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Agronomic and economic (dis)advantages of intercropping young coffee and banana in central Burundi

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Abstract

Coffee (*Coffea arabica* L.) is an important crop for Burundian economy, and banana (*Musa acuminata*) residues are used for coffee mulching. To evaluate the option of producing banana residues in coffee plots and to assess interactions between crops, multi-location field trials were set up at Gitega and Kayanza sites from January 2009 to July 2012. Two density levels for coffee (1333 and 2667 trees ha^{-1}) and banana (800 and 1600 plants ha^{-1}) were combined in full factorial design complemented with monocropped plots for each density in Randomized Complete Block Design with three replications per site. Banana and coffee yields, land equivalent ratio and competitive ratio, growth characteristics, effect of shading on nutrient content in leaves, and economic benefits were determined. Banana had a significant ($p \leqslant 0.05$) negative effect on coffee yield and growth. With high density of coffee, banana reduced coffee yield by 35%–40% at low density and 67%–84% at high density. Land equivalent ratio values were always >1 in both sites, showing that intercropping is beneficial. In high density of coffee, net benefit increase was 58% at Gitega and 201% at Kayanza when intercropped with high density of banana compared to monoculture. Growing bananas with young coffee was financially profitable. However, banana density and suckers need to be managed to reduce their negative impact on coffee performance.

Plain Language Summary

Coffee is an important source of income for smallholder farmers in Burundi, and banana residues are commonly used to mulch coffee fields, which can reduce soil fertility in banana plots. To promote a more sustainable production system, field trials were conducted at two sites in major coffee-growing areas of Burundi, focusing on the intercropping of young coffee and young banana plants. Plots with different planting densities were established under both monocropping and intercropping systems.

Abbreviations: CR, competitive ratio; HDB, high density banana; HDC, high density coffee; LDB, low density banana; LDC, low density coffee; LER, land equivalent ratio; MAI, monetary advantage index; NB, zero banana; RCBD, randomized complete block design.

Banana reduced coffee growth and yield, whereas coffee had no effect on banana performance. However, growing the two crops together produced higher overall benefits than growing them separately. Intercropping young coffee and banana plants is therefore advantageous, but maintaining coffee productivity requires proper management of banana density, suckers, and leaves to reduce competition.

1 | INTRODUCTION

Intercropping a cash crop such as coffee (*Coffea arabica* L.) with a shade food crop such as banana (*Musa acuminata*) can be an appropriate solution for the sustainability of coffee production under Burundian conditions, where recommendations encourage coffee monoculture (Gaie & Flémal, 1988). In general, intercropping has many advantages, such as land use efficiency (Raza et al., 2023), increased profitability (Alcon et al., 2020), rational use of water and nutrients (Alcon et al., 2020; Muñoz-Villers et al., 2020; Saidia et al., 2019), and optimal nutrient uptake (Saidia et al., 2019). Shade from trees and food crops can mitigate drought stress (Gomes et al., 2020) by reducing evaporation (Beer, 1987; Lin, 2010) and stabilizing temperature (Siles et al., 2010) by reducing direct solar radiation during the day (Lin, 2010) and heat loss during night (Damatta & Ramalho, 2006). Shade also reduces wind speed (Pezzopane et al., 2007).

On the other hand, shade affects the growth characteristics of coffee by stimulating coffee height and increasing leaf size, while girth, number of primary branches, number of leaves, and flower buds are lower in shade systems (Campanha et al., 2004; Rigal et al., 2020). Research has shown that coffee yield was lower in an agroforestry coffee system than in an unshaded system (Campanha et al., 2004; Jaramillo-Botero et al., 2010). Although shade can have a negative effect on coffee yield, shade stabilizes coffee production by reducing biennial yield variability (Jaramillo-Botero et al., 2010) and improves coffee quality (Rigal et al., 2020). The improvement of coffee quality by shade has been demonstrated in several studies (Bosselmann et al., 2009; DaMatta et al., 2008; Siles et al., 2010) by increasing cherries and green beans size as well as enhanced organoleptic quality (DaMatta et al., 2008), especially at high altitudes (Leonel & Philippe, 2006).

Some species are more suitable for coffee shading than others (Schnabel et al., 2018). The main desirable characteristics are (i) species with deep root systems to limit competition with coffee (DaMatta et al., 2008) and strong roots to prevent trees from falling; (ii) species without suckers and with good apical growth; (iii) species with nitrogen fixation; and (iv) species with relatively few branches and stems to facilitate management (Beer, 1987). These characteristics can limit competition for nutrients (Ghosh et al., 2009), water (Mugi-Ngenga et al., 2023), and light (Feng et al., 2021).

In some cases, farmers' interests may not be in these characteristics for various reasons, mainly food security (Desiere et al., 2015) and income generation (Raseduzzaman, 2016). For example, banana–coffee systems are often observed in the African Great Lakes regions (Hemp, 2006; Nzeyimana et al., 2013; van Asten et al., 2011). although, both banana and coffee have high N and K requirements (Lahav, 1995; Padovan et al., 2015) and superficial root systems (Sebuwufu et al., 2004; Wrigley, 1988), banana produces suckers. Under these conditions, banana plants become more competitive and negatively affect the growth and yield of coffee.

The intercropping of banana and coffee is supported by the insufficiency of mulch for coffee plots and the widespread use of banana residues in coffee mulching, leading to a reduction of soil fertility in banana plots (Cochet, 2001). Recent studies on banana–coffee intercropping have demonstrated that (i) coffee and banana yields, as well as farm income, are higher under intercropping than under monocropping in coffee-growing regions of Uganda (van Asten et al., 2011); (ii) banana–coffee intercropping systems are more economically profitable than monoculture systems (Leonida, 2014); and (iii) coffee growth and yield components are influenced by the proximity of banana plants in coffee and banana adjacent plots (Nibasumba et al., 2021).

Despite these advances, limited information is available on the interactions and competitive processes between coffee and banana in intercropping systems, particularly with respect to the effects of banana on coffee agronomic performance, including yield, growth parameters, and biomass recycling. Furthermore, most previous studies have focused on already established plantations (Leonida, 2014; Nibasumba et al., 2021; van Asten et al., 2011), providing little insight into crop interactions and competition during the early years of system establishment.

We hypothesize that banana–coffee intercropping can sustain the productivity of both crops through complementary interactions while remaining economically profitable, despite potential competition for resources during the early years of plantation. The objectives of this study are to determine (i) the interactions between the two crops; (ii) the profitability of the banana and coffee intercropping system; and (iii) the possible competition and complementarities between the two crops, in order to propose an agronomic management of coffee and banana intercropping that will allow the sustainability of the productivity of both coffee and banana.

Core Ideas

- Low yield of coffee was observed in coffee plots with high density of banana.
- Banana reduced coffee growth characteristics, increased N and Mg in coffee leaves, and decreased K.
- Banana was dominant with a competitive ratio >1.
- Banana-coffee intercropped plots had higher net benefit and monetary advantage index.
- Management of banana density and shade, with an appropriate nutrient supply, sustains coffee yield.

2 | METHODOLOGY

2.1 | Site description

The study was conducted during three years at the Gitega and Kayanza research stations in Burundi. Gitega is located at 1651 m above sea level, at +29.93323° of longitude and −03.36162° of latitude. Kayanza is located at an altitude of 1812 m, at a longitude of +29.71292° and a latitude of −02.90188°. Based on the World Reference Base for Soil Resources classification, the soils of Gitega are Acrisols, while those of Kayanza are Nitisols. Furthermore, in Gitega, the site consisted of newly opened land, while in Kayanza, the site was occupied by old coffee trees. The difference in soil fertility was due to the soil type and previous field use. Average soil characteristics from laboratory analysis performed at the beginning of the study are mentioned in Table 1. In each plot, two composite soil samples were collected at 0- to 30-cm depth before trials. Soil analyses were carried out at the Kawanda National Agricultural Research Laboratory in Uganda. Soil organic carbon was determined using the Walkley–Black method. Total nitrogen was extracted by Kjeldahl digestion and measured by spectrophotometric method. Extractables of P, Ca, Mg, and K were obtained using Mehlich-3 solution (Mehlich, 1984). P was determined by colorimetry, while K, Ca, and Mg were determined by atomic absorption spectrometry.

Average annual rainfall during the data collection period was 1277.3 mm and 1524.2 mm in Gitega and Kayanza, respectively. The mean annual temperature was 20.1°C in Gitega and 19.2°C in Kayanza. Monthly averages of rainfall and temperature from March 2009 to April 2012 are shown in Figure 1.

2.2 | Trials design and field management

The trials were established in January 2009. The elementary plot had 15 m × 10 m. The coffee lines were always between two banana lines when coffee was intercropped with banana. Each block consisted of eight treatments, as detailed in Table 2.

