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Impact of tree management on coffee and common bean productivity in smallholder agroforestry systems in Uganda

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Abstract. In this study, we hypothesized that tree canopy pruning would positively influence the relative growth performance and productivity of coffee (*Coffea arabica* L.) and common beans (*Phaseolus vulgaris* L.) growing under *Cordia africana* and *Albizia coriaria* trees. The trees were subjected to a 50% pruning regime at a 6-month interval over a period of 20 months (July 2018 - February 2020), and common beans were introduced following local planting seasons. Yields of parchment coffee were highest under pruned Albizia (949 kg/ha). Unshaded coffee produced the least yield at 402 kg/ha and 422 kg/ha in the Albizia and Cordia sites respectively. While the highest common beans yields (708 kg/ha) were obtained from open field sites, beans that were planted under unpruned Cordia gave the least yield of 420 kg/ha. Unlike coffee, there was a significant variation in yield of common beans across the different management options ($P<0.05$). The results show that agroforestry tree canopy pruning is an important on-farm management decision for controlling competition while prolonging the period of intercropping in intensive farming systems. Farmers should deliberately prune agroforestry shade trees to minimize the negative effects of dense shading.

Keywords: Pruning, Common Beans, Coffee, Agroforestry, Yield Components.

Introduction

Millions of farmers in developing countries are struggling to feed their families as a result of land degradation and land use pressures (Hazell & Wood, 2008; Winterbottom et al., 2013). Eighty percent of the chronically hungry in Africa are smallholder farmers and their hunger is related to low crop yields (Descheemaeker et al., 2013). Land use pressures arising from increasing human population in sub Saharan Africa dictate a shift to intensive agricultural farming systems (Sebatta et al., 2019), such as agroforestry to optimize benefits from the biological interactions created when trees are deliberately combined with agricultural crops (Brown et al., 2018; Pinho et al., 2012). While agroforestry is one promising option for sustainable use of land (Das et al., 2020; Laudares et al., 2017; Ong & Swallow, 2003), competition for growth resources in such intensive farming systems is inevitable as tree and crop roots and canopies occupy the same space and overlapping growth cycles.

There is a growing desire for attaining agricultural sustainability (Nair & Toth, 2016; Santiago-Freijanes et al., 2018) rather than increasing production. For agroforestry, sustainability refers to the concept that production can occur on a given land management unit on an indefinite basis. For example, while use of inorganic fertilizers can increase production over a short period, it is regarded as unsustainable given the short period of fertilizer efficiency, and the negative land and environmental effects associated with its use. To achieve agricultural sustainability, researchers need to come up with innovative technologies aimed at adaptive management of farming systems. Sustainable intensification of farming systems through agroforestry has been suggested as a strategy to improve farmers' livelihoods and facilitate adaptation of coffee production to climate change (Rahn et al., 2018). Use of fertilizer or leguminous trees in farming systems can enhance agricultural sustainability (Nair & Toth, 2016; Nyong & Martin, 2019). Global food production has, to some extent, been dependent upon biological nitrogen (N) fixation (about 100 million tons per year globally) in agroecosystems (Jhariya et al., 2018). It is common knowledge that trees provide a cheap alternative for sustaining agricultural production and yet most of the smallholder farmers in the Mt. Elgon region of Uganda with trees on their farms have failed to realize the co-benefits due to poor management of the tree component.

Tree canopy pruning of live branches is usually done to enhance production of high-value knot-free timber in plantation trees (Alcorn et al., 2013). However, it is also a practical way of controlling competition for growth resources in an intensive farming system (Buyinza et al., 2023; Jackson et al., 2000) such as coffee agro-ecosystems reported in this study. Mt. Elgon region of Uganda has three coffee agro-ecosystems practiced by smallholder farmers namely open canopy coffee system, coffee-banana intercropping, and coffee-shade tree systems (Rahn et al., 2018; Sarmiento-Soler et al., 2020). This study focused on the coffee-tree system, where farmers introduce the common bean (*Phaseolus vulgaris* L.) crop under the same land management unit. Failure of farmers to adopt shade tree canopy pruning as a deliberate agricultural land management practice has negatively affected crop productivity and hindered development of appropriate pruning regimes for agroforestry trees. While there have been commendable efforts in promoting shaded coffee in the region (Bukomeko et al., 2017; Gram et al., 2018; UCDA, 2017, 2018), minimal effort has been put into the management of shade trees that would maximize benefits and minimize the associated trade-offs.

The aim of this study was to assess the impact of tree canopy pruning of *Cordia africana* Lam. and *Albizia coriaria* Welw. ex Oliv (hereafter simply referred to as Cordia and Albizia respectively) on the relative performance of coffee - common bean agroforestry system. These semi-deciduous tree species are commonly integrated in coffee plantations occurring in more than 25% of the agroforestry systems in this region (Rahn et al., 2018). The following hypotheses are tested: (i) tree canopy pruning minimizes the competitive effects of Cordia and Albizia trees on coffee and common beans and (ii) tree canopy pruning positively influences the relative growth performance and productivity of agricultural crops.

Materials and Methods

The study was conducted in Manafwa district located in Eastern Uganda, bordering the Republic of Kenya in the East, Bududa district to the North, Mbale district to the West and Tororo to the Southwest. The average annual rainfall is 1500 mm, with two peak rainy seasons that occur in April-May and September-November. The topography of the slope is characterized by two escarpments that naturally separate three altitude classes of <1400 m.a.s.l, 1400–1700 m.a.s.l, and >1700 m.a.s.l within the inhabited area of the mountain ecosystem (Rahn et al., 2018; Sarmiento-Soler et al., 2020). Local farming communities live between 1000 m.a.s.l. at the foothill and 2200 m.a.s.l. close to the protected Mt. Elgon National Park. Coffee (*Coffea arabica* L.) is the main cash crop and it is traditionally grown in combination with bananas, common beans, maize and multi-purpose shade-trees.

