser* 6(3):238–246
- Tscharntke T, Clough Y, Bhagwat S, Buchori D, Faust H, Hertel D, Hölscher D, Jührbandt J, Kessler M, Perfecto I, Scherber C, Schroth G, Veldkamp E, Wanger TC (2011) Multifunctional shade-tree management in tropical agroforestry landscapes—a review. *Appl Eco* 48:619–629
- Tully K, Sullivan C, Weil R, Sanchez P (2015) The state of soil degradation in Sub-Saharan Africa: baselines, trajectories, and solutions. *Sust* 7(6):6523–6552
- Van Khuc Q, Tran BQ, Meyfroidt P, Paschke MW (2018) Drivers of deforestation and forest degradation in Vietnam: An exploratory analysis at the national level. *For Policy Econ* 90:128–141
- Vigbedor BY, Osafo AS, Gyan BA (2015) Ethnobotanical survey of plants used in the treatment of Malaria in the Sekyere Central District of Ashanti Region of Ghana. *Int J Novel Resear Life Sci* 2:17–25
- Vira B, Agarwal B, Jamnadass RH, Kleinschmit D, McMullin S, Mansourian S, Wildburger C (2015) Forests, trees and landscapes for food security and nutrition. *Forests and Food: Addressing Hunger and Nutrition across Sustainable Landscapes*. Open Book Publishers, Cambridge, pp 31–37
- Wang Z, Jin X, Li L, Christie P, Jian-hua Z, Li X, Sun J (2014) Intercropping enhances productivity and maintains the most soil fertility properties relative to sole cropping. *PLoS ONE J*. <https://doi.org/10.1371/journal.pone.0113984/>
- Zhao H, Wang L, Dong L, Sun H, Gao Z (2014) Discovery and comparative profiling of micro RNAs in representative monopodial bamboo (*Phyllostachys edulis*) and sympodial bamboo (*Dendrocalamus latiflorus*). *PLoS ONE J* 9(7): e102375
- Zingore S, Mutegi J, Agesa B, Tamene L, Kihara J (2015) Soil degradation in sub-Saharan Africa and crop production options for soil rehabilitation. *Better Crops Plant Food* 99(1):24–26

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