The experiment was laid out in a Randomized Complete Block Design with three replications per site. High densities referred to the density proposed by Gaie and Flémal (1988) in Burundi for coffee and by Odeke et al. (1999) in the African Great Lakes Region for banana in a monoculture system. Low densities were half of high densities.

Planting pits of 60 × 60 × 60 cm were prepared for coffee, while pits of 40 × 40 × 40 cm were prepared for banana. Before planting, 10 and 5 kg of well-decomposed cattle manure were applied per pit of banana and of coffee, respectively. After plant establishment, 100 g of urea (46-0-0) and 50 g of diammonium phosphate (DAP) (18-46-0) were applied by hands to each banana and coffee plant. Any mineral fertilizer or manure was applied after. Annual external top mulching of 10 Mg ha^{-1} of fresh matter was applied in 2009, 2010, 2011, and 2012 using *Themeda sp* at Kayanza *and Eragrostis sp* at Gitega. All mulches were thoroughly mixed to form a composite, which was applied uniformly to all plots at each site. Hand weeding was carried out whenever necessary.

The banana variety used was *Igitsiri*, an East Africa highland banana (AAA-EAHB), and the coffee variety was *Jackson 2/1256*, an Arabica (*Coffea arabica* L.) variety widely grown in Burundi. In June 2009, the bending of coffee plants was carried out, allowing the emergence of multiple stems. In November 2009, three more vigorous stems were selected on each coffee plant (Gaie & Flémal, 1988).

For bananas, only three suckers were maintained. Unselected emergent suckers, dead leaves, and residues obtained after the banana harvest were weighed and distributed over the entire plot of origin as complementary mulch. For coffee, the Antestia bug was controlled, according to the recommendations used in Burundi, with lambda-cyhalothrin application carried out in November 2011 and imidacloprid in February 2012 (Gaie & Flémal, 1988). For bananas, any disease or pest treatment was applied.

2.3 | Coffee and banana growth parameters and yields

Growth parameter measurements for coffee included plant height, girth at 15 cm above ground, number of pairs of pri-

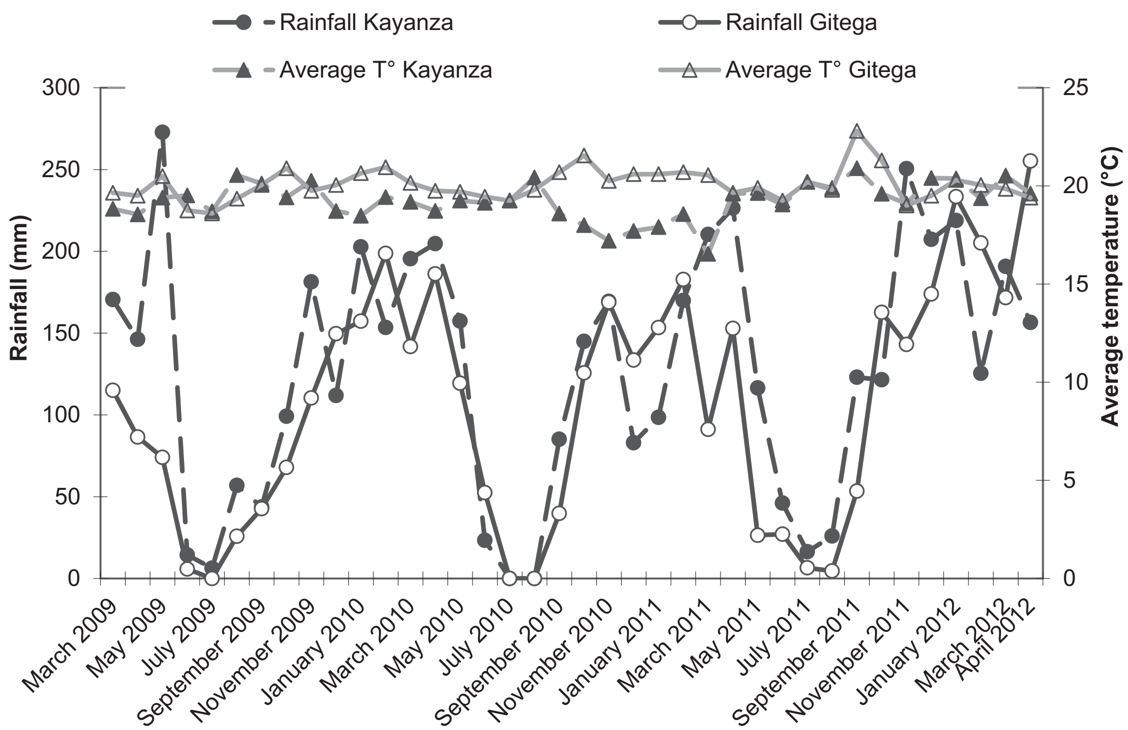

FIGURE 1 Average monthly rainfall and average monthly temperature (T°) in Gitega and Kayanza from March 2009 to April 2012.

mary branches, and canopy radius. Coffee growth data were collected in November 2009, March 2010, June 2010, October 2010, January 2011, June 2011, and November 2011. Canopy radius for coffee was first recorded in June 2010 by measuring the longest primary branch. Measurements were taken on 18 and eight coffee trees in high- and low-density plots, respectively. Bordering plants were excluded from all measurements, and data were collected from all remaining plants.

Banana yield was assessed over two production cycles, from December 2010 to March 2012, by progressively recording the weight of harvested bunches per plot, that is, 15 plants

TABLE 1 Soils characteristics of experimental sites at the beginning of the study at 0–30 cm deep.

Sites	SOC (%)	N (%)	P (ppm)	K (cmolc kg^{-1})	Ca (cmolc kg^{-1})	Mg (cmolc kg^{-1})
Gitega	2.9	0.2	1.2	0.4	0.2	0.1
Kayanza	3.6	0.3	21.8	1.1	2.3	0.6

Abbreviation: SOC, soil organic carbon.

TABLE 2 Treatment description for each block: Spacing between coffee and banana plants, as well as the number of coffee and banana plants per hectare.

No.	Treatments	Spacing of coffee plants	Spacing of banana plants	Number of coffee plants ha^{-1}	Number of banana plants ha^{-1}
1	High density coffee (HDC)	2.5 m × 1.5 m	–	2 667	–
2	Low density coffee (LDC)	2.5 m × 3.0 m	–	1 333	–
3	High density banana (HDB)	–	2.5 m × 2.5 m	–	1 600
4	Low density banana (LDB)	–	2.5 m × 5.0 m	–	800
5	HDC-HDB	2.5 m × 1.5 m	2.5 m × 2.5 m	2 667	1 600
6	HDC-LDB	2.5 m × 1.5 m	2.5 m × 5.0 m	2 667	800
7	LDC-HDB	2.5 m × 3.0 m	2.5 m × 2.5 m	1 333	1 600
8	LDC-LDB	2.5 m × 3.0 m	2.5 m × 5.0 m	1 333	800

for high density of banana (HDB) and six plants for low density of banana (LDB) plots. The first coffee harvest occurred in 2012, between March and July, with the weight of fresh cherries per plot recorded. Additionally, the weight of 100 fresh cherries was determined by harvesting mature cherries from five randomly selected plants, from which 300 cherries were harvested and weighed in April 2012.

2.4 | Competitions between coffee and banana

The land equivalent ratio (LER) was calculated using Formula 1 (Willey, 1985). This method has been widely used by several authors to evaluate intercropping performance for tropical intercrops (Perfecto & Vandermeer, 2008), for maize–legume systems (Li et al., 2003), for cereal–legume mixtures (Bedoussac et al., 2015), and in soybean and maize systems (Raza et al., 2020) across diverse ecosystems.

$$\mathrm{LER} = \frac{Yc_{\mathrm{int}}}{Yc_{\mathrm{mon}} \frac{Yb_{\mathrm{int}}}{Yb_{\mathrm{mon}}}} = \mathrm{LER}_{\mathrm{coffee}} + \mathrm{LER}_{\mathrm{banana}} \quad (1)$$

With Yc_{int} is the coffee yield in intercropping with banana (Mg ha^{-1}); Yc_{mon} is the coffee yield in monocropping (Mg ha^{-1}); Yb_{int} is the banana yield in intercropping with coffee (Mg ha^{-1}); and Yb_{mon} is the banana yield in monocropping (Mg ha^{-1}). The intercropping is advantageous when LER > 1.

The competitive ratio (CR) was calculated using Formula 2 (Willey, 1985).

$$\text{Competitive ratio}_{\mathrm{coffee}} = \frac{\mathrm{LER}_{\mathrm{Coffee}}}{\mathrm{LER}_{\mathrm{Banana}}} \times \frac{\mathrm{Pb}_{\mathrm{int}}}{\mathrm{Pc}_{\mathrm{int}}};$$

$$\mathrm{CR}_{\mathrm{banana}} = \frac{\mathrm{LE}_{\mathrm{Banana}}}{\mathrm{LER}_{\mathrm{Coffee}}} \times \frac{\mathrm{Pc}_{\mathrm{int}}}{\mathrm{Pb}_{\mathrm{int}}} \quad (2)$$

If $\mathrm{CR}_{\mathrm{coffee}} > 1$, coffee is more competitive than banana; if $\mathrm{CR}_{\mathrm{coffee}} < 1$, coffee is less competitive than banana.