The field experiment was conducted in two separate farms, approximately 2 km apart; each having either Cordia or Albizia mature trees integrated in coffee agroforestry systems. The Albizia experimental site was located at N00^{0}56.007' and E034^{0}16.605' at 1196 metres above sea level (m.a.s.l) while the Cordia site was located at N00^{0}55.582' and E034^{0}15.244' at 1233m.a.s.l in Butta sub-county, Manafwa district. The study sites fall within the lower altitude class (<1400 m.a.s.l) on the foothills of Mt. Elgon, following an altitudinal classification of the region by Rhan et al. (2018).

Components under study

Arabica coffee

Uganda's smallholder farmers contribute about 90% of the country's coffee production (Gram et al., 2018). While Uganda grows both arabica (accounting for 10-15%) and robusta coffee, the prices received for arabica coffee on the international market are greater than for robusta (Van Asten et al., 2011). Coffee is a shade tolerant crop and it is traditionally grown under shade trees in complex agroforestry systems (Gram et al., 2018). While the competition for water and nutrients, and pest/disease incidence are critical in shaded coffee agroforestry system (Ayalew, 2018; Beer et al., 1998), unshaded plantations generally require higher levels of external inputs to maximize yield (Damatta, 2004). Many smallholder farmers have intensified coffee management by eliminating shade trees and increasing agrochemical inputs to raise coffee productivity. Arabica coffee was selected for this study because it is the predominant coffee variety grown in the Mt. Elgon region.

Common beans

Common beans (*Phaseolus vulgaris* L.) is an important commodity grown as a rotation crop and intercrop and it is vital for food security, especially in Sub-Saharan Africa (Lupwayi et al., 2011; Namugwanya et al., 2018). In Uganda, the per capita consumption of common beans averages about 9.8 kg annually contributing, on average, 12% of the total protein intake, about 4% calorie intake, selected minerals and vitamins consumed per person (Broughton et al., 2003; Ronner et al., 2018). The crop is ranked fifth behind banana, cassava, cattle meat and milk in terms of value of output (Sibiko et al., 2013). Majority of Ugandan farming households grow beans during March to June and September to December cropping seasons. However, the crop has registered low productivity with a yield gap of about 75% below its potential in Uganda (Goettsch et al., 2016), and the least yield (200 - 250 kg/ha) was reported in Eastern Uganda (FAO et al., 2019). The low yields have been attributed to poor agronomic practices, low soil infertility, lack of improved cultivars, moisture stress, weed competition, and damage caused by pests and diseases (Sinclair & Vadez, 2012). In view of these challenges, there is need for farmers to reverse soil nutrient depletion through better soil management and cropping systems (Bekunda et al., 2004) as cultivable land continues to be scarce in the Mt. Elgon region of Uganda (Vedeld et al., 2016).

Albizia coriaria and Cordia africana agroforestry trees

Albizia coriaria Welw. ex Oliv. is a deciduous nitrogen fixing tree in the family Fabaceae (Katende et al., 1995). It is commonly found growing around homesteads and crop fields. The absence of Albizia in closed canopy rainforests is largely the result of its high light requirements (Janani et al., 2014). The tree can be established through direct seed sowing, planting seedlings and from wildings. A related study in Uganda revealed that the species is multipurpose and valued for fourteen products and services (Tabuti & Mugula, 2007). Albizia is one of the most common tree species used in indigenous agroforestry systems in Uganda. It was chosen for this study because it is widely grown by farmers in Mt. Elgon region and can fix nitrogen.

Cordia africana Lam. belongs to *Boraginaceae* family. In Uganda, it is found mostly on the edges of moist forests, riverine gallery forest, wooded grassland in the Mt Elgon ecosystem, Ankole and Kigezi regions at 1200-2000 m above sea level (Katende et al., 1995). Mature fruits of Cordia have a sweet edible pulp and the flowers yield plenty of nectar (Mbere et al., 2020). Cordia is planted as a shade tree in coffee plantations to provide shade for crops and leaf fall in the dry season for mulch (Alemayehu et al., 2016). Gram *et al.* (2017) reported that Cordia is an important agroforestry tree species in coffee plantations in Eastern Uganda. It was selected for the study because of its unsynchronized deciduous leafing phenology and widely integrated in coffee agroforestry systems in Mt. Elgon region.

Soil characterization

Soil samples at the study sites were obtained using a soil auger in July 2018 (to obtain baseline scenario) and in January 2020 to establish the soil physical and chemical properties that may have resulted from the tree management interventions of the study. The soil samples were obtained from six sites as follows: under coffee growing below pruned Albizia, coffee below unpruned Albizia, coffee below pruned Cordia, coffee below unpruned Cordia, unshaded coffee and in the open field with neither coffee nor trees. At each sampling point (in quadrants), soil samples were collected at 3 depths i.e. 0-15 cm, 15-30 cm and 30-45 cm. The soil was mixed well and a composite sample (about 500 g) kept in a labelled plastic bag. The samples were taken to the Makerere University soil science laboratory for analysis. The composite samples were analysed for organic matter content, soil texture, and major and trace elements following procedures by Okalebo et al. (2002).