Yields used were the total yields obtained during trials duration (one cycle of coffee production and two cycles of banana production).

2.5 | Determination of shade from banana

A hemispheric camera was used to determine the shade provided by banana. This is a widely used method for measuring shade (Jonas et al., 2020). Images were taken at the top of each coffee tree and then cleaned using ImageJ software to retain only the shade above the coffee tree (Schneider et al., 2012). Images were taken along the east-west direction on the same coffee plants used for the assessment of yield and growth parameters. Shade percentage was quantified using ImageJ software by converting the images into black-and-white binary format, where black pixels represented shade percentage (Figure 2).

Measurements taken above each coffee plant within each plot were then averaged to calculate the mean shade percentage per plot.

2.6 | Coffee and banana leaf analysis

Banana leaves were sampled at the flowering stage using the International Reference Sampling Method proposed by Martin-Prével et al. (1969). Coffee leaf sampling was carried out in October 2011. Coffee leaves were sampled at the flowering stage (Wrigley, 1988). Analysis of coffee and banana leaves was carried out at Kawanda National Agricultural Research Laboratory in Uganda. The elements analyzed were N, P, K, Ca, and Mg. The leaves were dried and crushed. The product obtained was digested in a solution of sulfuric and selenic acid. N and P were determined by colorimetry, and K, Ca, and Mg by atomic absorption spectrometer.

2.7 | Banana biomass recycling measurement

Banana residues, consisting of dead leaves, removed suckers, and pseudo-stems after harvest, were measured progressively as they were produced before being spread on the original plot. Moisture content was determined in the laboratory by oven-drying at 105˚C for 96 h, and dry matter (DM) per plot was calculated and expressed per hectare.

2.8 | Economic benefit

Income from coffee and bananas and related expenses were calculated. Selling prices, labor, and input costs were obtained from existing price information systems in Burundi. In 2009 (fertilizer application period), the selling price for coffee was \$0.35 and \$0.20 kg^{-1} for banana. The price of mulch was \$0.02 kg^{-1}, \$1.15 kg^{-1} for urea and \$1.64 kg^{-1} for DAP (Ministère des Finances et de la Planification du Développement Economique & Ministère de l'Agriculture et de l'Elevage, 2012; FEWSNet, 2012). The price of manure was \$16.4 Mg^{-1} including transport and the average labor cost was \$1.2 day^{-1} during the experimental period. (Ministère des Finances et de la Planification du Développement Economique & Ministère de l'Agriculture et de l'Elevage, 2012). Labor requirements were from literature: Gaie and Flémal (1988) for coffee and Bagamba et al. (1998) for banana.

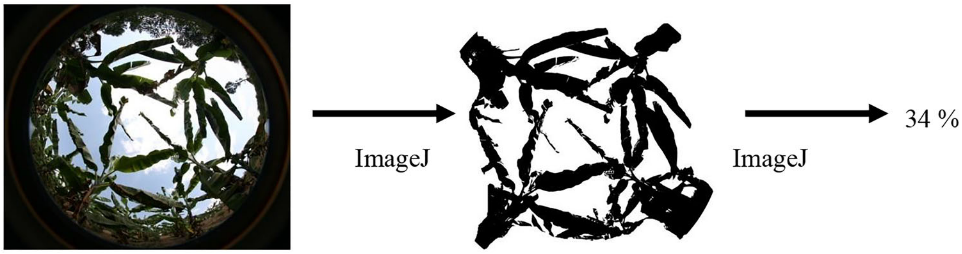

FIGURE 2 Percentage of shade obtained using a hemispheric camera and ImageJ software.

Net benefit of each treatment was calculated using Formula 3.

$$\text{Net benefit} = \text{Global income} - \text{all cost} \quad (3)$$

To determine the economic advantage of intercropping, monetary advantage index (MAI) has been used and was calculated as follows (Formula 4):

$$\text{MAI} = \frac{(\text{Value of combined intercrops}) \times \left(\text{LER}^{-1}\right)}{\text{LER}} \quad (4)$$

Most profitable intercropping treatment is the one with higher MAI (Mahapatra, 2010).

2.9 | Statistical analyses

First, a one-way analysis of variance (ANOVA I) was performed to test differences between sites. When significant differences were detected, the two sites were analyzed separately. Significant differences between sites were observed for all variables analyzed. Subsequently, a two-way analysis of variance (ANOVA II) was conducted at each site, with banana density and coffee tree density as the two factors. The experimental design was fully crossed (coffee tree density × banana density), allowing the assessment of the main effects of coffee density, banana density, and their interaction. When the interaction was significant, the means of all treatments were presented; otherwise, only the means of the significant main factors were reported. Principal component analysis (PCA) was performed separately for banana- and coffee-related factors at each site. Data analyses and mean separation using Tukey's test were performed in R (version 4.3.2). The significance level was set at $p \leq 0.05$.

3 | RESULTS

3.1 | PCA for banana and coffee factors

A cumulative variance of 61.1% was explained by the first two principal components (PC1 and PC2) of the PCA conducted on 15 variables related to coffee growth characteristics and coffee leaf nutrient contents at Gitega (Figure 3a). The first principal component (PC1) accounted for 44.7% of the total variance, while the second principal component (PC2) explained 15.4%. The variables leaf phosphorus (Leaf P), weight of 100 fresh coffee cherries, percentage of shade, banana density, banana yield, leaf nitrogen (Leaf N), leaf calcium, and leaf magnesium (Leaf Mg) contributed strongly and consistently to PC1 and showed significant positive correlations with one another. Particularly strong correlations were observed between percentage of shade, banana density, and banana yield, as well as between Leaf N and Leaf Mg.

At Kayanza, the PCA explained a variation 68.2% based on the relationship of parameters analysis across the first two axe, respectively, a variation of 55.1% and 13.1% in first PC and second (Figure 3b). The 15 variables related to growth parameters, yield components, and nutritional contents of the leaves were divided into two main groups. The variables on the right (up and down) of the PCA comprised the first subgroup, while the variables on the left (up) of the PCA comprised the second subcle while in set. A significant negative collinearity between the variables was found in the two subsets.

3.2 | Coffee and banana yield

Banana yield (Mg ha^{-1}) per cycle (when all mother plants are harvested) and bunch weight were not significantly affected by coffee density. Banana yield increased with its density, while bunch weight decreased significantly with density (Table 3). Banana yield during the two production cycles and bunch weight were higher at Kayanza. At Gitega, banana yield decreased by 14% at the second cycle compared to the first cycle, while in Kayanza, banana yield increased by 23% at the second cycle compared to the first production cycle.

In the two sites, there was significant difference between cherry yield among treatments. Cherry yield per ha and per tree was lower in coffee plots intercropped with HDB and higher in zero banana (NB) coffee plots (Table 4). At Gitega, reduction of coffee yield in low density coffee (LDC) plots was 53% when banana is intercropping at LDB and 75%