Research design, instrumentation and installation

Pruning of selected trees

In each site, 2 trees were pruned while the other 2 remained unpruned. This study adopted the 50% pruning regime. To attain the 50% canopy-pruning regime, all secondary branches on the tree under investigation were counted and divided by two. Thereafter, branches to be pruned were randomly selected, labelled by making slit cuts and later pruned using a three-cut procedure (Buyinza et al., 2023; Bedker et al., 2012). The three-cut procedure was preferred because it minimizes splitting of the branch and damage during pruning. The three-cut procedure was conducted as follows: first, at 30 cm from the trunk, a cut was mad halfway through the branch from the underside. Second, about 3cm past the first cut, another cut was made through the branch from the top side until the branch fell off. The weight of the branch broke it off between the two cuts. Lastly, the resulting stub was then cut back to the collar of the branch. Tree canopy was pruned three times at six months intervals. The first pruning was done in October 2018, followed by the second and third pruning in April and November 2019 respectively.

Coffee yield and yield components assessment

Coffee yields were assessed from 20 randomly selected and tagged coffee trees growing under five treatments including (i) coffee growing under pruned Cordia, (ii) coffee under unpruned Cordia, (iii) coffee under pruned Albizia, (iv) coffee under unpruned Albizia and (v) unshaded or coffee exposed to sun shine. Yields were assessed in three consecutive coffee harvesting seasons (August - October 2018, February-April 2019 and August-October 2019) by handpicking ripe coffee cherries (when bright red in colour) and processing them using the wet process method (Joët et al., 2010). Ripe cherries were handpicked three to five times from each coffee tree in a season until all the cherries had been completely harvested, over a period of two to three months. For each coffee plant yield, fresh weight of the harvested coffee beans (before pulping), fresh weight after pulping and washing were measured. The dry weight of the parchment was determined at 12% moisture content using a digital weighing scale. Parchment are coffee beans with endocarp, obtained after wet-processing of ripe coffee cherries using a pulping machine. Coffee yield per hectare (kg ha^{-1}) is a product of coffee yield per tree (kg $tree^{-1}$) and density of coffee trees per hectare (number of coffee trees ha^{-1}).

Other parameters assessed were coffee tree diameter, height, age (based on the farmer's recollection of planting date), number of stems per bush, branches per coffee tree, number of berry clusters per branch (assessed from five randomly selected branches) and number of berries per cluster (assessed from five randomly selected berry clusters) documented from each of the tagged coffee trees.

Common beans variety selection and planting

Common bean variety was selected on the basis of abundance and preference revealed by a rapid survey of 15 randomly selected household heads in Butta Sub County (Table 1). While common bean variety abundance was influenced by location, preference was based on taste, yield and ease to cook. NABE 15, a mottled pink variety (Sebuwufu et al., 2015), was subsequently selected and planted because it was abundant and preferred by households. It is one of the multi-stress tolerant varieties in Uganda (FAO/TECA, 2017). However, it is highly susceptible to bean fly (bean stem maggot) that has threatened bean production in East Africa (Ssekandi et al., 2016). Farmers have been able control the bean stem maggot damage by planting NABE 15 together with resistant varieties in a systematic random arrangement.

The beans were planted in the two study sites at a spacing of 30 x 30 cm at the beginning of each rainfall season in August 2018 (season 1), April 2019 (season 2) and August 2019 (season 3). Beans were also planted at sites with unshaded coffee and an open field approximately 50 m from each of the Cordia and Albizia study sites. The seeds were locally sourced, sorted but not subjected to pre-treatment before planting. After germination, data on bean height, number of leaves, flowers and pods were collected weekly until the day of harvest. A single weeding regime was applied in line with the local practice by farmers.

Table 1: Some bean varieties among the Mt. Elgon communities

Variety	Local description	Abundance[1]	Preference[2]	Remarks
Nambale	Long	2	5	Easy to cook, with a tasty rich rea stew when cooked
Obweru	White and small	4	3	High yielding but easily affected by too much rain
Kanyebwa	Cream with red stripes	1	1	High yielding, grows at any altitude, tasty, short time to cook and swells on cooking
Yellow beans	Large	5	2	High yielding but yield is easily affected by too much rain
Black beans	Small and long	5	6	Has good taste
Lwakhakha	Faba beans	3	7	High yielding but location specific
Kachuma	Small & round red bean	7	3	Easy to cook, but low yielding

[1]Abundance was generally influenced by area/location, where 1=most abundant variety.

[2]Preference was mainly based on taste, yield and ease to cook, where 1=most preferred variety.

Common beans yield and yield components assessment

Growth performance parameters including height, number of leaves and flowers per plant were assessed fortnightly until maturity. At the end of each physiological maturity period (approximately three months after planting) during the planting season, bean plants were manually harvested from each site from five randomly sampled plots measuring 2 x 2 metres. The number of pods was on all the harvested plants was recorded for each treatment replicate. A pod was recorded if it contained at least one mature seed. The pods were threshed traditionally using a stick and sun dried. Grain yield per treatment was estimated using a digital weighing balance at 13% moisture content using a moisture meter (Steinlite SL95, Atchison, Kansas, USA), and then extrapolated to yield per hectare.

Soil moisture measurement

Soil moisture was determined using an MPKit (ICT International, Australia), a portable soil moisture sensor used for rapid sampling of Volumetric Soil Water Content (VSW%). To allow routine measurement of soil moisture at the same location and depth over a period of time, a series of holes were augured to depths of 20 cm, 40 cm, 60 cm, 80 cm and 100 cm. A set of 50 mm PVC tubes (representing the five depths) were installed 1.5 m from the tree, under each experimental tree (4 Cordia and 4 Albizia trees), in the unshaded coffee and in the open field. The MP406 was then inserted into each PVC tube to the required depth of measurement and the corresponding soil moisture content displayed on the MPM160 meter was recorded. The readings were taken fortnightly and automatically saved and downloaded into a computer.

Data Analysis

Data on coffee and common beans yield from the two experimental sites were summarised as mean, maximum, minimum and further subjected to analysis of variance (ANOVA) to show the variations in yield components across the different management options. Coffee and common beans yield data collected over three planting seasons were in the two experimental sites were analysed. In addition, data were subjected to a single factor one-way analysis of variance to show differences in yield across the different treatment options. Lastly, data were subjected to Pearson correlation analysis to determine the relationship between yield components and management options.

Results

Baseline results

Unshaded coffee sites generally had the least organic matter content (Table 1). At baseline, both Cordia and Albizia sites had relatively the same organic matter content ranging from 1.8-2.8%. However, there was a relative increase in organic matter content following pruning of Cordia and Albizia, more predominantly under pruned Albizia trees, where organic matter above 4% was recorded.

Table 2. Organic matter content, soil texture range and textural class of the experimental sites

Experimental site	Organic matter		Soil texture ranges (%)			Soil textural class*
	Baseline	*End line*	*Sand*	*Clay*	*Silt*	
Open field (Albizia site)	2.3±0.5	2.4±0.1	45 - 46	30 - 31	23 - 25	Sandy clay
Open field (Cordia site)	2.3±0.4	2.4±0.3	59 - 60	18 - 19	22 - 23	Sandy loam
Unshaded Coffee (Albizia site)	1.8±0.3	2.1±0.1	33 - 35	45 - 48	19 - 20	Clay loam
Unshaded Coffee (Cordia site)	2.3±0.2	2.3±0.4	61 - 63	14 - 16	22 - 23	Sandy loam
Unpruned Albizia site (with coffee)	2.6±0.3	3.2±0.4	30 - 41	32 - 47	23 - 27	Clay loam
Pruned Albizia site (with coffee)	2.7±0.2	4.1±0.1	39 - 45	28 - 48	19 - 27	Clay loam
Unpruned Cordia site (with coffee)	2.8±0.1	2.8±0.4	61 - 64	12 - 20	19 - 24	Sandy loam
Pruned Cordia site (with coffee)	2.4±0.1	3.3±0.3	62 - 63	11 - 18	19 - 27	Sandy loam

* The USDA textural triangle.

In terms of soil texture, the Cordia site generally had a high composition of sand, exhibiting a sandy loam textural class (Table 2). However, unlike the open field in the Albizia site which had sandy clay soils, the rest of the Albizia sites had clay loam soil texture. Total phosphorus was highest in the Cordia site ranging between 32-46 ppm and as low as 5-9 ppm in the Albizia sites. Conversely, the Cordia site had the least potassium (k), magnesium (M) and sodium (Na). However, available phosphorus (Total P) and total nitrogen (N) have been reported to be below the optimum required level, while potassium (K) is optimally available in the Mt. Elgon region (UCDA, 2017). The highest base saturation (BS) was found in the Cordia site (28-52%).

Impact of pruning Cordia africana and Albizia coriaria trees on coffee yield

Results revealed that coffee yields were relatively higher from the Albizia site than the Cordia site (Figure 1). In terms of seasons, season 2 coffee yields were generally low across all sites and management options, with the highest yield obtained from unshaded coffee in the Albizia site. This was mainly because the second season (February-April) was a 'fly crop' season (where coffee yields were usually minimal) while the first season (August - October 2018) and third season (August-October 2019) were the main annual coffee harvesting seasons. In either site, the highest coffee yields were obtained in the third season from coffee grown under pruned Albizia (1418 kg/ha) and under pruned Cordia (1091 kg/ha). The lowest coffee yields were obtained from unshaded coffee in both sites across the three seasons.

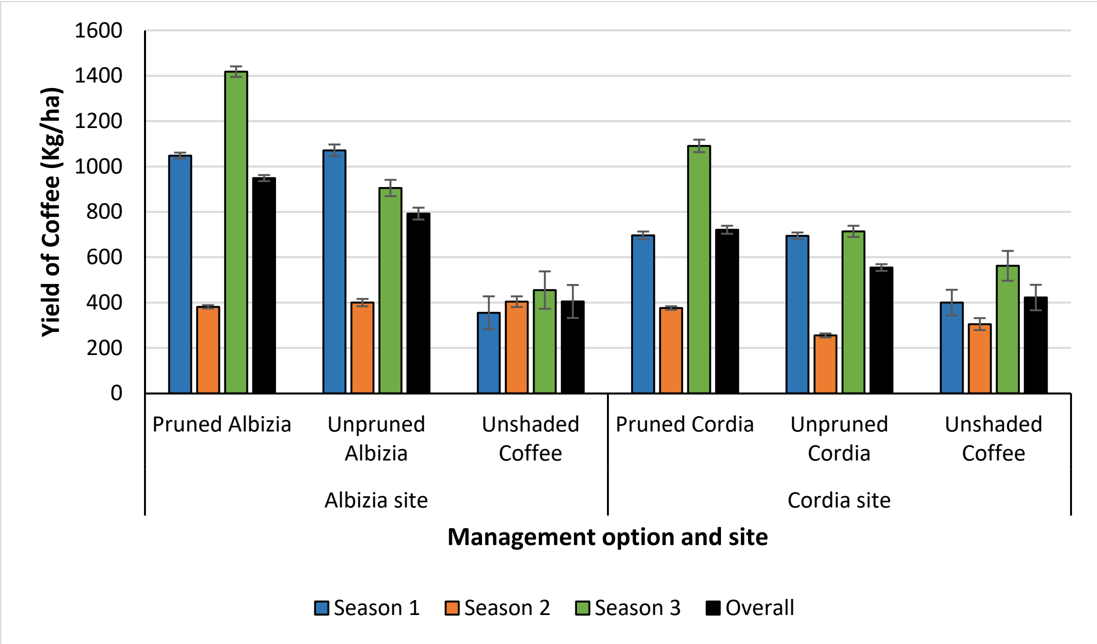

Figure 1. Average coffee yields

Overall, coffee under pruned Albizia gave the highest yield (949 kg/ha) of parchment coffee, followed by coffee under pruned Cordia (Figure 1). Unshaded coffee produced the lowest yield of 405 kg/ha and 422 kg/ha in the Albizia and Cordia site respectively. Although there was a 20 and 30% increase in coffee yield resulting from pruning Albizia and Cordia trees, there was no statistically significant difference in coffee yield across the tree management options.