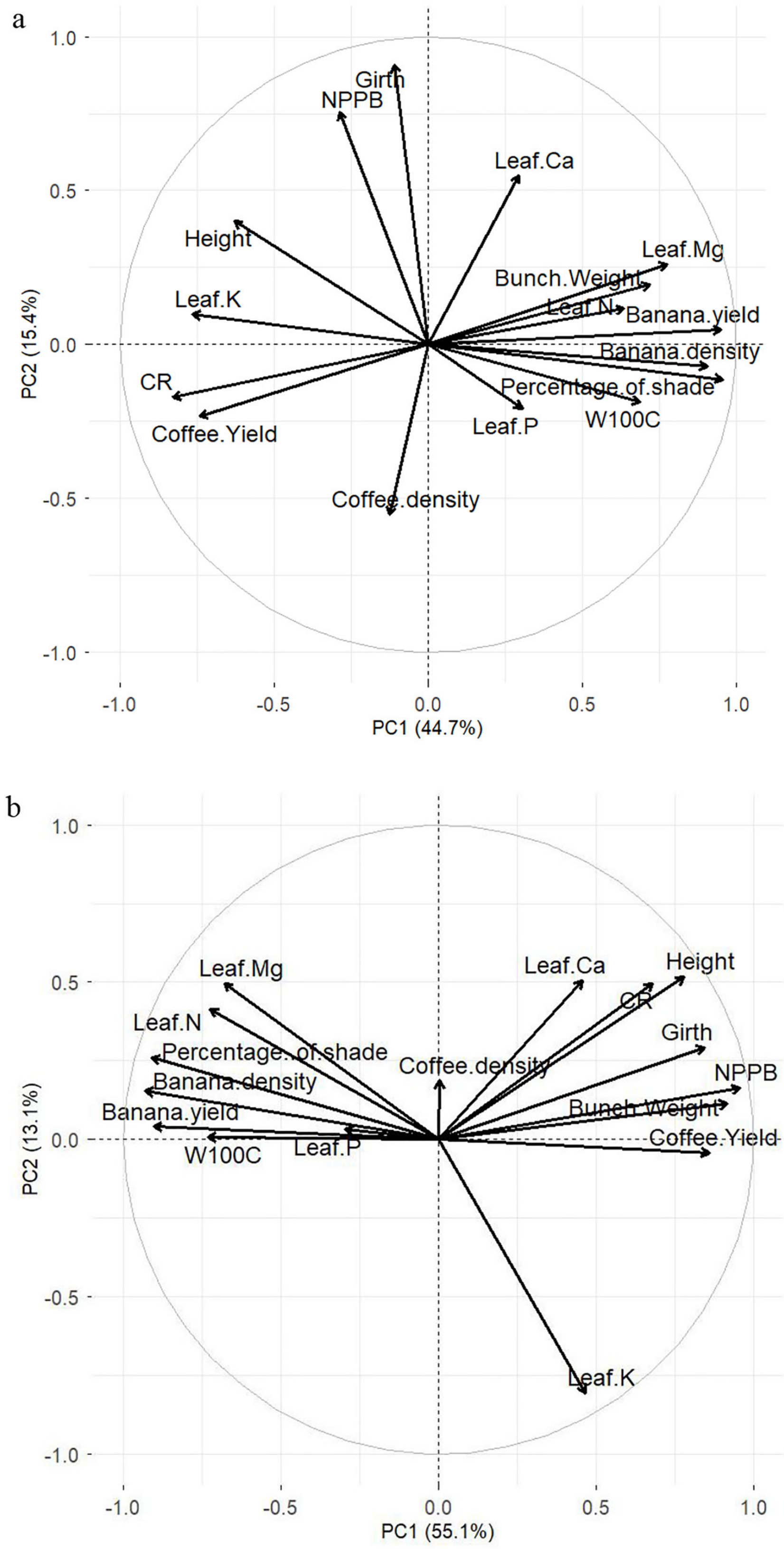

FIGURE 3 Principal component analysis (PCA) for banana and coffee factors at Gitega (a) and Kayanza (b) (NPPB, number of pairs of primary branches; CR, canopy radius; W100C: weight of 100 fresh cherries).

TABLE 3 Banana yield per hectare and bunch weight (mean ± standard deviation) over the two cycles as a function of banana density in Gitega and Kayanza.

	LDB	HDB	Cycle 1	Cycle 2
Gitega				
Fresh banana yield (Mg ha^{-1})	9 ± 1a	9 ± 2a	9 ± 3a	8 ± 2a
Average bunch weight (kg)	9 ± 1b	6 ± 1a	7 ± 2b	6 ± 1a
Kayanza				
Fresh banana yield (Mg ha^{-1})	15 ± 3a	27 ± 5b	19 ± 6a	23 ± 8 b
Average bunch weight (kg)	17 ± 3a	16 ± 3a	15 ± 2a	18 ± 3b

Note: Values with different letters in the rows are statistically different at $p \leq 0.05$.
Abbreviations: HDB, high density banana; LDB, low density banana.

TABLE 4 Average cherry coffee yield ± standard deviation per hectare and per tree as a function of coffee and banana density in Gitega and Kayanza.

	Gitega			Kayanza		
	NB	LDB	HDB	NB	LDB	HDB
LDC						
Cherry yield (kg ha^{-1})	456 ± 80c	214 ± 46b	58 ± 4a	236 ± 36b	104 ± 68a	73 ± 0a*
Cherry weight/tree (g^{-1})	326 ± 58c	160 ± 33b	40 ± 3a	169 ± 26b	74 ± 49a	53 ± 0a
HDC						
Cherry yield (kg ha^{-1})	898 ± 32c	593 ± 68b	293 ± 195a	398 ± 36c	238 ± 77b	65 ± 38a
Cherry weight/tree (g^{-1})	328 ± 11c	216 ± 25b	107 ± 71a	145 ± 13b	87 ± 28ab	25 ± 14a

Note: Values with different letters in the rows are statistically different at $p \leq 0.05$.
Abbreviations: HDB, high density banana; HDC, high-density coffee; LDB, low density banana; LDC, low density coffee; NB, zero banana.

with HDB compared to coffee monocropped plots. With high-density coffee (HDC), coffee yield decrease was 34% and 68%, respectively, for LDB and HDB compared to coffee monocropped plots. At Kayanza, yield was reduced by 56% and 69%, respectively, with LDB and HDB when coffee was at LDC and 40% and 84% when coffee was at HDC compared to respective yields of coffee in monocropped plots. Coffee yield in monocropped HDC plots was equal to 898 kg fresh coffee cherries ha^{-1} at Gitega and 456 kg ha^{-1} at Kayanza.

A strong and significant negative relationship ($p < 0.001$) was observed between banana-induced shade and coffee cherry weight per plant, with R^2 values of 0.88 at Gitega and 0.83 at Kayanza (Figure 4a). At Gitega, coffee yield per tree declined sharply, with a predicted yield of zero at 26% shade. At Kayanza, yield reduction was more moderate, with zero yield predicted at 43% shade.

Conversely, a significant positive relationship was found between banana shade and the weight of 100 coffee cherries, with R^2 values of 0.50 and 0.58 for Gitega and Kayanza, respectively ($p = 0.002$ for Gitega; $p < 0.001$ for Kayanza). Increasing banana shade was associated with an increase in the weight of 100 cherries (Figure 4b).

3.3 | Interspecific competition between coffee and banana

At all density levels of the two intercropped crops, the LER was always >1 at both sites (Table 5). At Kayanza, there was a significant difference in LER values, with a higher LER for HDC intercropped with banana at LDB. The competitive ratio was always below 1 for coffee and above 1 for banana. A significant difference between coffee competitive ratios was observed, with a lower value for LDC intercropped with LDB.

3.4 | Evolution of banana-provided shade in relation to banana density

A significant difference in banana shading was observed between the sites, with higher values in Kayanza. The evolution of banana shade was different in the two sites. At Gitega, shade increased until the 15th month after planting, with higher values for HDB plots (Figure 5a). The effect of banana density on banana shade was significant at seventh month ($p < 0.001$), 12th month ($p < 0.001$), and 15th month

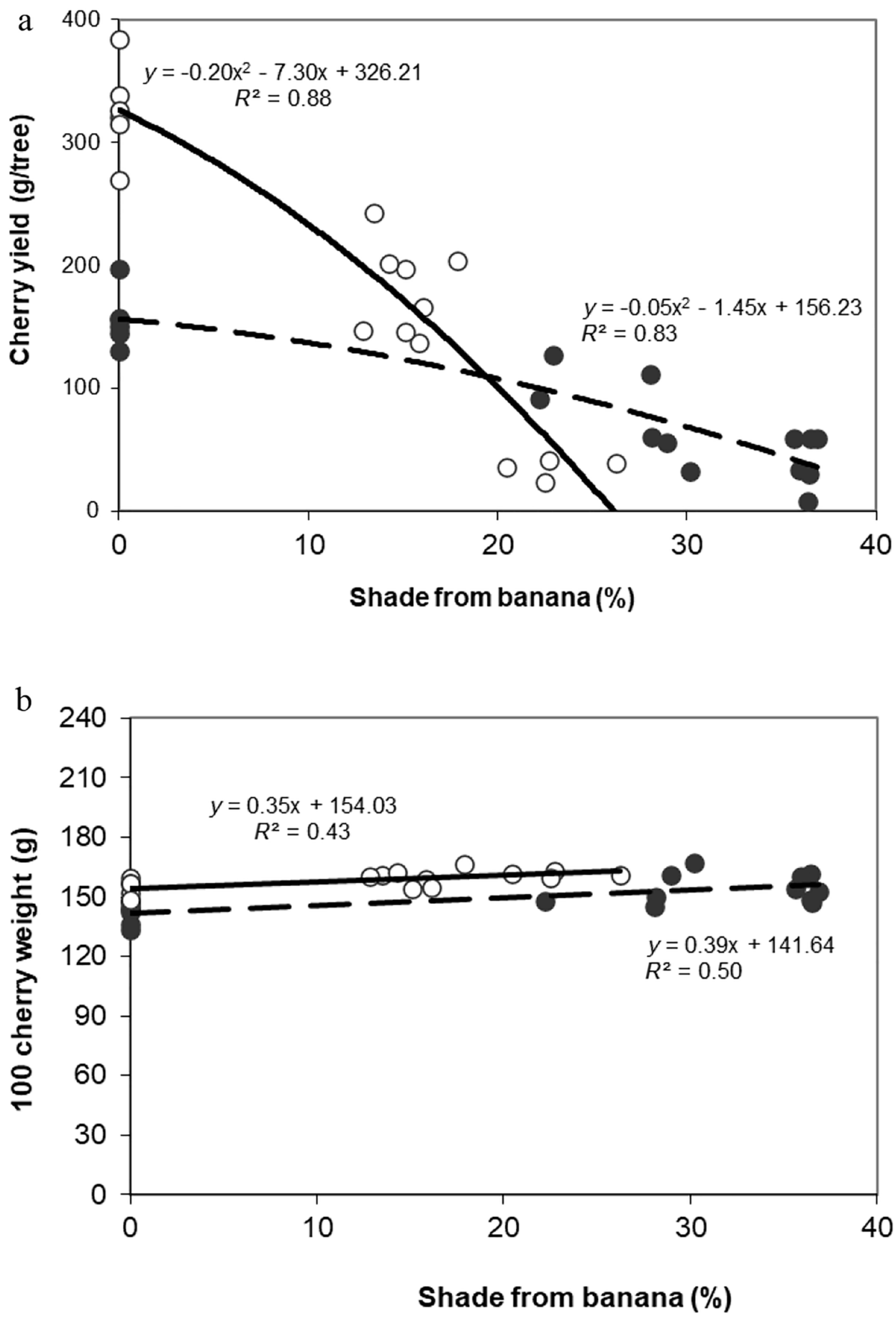

FIGURE 4 Relationship between banana shade and cherry weight per plant (a) and between banana shade and 100 fresh cherry weight (b). Unfilled circles and continuous line represent Gitega site, and filled circles and a discontinuous line represent Kayanza site. Each point represents a coffee plot with different banana densities.

($p = 0.003$) after planting, with higher values for HDB plots. After the 15th month, shade decreased, and the two banana densities had statistically the same values. At Kayanza, the difference in shade between banana densities was always significant with higher values for HDB plots (Figure 5b).

3.5 | Coffee growth characteristics in relation to banana density and shade from banana

At Gitega, significant differences among treatments were observed in coffee growth characteristics, namely, stem

TABLE 5 Interspecific competition indexes of banana and coffee as a function of the densities of coffee and banana in intercropping.

Indices	LDC-HDB	HDC-LDB	HDC-HDB	LDC-LDB	*p*-value	DF
Gitega						
LER	1.5 ± 0.2	1.3 ± 0.1	1.7 ± 0.2	1.2 ± 0.1	0.13	2
Competitive ratio						
Coffee	0.3 ± 0.03	0.1 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	0.07	2
Banana	4.7 ± 0.5	12.7 ± 6.8	7.0 ± 6.5	10.3 ± 0.7	0.33	2
Kayanza						
LER	1.3 ± 0.4a	1.8 ± 0.1b	1.1 ± 0.3a	1.2 ± 0.2a	0.03*	2
Competitive ratio						
Coffee	0.3 ± 0.1b	0.3 ± 0.2b	0.4 ± b	0.1 ± 0.1a	0.03*	2
Banana	5.4 ± 4.8	4.3 ± 4.4	5.9±	8.9 ± 0.6	0.11	2

Note: Values with the same letters in the rows are not significantly different at $p \leq 0.05$.
Abbreviations: DF, degree of freedom (mean ± standard deviation); HDB, high density banana; HDC, high-density coffee; LDB, low density banana; LDC, low density coffee; LER, land equivalent ratio.
*Significantly different at $p \leq 0.05$.

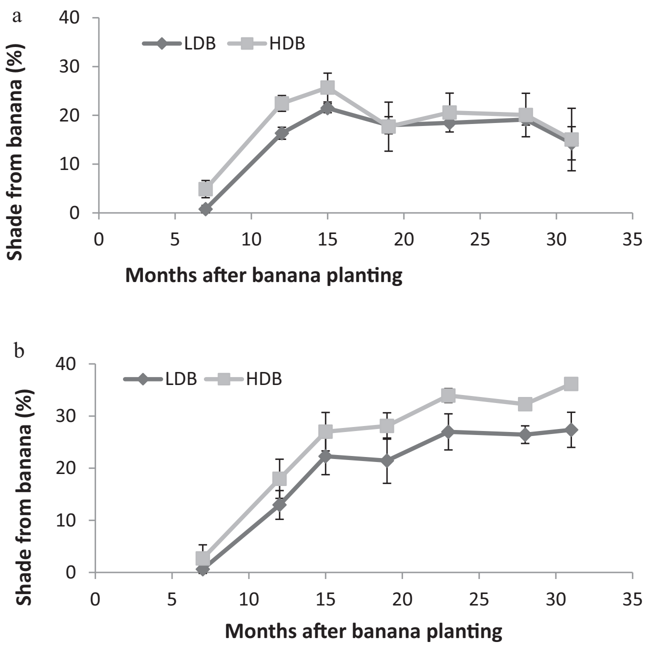

FIGURE 5 Banana shade development in relation to banana density at Gitega (a) and Kayanza (b). HDB, high banana density; LDB, low banana density. Error bars represent the standard deviation.

girth, stem height, number of primary branch pairs, and canopy radius. For stem girth, significant differences were observed up to 19th month after stem selection, with *p*-values always < 0.026. The highest values were observed in monoculture plots. The corresponding values of the plots with NB, LDB, and HDB at 14th month were 2.0, 1.7, and 1.6 cm (Figure 6a). For height, significant differences were observed only at the 11th and 14th months after coffee stem selection. The *p*-value was < 0.001 at 11th month and 0.043 at 14th month. Higher values were observed in monoculture plots (Figure 6b). At the 14th month, the height values were 91 cm in the monoculture coffee plots and 86 cm in the other plots. Significant differences were observed for the number of pairs of primary branches with *p*-values always < 0.008. The number of pairs of primary branches was significantly higher in monocropped coffee plots (Figure 6c). At the 14th month, the number of pairs of primary branches for NB, LDB, and HDB coffee plots was 13, 11, and 10, respectively. Throughout the data collection period, the canopy radius was significantly higher in the monocropped coffee plots (Figure 6d). At the 23rd month, the canopy radius was 34 cm in the monoculture coffee plots and 32 cm in the HDB plots.

At Kayanza, significant differences between treatments were observed for coffee girth and number of primary branches from seventh month onward. The highest values were observed in coffee monoculture plots and the lowest in coffee plots with HDB (Figure 7a,c). Coffee plots with LDB had an intermediate value. At the 23rd month, the girth at 15 cm above the ground was 1.6 cm for monoculture coffee plots, 1.4 cm for LDB, and 1.3 cm for HDB coffee plots. The number of primary branch pairs for these treatments was 11, 10, and 9, respectively. For height and canopy radius, the values were significantly higher in monoculture coffee plots and lower in HDB coffee plots (Figure 7b,d).

The correlations between growth characteristics and the percentage of shade at the end of the data collection are shown in Figure 8. At Gitega, a significant correlation was only observed between banana shade and canopy radius (Figure 8d). The correlation was negative, and the coefficient of determination R^2 was 0.68 with a *p*-value of < 0.001.

At Kayanza, there were negative and significant correlations between all coffee growth characteristics and banana shade (Figure 8a–d). Coefficients of determination R^2 were 0.43, 0.24, 0.63, and 0.25 for girth, coffee height, num-