Coffee yield components under different management options

Coffee growing at Cordia site had more stems per bush than coffee growing in the Albizia site (Table 3). Coffee growing under Albizia and Cordia trees (both pruned and unpruned) had the same number of stems per bush. Furthermore, unshaded coffee in both sites had the highest number of branches, with a maximum and minimum number of 368 and 44 branches recorded respectively. While there was no significant difference in the number of berry clusters per branch, the number of berries per cluster was significantly different across the management options ($p<0.05$). Coffee growing under pruned Albizia had the highest number of berries per cluster.

Table 3: Coffee tree yield components in the management options

Variables	Albizia site			Cordia site			Overall		
	Unpruned	*Pruned*	*Unshaded*	*Unpruned*	*Pruned*	*Unshaded*	*Max*	*Min*	*p.*
No. of stems per bush	1.3	1.3	2.8	2.6	2.6	4.9	7	1	0.000*
No. of branches per coffee tree	89.1	84.6	123.1	101.5	115.2	250.3	368	44	0.001*
No. of berry clusters per branch	9.3	9.2	10.3	7.9	8.7	10.1	13	1	0.208
No. of berries per cluster	8.4	9.6	8.2	7.0	6.7	8.9	18	0	0.005*
Coffee tree diameter (cm)[a]	4.5	4.5	4.7	3.7	3.7	4.2	4.9	3.2	0.000*
Coffee tree height (m)	2.4	2.4	2.1	2.6	2.6	2.2	2.8	1.9	0.001*
Age of coffee trees (years)	5	5	5	6	6	6	6	5	0.070

[a]Diameter measured at 30cm above ground; *Significant at the level of $P < 0.01$.

Table 3 also shows coffee stem diameters (measured at 30 cm above ground), heights and age. Stems of coffee trees at the Albizia site were bigger than those at the Cordia site while coffee plants at the latter site were shorter and younger. There were significant differences in coffee tree diameters and heights across the treatment options ($p<0.05$) and unshaded coffee plants had the biggest coffee diameters.

Correlation between management, coffee yield and yield components

There was a significant negative correlation between management and third season coffee yield as well as the overall yield in the Albizia and Cordia sites (Table 4). Management was positively correlated with number coffee branches in the Albizia site ($p<0.05$). However, there was a negative correlation between first season yields and the number of coffee stems per bush and the number of branches per coffee stem. On the other hand, there was a positive correlation between the number of berry clusters per branch and the number of berries per cluster in the Albizia site and negative correlation with the same in the Cordia site. There was a positive correlation between the number of berries per cluster and the first season's yield in the Albizia site ($p<0.05$).

Yield of common beans under different management options

There was a higher yield of common beans at the Albizia site than the Cordia site. The highest yield was obtained from the open field (842.3 kg/ha) in the second planting season (Figure 2). While the yield of common beans growing under unpruned Albizia and Cordia trees declined in the subsequent planting seasons, the yields from beans growing under pruned trees gradually increased from the first to the third planting season.

Table 4. Coffee Yield components, management option and yield

Coffee yield components		Albizia site	Cordia site
Management option	Season 1 yield	-0.852	-0.869
Management option	Season 2 yield	0.836	-0.584
Management option	Season 3 yield	-0.998*	-0.971*
Management option	Overall yield	-0.971*	-0.998*
Management option	No. of coffee stems/bush	0.708	0.642
Management option	No. of coffee branches	0.915	0.821
Management option	No. of berry clusters/ branch	-0.843	0.629
Management option	No. of berries/ cluster	-0.986*	0.922*
No. of coffee stems/bush	Season 1 yield	-0.973*	-0.937*
No. of coffee stems/bush	Season 2 yield	0.414	0.247
No. of coffee stems/bush	Season 3 yield	-0.681	-0.441
No. of coffee stems/bush	Overall yield	-0.855	-0.590
No. of coffee branches	Season 1 yield	-0.991*	-0.997*
No. of coffee branches	Season 2 yield	0.713	-0.160
No. of coffee branches	Season 3 yield	-0.899*	-0.662
No. of coffee branches	Overall yield	-0.984*	-0.781
No. of berry clusters/ branch	Season 1 yield	0.999*	-0.931*
No. of berry clusters/ branch	Season 2 yield	-0.599	0.264
No. of berry clusters/ branch	Season 3 yield	0.822	-0.425
No. of berry clusters/ branch	Overall yield	0.947*	-0.575
No. of berries/ cluster	Season 1 yield	0.927*	-0.993*
No. of berries/ cluster	Season 2 yield	-0.864	-0.224
No. of berries/ cluster	Season 3 yield	0.979*	-0.803
No. of berries/ cluster	Overall yield	0.997*	-0.894

*Significant (P<0.05).

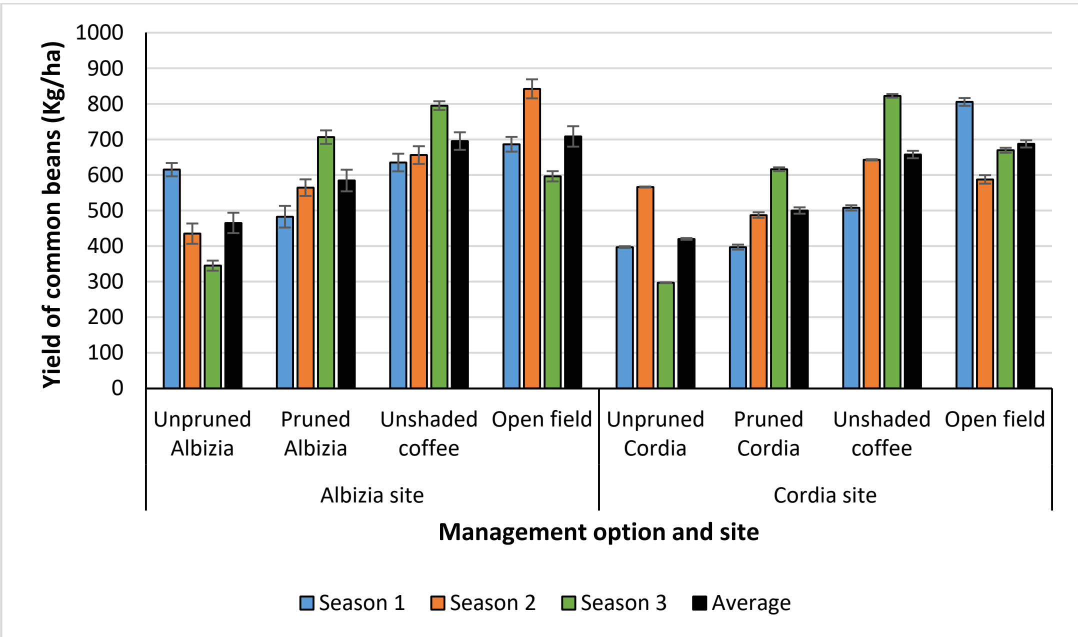

Figure 2. Common beans yield

The highest yield of common beans was obtained from the open fields in the Albizia (708.3 kg/ha) and Cordia (687.5 kg/ha) sites, followed by unshaded coffee (Figure 2). Lowest yields were obtained from beans planted under unpruned Cordia trees. Analysis of variance showed a statistically significant variation in yield of common beans harvested from the different management options. There was a 26% and 19% yield difference.

Common beans yield components under different management options

The tallest common bean plants were recorded under unpruned Albizia trees growing together with coffee trees and under unpruned Cordia growing together with coffee at 34.2 cm and 32.4 cm respectively (Table 5). However, there were no significant differences in height of common beans across the management options in the two experimental sites ($p<0.05$). Common beans planted in the open field had the highest number of flowers and pods per plant. The number of flowers and pods per plant were significantly different across the management options in the two experimental sites.

Table 5. Growth performance variable of common beans measured during the study

	Albizia site				Cordia site				Overall		p.
	Unpruned	Pruned	Unshaded	Open field	Unpruned	Pruned	Unshaded	Open field	Max	Min	
Height (cm)	34.2	31.3	26.3	26.0	32.4	31.5	29.4	25.7	38.5	12	0.939
No. of leaves per plant	6.3	6.8	6.0	7.0	7.0	6.8	7.5	7.7	10	4	0.225
No. of flowers per plant	6.5	7.3	8.6	12.0	6.8	6.3	5.8	9.3	20	3	0.003*
No. of pods per plant	5.9	6.7	6.5	10.0	6.0	6.3	5.5	8.1	20	4	0.001*

*Significant at the level of $P < 0.01$; Sites with trees also have coffee trees.

Correlation between management, common beans yield and yield components

Management option positively correlated with the overall yield of common beans in both experimental sites ($p<0.05$) (Table 6). However, the height of beans negatively correlated with management option and the overall yield in the two experimental sites. Apart from the positive correlation between number of flowers per plant and first season yield in the Cordia site, there was no significant correlation between other yield components and yield ($p>0.05$).

Table 6: Common beans yield components, management option and yield in the study sites

Common beans yield components		Albizia site	Cordia site
Management option	Season 1 yield	0.545	0.894
Management option	Season 2 yield	0.990*	0.441
Management option	Season 3 yield	0.558	0.774
Management option	Overall yield	0.957*	0.972*
Management option	Height of bean plant	-0.922*	-0.987*
Management option	No. of leaves/plant	-0.800	-0.544
Management option	No. of flowers/plant	0.905*	0.767
Management option	No. of pods/plant	0.840	0.627
Height of bean plant	Season 1 yield	-0.487	-0.932
Height of bean plant	Season 2 yield	-0.859	-0.329
Height of bean plant	Season 3 yield	-0.748	-0.685
Height of bean plant	Overall yield	-0.985*	-0.921*
No. of leaves/plant	Season 1 yield	-0.892	-0.787
No. of leaves/plant	Season 2 yield	-0.828	0.210
No. of leaves/plant	Season 3 yield	0.026	0.038
No. of leaves/plant	Overall yield	-0.630	-0.340
No. of flowers/plant	Season 1 yield	0.802	0.935
No. of flowers/plant	Season 2 yield	0.868	0.051
No. of flowers/plant	Season 3 yield	0.406	0.221
No. of flowers/plant	Overall yield	0.874	0.607
No. of pods/plant	Season 1 yield	0.720	0.848
No. of pods/plant	Season 2 yield	0.894	-0.118
No. of pods/plant	Season 3 yield	0.028	0.049
No. of pods/plant	Overall yield	0.649	0.436