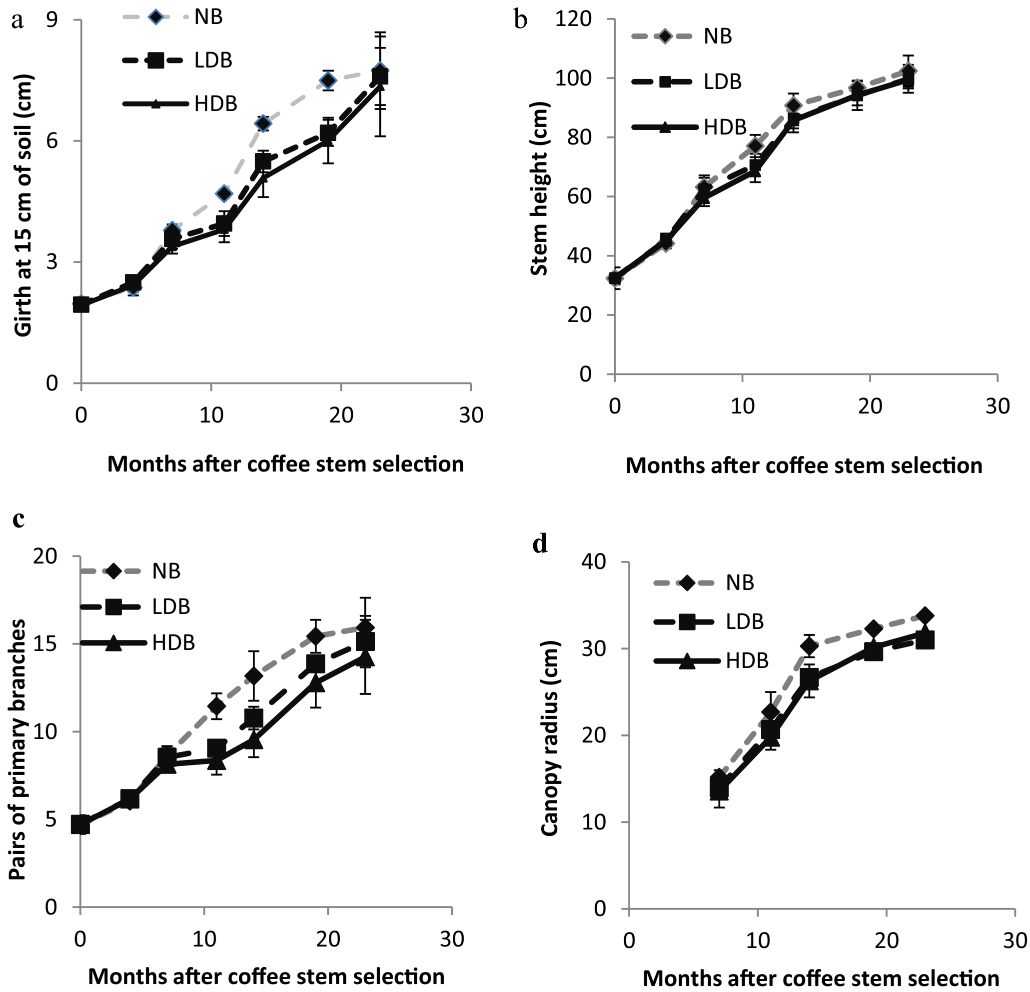

FIGURE 6 Growth characteristics of coffee trees, namely, girth at 15 cm above ground (a), height (b), number of pairs of primary branches (c), and canopy radius (d) at Gitega according to banana density (HDB, high banana density; LDB, low banana density; NB, zero banana). Error bars are standard deviations.

ber of pairs of primary branches, and canopy radius, respectively.

3.6 | Nutrients in coffee leaves in relation to banana density and shade

There was a significant relationship ($p \leq 0.05$) between N, K, and Mg content in coffee leaves and banana shade. N and Mg contents increased with shade, while K contents decreased with shade (Figure 9a–c).

3.7 | Recycled biomass from banana residues

The amount of recycled biomass expressed as DM was 9.2 and 6.4 Mg ha^{-1} at Gitega for HDB and LDB, respectively. At Kayanza, 15.0 and 9.9 Mg ha^{-1} were recycled as banana residues for HDB and LDB, respectively (Figure 10). At both sites, the differences between HDB and LDB were statistically significant ($p < 0.001$).

3.8 | Economic benefits

Significant differences ($p < 0.001$) between treatments were observed at both sites for net benefit and MAI. Negative net benefit values were obtained in monocropped coffee plots in Kayanza. In Gitega, the net benefit was always negative. The highest values of net benefit were obtained with HDB (Figure 11a,b). In intercropped plots, the highest MAI was obtained with LDC-HDB treatment. The highest net benefit was observed at Kayanza with a value of \$4 097 ha^{-1} for HDB plots and the lowest net benefit at the same site with a value of −\$3 283 ha^{-1} for HDC plots. Net benefits and MAI were significantly lower at Gitega.

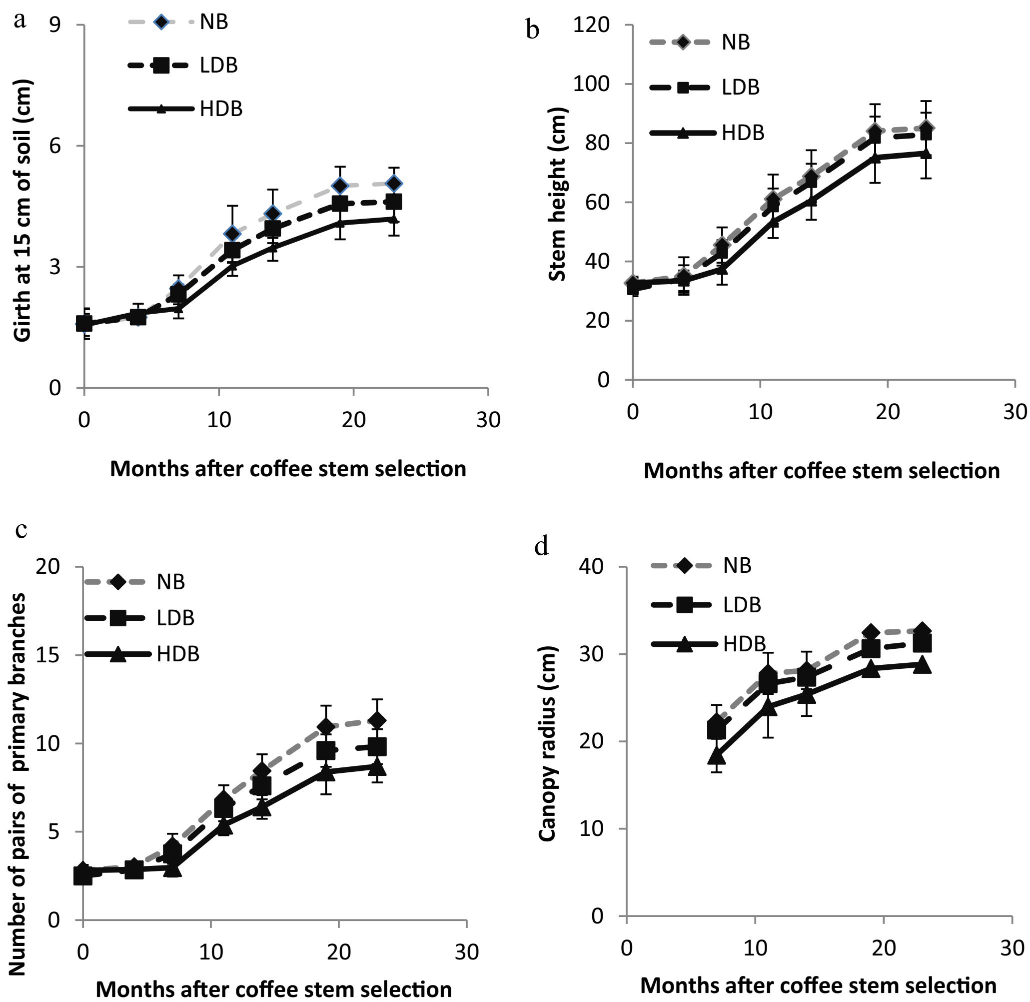

FIGURE 7 Growth characteristics of coffee trees: girth at 15 cm above ground (a), height (b), number of pairs of primary branches (c), and canopy radius (d) at Kayanza according to banana density (HDB, high banana density; LDB, low banana density; NB, zero banana). Error bars are standard deviations.

4 | DISCUSSION

4.1 | Complementarity between crops and benefit interactions

The banana–coffee intercropping system showed positive complementarities and benefit interactions. Specifically, physical quality, measured by cherry fresh weight, increased with higher shade levels resulting from increased banana plant density (Figure 3 and Figure 4). The positive correlation observed between the weight of 100 cherries and shade confirms the results of other authors who have worked on coffee shade trees (Bosselmann et al., 2009; DaMatta et al., 2008; Muschler, 2001; Siles et al., 2010). As 100 cherry weight is one of the indicators of coffee quality (Bosselmann et al., 2009), banana shade has contributed to improving coffee quality. High weigh cherries imply higher yields during pulping and hulling, with greater potential for economic valorization.

Additionally, the results showed LER values consistently >1 (Table 5), confirming that the intercropping of the two crops is more beneficial than monocropping in terms of yield. The advantages of intercropping were also observed in terms of income, with higher profits or reduced losses in plots where the two crops were intercropped (Figure 11). Net benefit and MAI were higher in intercropped plots and increased with banana density (Figure 11). In monoculture coffee plots, net benefits were negative. This shows that it takes a long time for coffee farmers to recover their investment in monoculture. The yield in the first year of coffee production is lower, as confirmed in Burundi (Gaie & Flémal, 1988). Therefore, bananas provide rapid income before the coffee begins producing.