**Significant correlations* ($P<0.05$).

Discussion

Yield performance of coffee under different management options

Coffee is an important cash crop in the smallholder farming rural livelihoods and national economies in the East African region (UCDA, 2018; Wang et al., 2015). Integration of shade trees for realizing sustainable coffee yield (DaMatta et al., 2007; Gram et al., 2017; Jezeer et al., 2018; UCDA, 2018), improved coffee quality (Muschler, 2001) and increased carbon storage (Jezeer & Verweij, 2015; Nair et al., 2009) have been widely documented. In this study, unshaded coffee produced the lowest overall coffee yield at 405 kg/ha compared to coffee under either pruned or unpruned Cordia and Albizia trees. The low yields may be attributed to soil nutrient deficiencies, high disease incidences and temperature extremes associated with exposure of coffee to direct sunshine (Ayalew, 2018). Shade trees also alleviate nutrient deficiencies in soils under coffee through decomposition of leaf litter (Alemu, 2015) and control incidences and severity of Coffee Leaf Rust disease in arabica coffee (Beer et al., 1998; UCDA, 2018). Furthermore, shade trees buffer high and low temperature extremes by as much as 5^{0} C (Beer et al., 1998; Wang et al., 2015). Production of arabica coffee can reduce temperatures higher than the optimum range (18–23 ^{o} C), while development and ripening of berry pulp are accelerated (Vaast et al., 2006), often leading to incomplete bean filling (Davis et al., 2012).

Integration of trees as buffer in coffee gardens ameliorates temperature and precipitation that enhance the sustainability and resilience of coffee-agroforestry system (Souza et al., 2012).

A related study carried out in the Mt. Elgon region of Uganda reported that shade trees enhance coffee yields at low altitudes, with no differences in yields in the coffee-agroforestry system at mid and high altitudes (Rahn et al., 2018). This finding resonates with those reported in a study conducted at low altitude range (<1400 m.a.s.l). Another study in the region reported 11% reduction in coffee yield obtained under Cordia shading (UCDA, 2017). Similarly, coffee-shade tree systems give the lowest yield compared with coffee-banana and coffee-open systems in in the Mt. Elgon region (Sarmiento-Soler et al., 2020). The low coffee yields from coffee-shade tree systems in the above studies may be attributed to poor/ lack of shade management of the trees integrated with coffee. Trees integrated with coffee compete for growth resources such as soil water, nutrients and sun light (Beer et al., 1998), thus requiring deliberate management to optimise shade levels. This study revealed 30% yield difference between sites with pruned and unpruned Cordia. Coffee under pruned Cordia trees produced 721 kg/ha, above the average 600 kg/ha yield reported by the UCDA (2017). Therefore, deliberate shade management may have contributed to the yield increase at the sites where coffee was integrated with pruned Cordia. Pruning could have reduced competition for growth resources and regulated incoming solar radiation.

Coffee under pruned Albizia trees gave the highest yield (949 kg/ha) of parchment coffee although it is still below the potential yield of 1701 kg/ha (Wang et al., 2015). The relatively high coffee yield from coffee integrated with pruned shade trees can be due to controlled competition for growth resources and addition of organic matter from decomposed leaf litter and branches cut during pruning. A related study in Hawaii reported that tree pruning mulch increased soil carbon and nitrogen in a shaded agro-ecosystem (Youkhana & Idol, 2009). The baseline and end line soil analyses revealed an increase in organic matter following pruning and less N in the unshaded coffee gardens. While studies have recommended unshaded coffee plantations where agrochemical inputs, mechanization, irrigation and modern, high-yielding varieties are available (Beer et al., 1998; Damatta, 2004), the costs are unaffordable for majority of smallholder farmers in the Mt. Elgon region. The small land holdings and the mountainous landscape also disfavour mechanization in the region.

Coffee yield components under different management options

Unshaded coffee had more stems per bush than shaded coffee under Albizia and Cordia trees (pruned and unpruned). A study in the Mt. Elgon region found that more than four coffee stems per bush reduces coffee yields (Sarmiento-Soler et al., 2020). This finding is in agreement with the results of this study indicating that the lowest yields were obtained from unshaded coffee which had the highest number of stems per bush. There was a significant negative correlation between number of stems per bush and season 1 yields. Unlike season 2 yields, number of stems per bush negatively correlated with season 3 and the overall yields. Studies have reported that more stems per bush imply more leaves which increase self-shading and negatively affect coffee yield (Njoroge et al., 1992; Sarmiento-Soler et al., 2020). In this regard, there is a potential trade-off between fruit load per branch and number of stems per bush. It is, therefore, likely that coffee yield can be improved by reducing the number of stems per bush (Dufour et al., 2019).

The results also show that unshaded coffee had the highest number of branches that were shortest in both experimental sites. Our results correspond with the findings of a related study in Brazil where fewer coffee branches were observed in high shading levels (Baliza et al., 2012).

Coffee plants grown under open field conditions have also been reported to score the minimum plant height (Bote et al., 2018). The tendency of increasing height by shaded coffee is to exploit light penetrating from tree canopies. Therefore, increase in coffee tree height under shade was possibly due to adaptation mechanism of the coffee plant for maximizing light interception.

It was found that unshaded coffee had the highest number of berry clusters compared to coffee integrated with Albizia and Cordia trees. However, this did not translate into higher yields as the lowest yields were obtained from unshaded coffee. This may be attributed to faster maturation of coffee berries resulting in poor bean filling and smaller coffee bean size from unshaded coffee (Bote & Struik, 2011; Muschler, 2001). Dense shading reduces flower bud formation and whole tree carbon assimilation (Damatta, 2004) which result in reduced yield as heavily shaded productive branches die (Kufa & Burkhardt, 2013). Dense shading also reduces coffee fruit load due to changes in coffee morphology such as longer internodes, fewer nodes per branch (where berry clusters are formed) and few flower buds at existing nodes (DaMatta et al., 2007). Considering that the number of nodes is a key component of coffee production, it is not surprising that coffee yields decline with increased shading. Reduction of shade by 50% in the current study may have contributed to the increase in number of berry clusters and overall yield from coffee integrated with pruned Albizia trees. It is important for farmers to deliberately prune agroforestry shade trees in coffee plantations to minimize the negative effects of dense shading.