Furthermore, plots with banana recycled substantial amounts of residues (Figure 10). Besides returning nutrients to the soil, these residues help conserve water and prevent soil erosion. On the farm level, using banana residues as self-mulch could help to maintain soil fertility by avoiding the

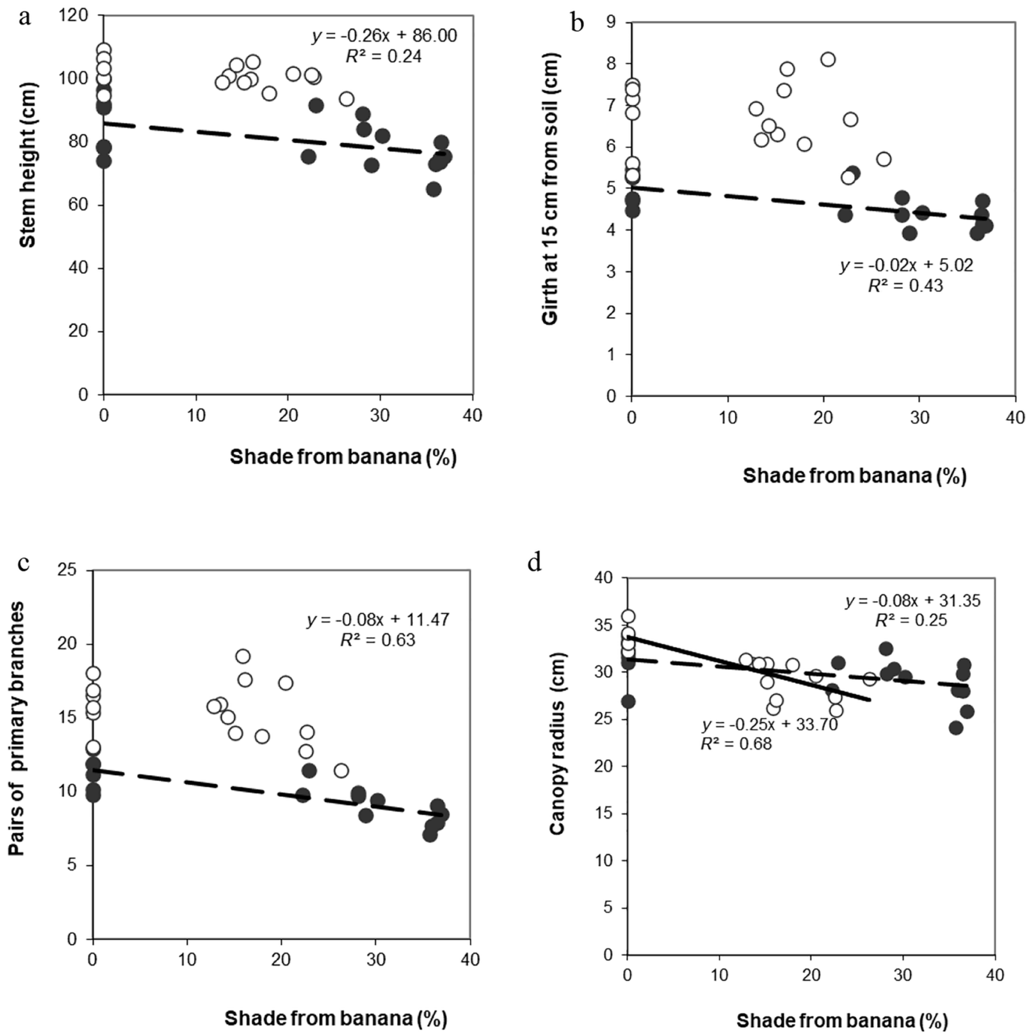

FIGURE 8 Relationship between banana shade and growth characteristics of coffee trees: girth at 15 cm above ground (a), stem height (b), number of pairs of primary branches (c), and canopy radius (d). Unfilled circles and solid line represent Gitega, and filled circles and dashed line represent Kayanza. Only significant relationships ($p \leq 0.05$) are shown.

need to use other parts of the farm to mulch the coffee plots (Cochet, 2001) and allowing the coffee plots intercropped with banana to become self-sufficient in mulch. Finally, the N and Mg contents in coffee leaves increased with shading (Figures 3 and 9). This increase should be related to the adaptation of coffee trees to shade conditions through higher chlorophyll production, as the content of N and Mg in coffee leaves is highly correlated with the total chlorophyll content (Partelli et al., 2009). Increasing the chlorophyll content improves the interception of the small amount of light that passes through the banana canopy (Evans et al., 1993; Niinemets, 2010; Niinemets & Tenhunen, 1997). This important investment in chlorophyll elements such as N and Mg for light interception under light-deficient conditions may divert nitrogen from objectives other than plant growth and cherry production (Niinemets & Tenhunen, 1997) but this adaptation should maximize the interception of available light.

4.2 | Competition between crops

In intercropping systems, crops compete for light, nutrients, and water (Zhang & Li, 2003). In this study, shading significantly reduced coffee yield and all measured growth parameters, namely, stem girth, plant height, canopy radius, and the number of primary branch pairs. Increasing shade intensity led to a progressive decline in both yield and vegetative growth (Figures 3 and 8). Significant differences in growth parameters emerged from the 10th month after stem selection, corresponding to the stage at which banana plants produced substantial shade (Figures 6 and 7).

Consistent with previous studies, shading reduced coffee yield, stem girth, and canopy radius (Campanha et al., 2004; DaMatta et al., 2008). However, unlike reports of increased coffee height under shade (Morais et al., 2006), no such response was observed here, indicating reduced plant vigor

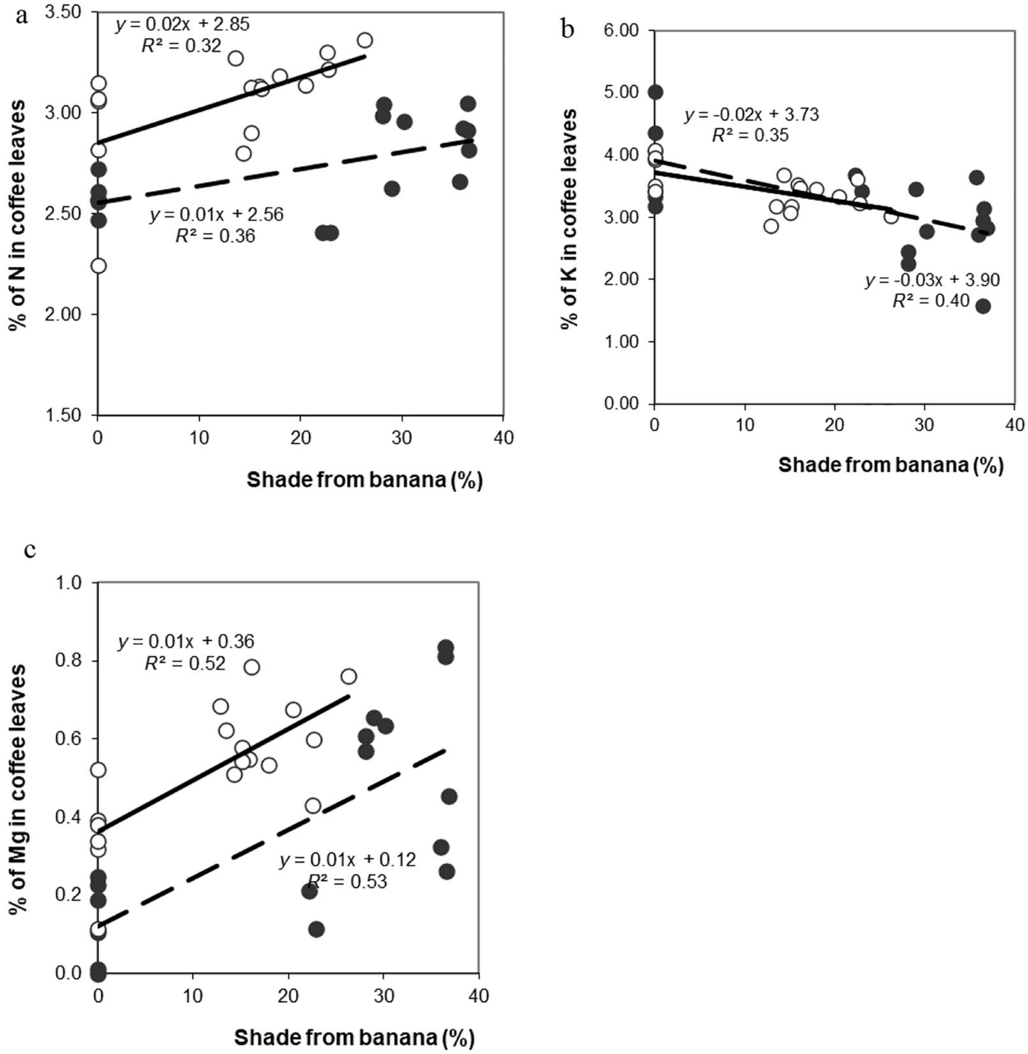

FIGURE 9 Relationship between N (a), K (b), and Mg (c) in coffee leaves as a function of banana shade. Unfilled circles and the continuous line represent the Gitega site, and filled circles and the dashed line represent the Kayanza site. Only significant relationships at $p \leq 0.05$ are shown.