Yield assessment of common beans planted below coffee integrated with trees

This study revealed that the overall common beans yields were highest in open fields. At the same time, tree pruning enhanced the yield of common beans planted under Cordia and Albizia trees with a 19% and 26% yield increase respectively. The increase in yield following pruning may be attributed to increased organic matter generated from the pruning residues. Shade trees have been reported to produce up to 14 Mg ha^{-1} yr^{-1} of litter fall and pruning residues (Beer et al., 1998), which is a good source of organic matter and nitrogen. The yields obtained from common beans planted under pruned Cordia (500 kg/ha) and Albizia (585 kg/ha) trees are comparable to those obtained from a study in Uganda where the same variety (Kanyebwa) was planted in an open field with 10t/ha manure applied at planting, and yielded 571.4 Kg/ha (Sebuwufu et al., 2015). The contribution of aboveground litter to the formation of mineral-associated organic matter has been reported to be more significant within the top 20 cm of soil (Liebmann et al., 2020), where the common beans rooting zone is located (Beebe et al., 2011). In another related study, canopy pruning of the shea nut tree (*Vitellaria paradoxa*) in West Africa was reported to reduce belowground competition through reduction of root density in the crop rooting zone, which consequently increased crop production (Bayala et al., 2004).

Beans that were planted under unpruned Cordia gave the least yield of 420 kg/ha. The low yield may have resulted from belowground competition consistently outweighing the benefits of shade (Ong & Swallow, 2003) and competition for light. A related study in the agroforestry parklands of Burkina Faso reported that competition for light limited sorghum growth more than competition from other resources in the studied system (Bazié. et al., 2012), suggesting that farmers need to deliberately manage tree shade in their farming systems. While tree canopy development can also be influenced by water and nutrient availability (Pinkard & Beadle, 2000), it is equally important to correctly choose the timing and intensity of canopy pruning (García-Barrios & Ong, 2004). It is similarly important that farmers select the right annual crops, tree species and densities to optimize trade-offs between positive and negative tree effects.

Common beans yield components under different management options

The tallest common bean plants were recorded under unpruned Albizia trees integrated with coffee under unpruned Cordia with coffee at 34.2 cm and 32.4 cm respectively (see Table 5). NABE 15 common bean is a short variety with an average height of 23 cm in a related study conducted in central Uganda (Goettsch et al., 2016). This corresponds with the average height recorded in this study from beans planted in the open fields, with height ranging between 25 and 26 cm. Therefore, the increase in height of bean plants under unpruned trees was an adaptation mechanism for maximizing light interception.

The pruning response of Cordia and Albizia trees also influenced the height of common beans in this study. While Cordia generated multiple sprouts around the cut branches following pruning, the wounds created on Albizia trees healed without any sprouts. Therefore, the multiple sprouts in Cordia created an additional shading effect to the common beans growing under the pruned Cordia trees. The impact of the shading effect of the sprouts is evident in the small common bean height difference between beans in the pruned and unpruned Cordia (0.9 cm) when compared with the height difference between beans under pruned and unpruned Albizia trees (2.9 cm) (see Table 5). Therefore, it would require the farmer to consistently remove the sprouts from the pruned Cordia trees to minimize shading effect on the common beans.

Common beans growing in the open field had the highest number of leaves, flowers and pods per plant in both sites. Development of more leaves tend to improve photosynthetic efficiency which nourishes flowering and pod development (Kebede et al., 2015). The number of pods per plant maintained to the final harvest also depends on management practices, such as weeding (Alfonso et al., 2013) and management of shade to regulate irradiance. In Ethiopia, decline in number of pods per plant at low irradiance to a source limited the supply of sufficient photosynthate for every developing pod (Worku et al., 2004). However, common beans can overcome this shortfall in radiation by increasing leaf area, thereby limiting seed yield loss under shade stress via increasing grain filling duration and grain weight (Hadi et al., 2006). While this study did not look into aspects such leaf area and grain filling duration, the ability of the bean plants under shade to compensate reduction in radiation through grain weight needs to be investigated further to deepen understanding of crop productivity under shaded coffee-agroforestry systems. It also highlights the importance of agroforestry tree management by canopy pruning as an important on-farm management practice that helps to maintain an optimal shade.

Conclusion

The study demonstrated that tree canopy pruning has the potential to minimize the competitive effects of Cordia and Albizia trees on coffee and common beans, while influencing the relative growth performance and productivity of agricultural crops. There was a gradual increase in yield from beans planted under pruned Cordia and Albizia trees through the three planting seasons during the study. While pruning generally increased the yield of coffee, it is still below the potential yield of 1701 kg/ha expected from such farming systems, an indication that either the impacts would be observed in the longer term or due to the presence of other coffee yield limiting factors that need to be explored. The study however observed that, unlike Albizia, the multiple sprouts from the pruned sections of Cordia compromise the purpose of pruning, as they increase the shading effect in pruned Cordia trees, requiring the farmer to continue removing the sprouts. Understanding the different coffee and common beans yield components and their interactions provided useful information on management interventions that can potentially improve coffee and common beans yields. This study has demonstrated that deliberately phased agroforestry tree canopy pruning is an important management decision that can potentially reduce competition for growth resources and prolong the period of intercropping in smallholder farming systems.

Conflict of Interest

The authors declare that they have no conflicts of interest in relation to this article.

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