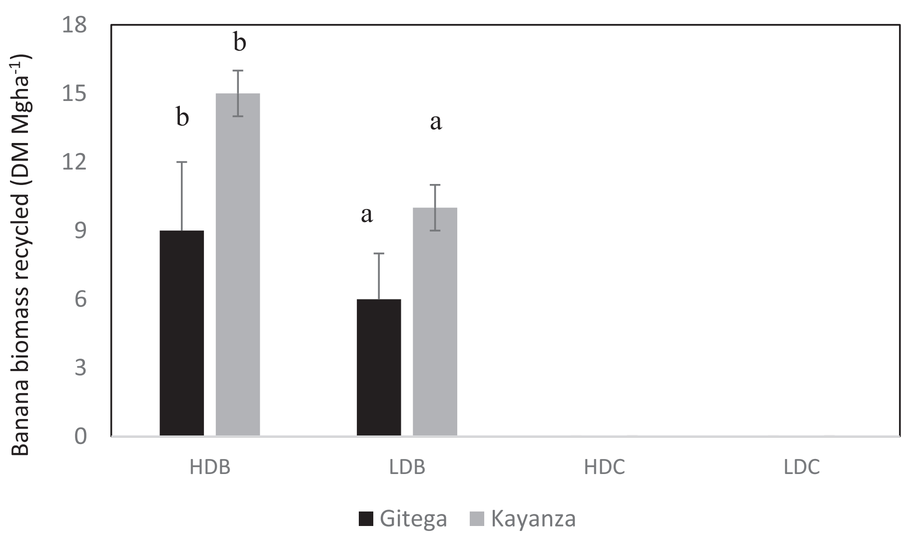

FIGURE 10 Total recycled dry matter (DM) biomass during experimental period through banana residues (HDB, high density banana; HDC, high-density coffee; LDB, low density banana; LDC, low density coffee). Values with different letters per site are statistically different at $p \leq 0.05$

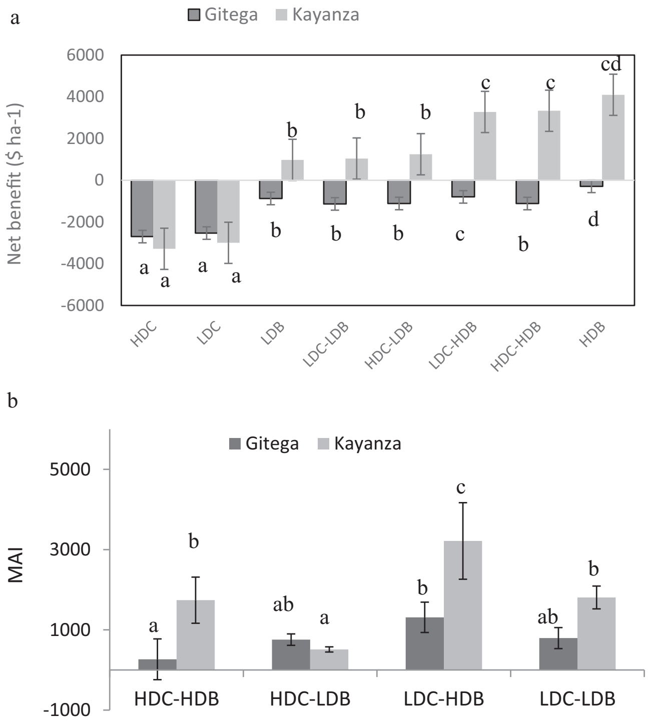

FIGURE 11 Net profit (a) and monetary advantage index (MAI) (b) at Gitega and Kayanza related to treatments and level of intercropping. Error bars are standard deviations. (HDB, high density banana; HDC, high-density coffee; LDB, low density banana; LDC, low density coffee). Values with different letters per site are statistically different at $p \leq 0.05$

and a declining long-term production potential. The negative effects of shading were closely associated with increasing banana aboveground biomass, which strongly correlated with shade intensity (Nyombi et al., 2009). As banana biomass increased, nutrient uptake by banana intensified at the expense of coffee. Same nutrient requirements for the two crops and similar rooting depths further exacerbated competition, particularly for water and nutrients (Jaramillo-Botero et al., 2010; Soto-Pinto et al., 2000). Although yield reductions in shaded coffee systems have been widely reported (Campanha et al., 2004; Jaramillo-Botero et al., 2010; Lyngbaek et al., 2001), the yield decline observed in this study occurred even at relatively low shading levels (Figure 4), contrasting with reports where significant yield losses occur only under higher shade intensities (Soto-Pinto et al., 2000).

Banana was consistently the dominant species in the coffee–banana intercropping system. The competitive ratio remained below 1 for coffee and above 1 for banana (Bi et al., 2019; Willey, 1985; Willey & Rao, 1980), indicating a clear yield disadvantage for coffee. However, under nutrient-poor soil conditions in Gitega, banana shading and biomass declined after 15 months (Figure 5a), suggesting that banana is more sensitive to soil nutrient depletion than coffee. Following the reduction in shading, coffee plants rapidly recovered, and differences in height and stem girth were no longer significant by the end of the observation period (Figure 6).

Shading also negatively affected potassium (K) concentration in coffee leaves, with K levels decreasing as shade intensity increased (Figures 3 and 9). This response likely reflects intensified competition with banana, which has high potassium demand (Lahav, 1995). Unlike nitrogen and magnesium, coffee appears to lack effective mechanisms to maintain high leaf K concentrations under competitive conditions, resulting in preferential K uptake by banana.

4.3 | Coffee-banana intercropping management

The management of coffee–banana intercropping requires a trade-off between maximizing coffee yield and increasing overall profitability through high banana production. This primarily involves shade management by maintaining an adequate number of living banana leaves. Indeed, the number of functional leaves is positively correlated with bunch weight (Soares et al., 2014). Although studies conducted across several countries have shown that maintaining a minimum of six living leaves per banana plant is sufficient to maintain bunch weight (Gran et al., 2012). Regular pruning of banana leaves to maintain no more than six functional leaves per plant can help preserve banana yield while minimizing light competition for coffee.

Planting density is another key management factor closely linked to shading, as higher densities result in increased shade intensity. Based on the study data (Table 3), coffee yield reductions in plots with high coffee density ranged from 34.9% to 40.2% under low banana density and from 67.3% to 83.7% under high banana density, compared with monoculture (percentages calculated from study data). The low banana density tested in this study (800 plants ha^{-1}) reduced coffee yield by >30%. While this density may be maintained, lower banana densities could be considered for farmers aiming to increase coffee yield. A density of approximately 600 banana plants ha^{-1} could limit coffee yield reduction to about 20% compared to monoculture.

Nutrient management represents another critical factor. Calculations based on the study results (Figure 4a) indicated that a 20% reduction in coffee yield occurred at 8.1% shade in Gitega and at 14.4% shade in Kayanza. This suggests that richer soils can support higher levels of shade. The strong competition observed for potassium, together with higher nitrogen and magnesium concentrations in smaller and less vigorous plants, highlights the need for adequate nutrient inputs. Both crops have high requirements for nitrogen, potassium, and magnesium (Gaie & Flémal, 1988; Wrigley, 1988). Fertilizer application limited to the beginning of the experiment likely intensified competition and cannot be considered an appropriate management practice.

4.4 | Limit of the study

Coffee production reaches its maximum from the fifth year onward (Gaie & Flémal, 1988; Wrigley, 1988), with a production cycle of approximately 7 years before rejuvenation pruning. Yield measured in the third year, therefore, does not represent the maximum production potential under the conditions of this study. Nevertheless, the interactions observed clearly indicate the effects of banana on coffee. Banana plants had already completed two production cycles, which is sufficient to assess overall trends.

5 | CONCLUSION

Banana and coffee are in constant competition for light and nutrients. Although the banana appears to be the dominant crop, its nutrient requirements are so high that, if resources start to decline, banana growth and yields will decline before coffee. Thus, the sustainability of the intercrop can only be envisaged in an intensive system that can provide required nutrients for both coffee and banana. Given the high investment required for coffee in the early years, coffee monoculture is not economically viable, and banana intercropping is a profitable alternative that can allow coffee growers to recover the investment with profit in the early years of coffee growing. Banana has the advantage of providing mulch to the system through recycled residues, although nutrient export will always be higher in banana plots. For the sustainability of the system, it will be necessary to find a trade-off between the best profitability obtained by increasing banana density in coffee plots and the reduction in coffee yield due to banana dominance in the intercrop. Depending on the priority crop for farmers, two options are possible. If the main crop is coffee, banana is introduced at low density with management of suckers and shade to reduce banana competition. If the main crop is banana, the introduction of coffee will not affect the performance of the banana in the early years, with the additional yield from coffee. Thus, young coffee and banana intercropping is an opportunity because of its additional yield and income, but it needs more investment in nutrient supply to cover crop requirements and requires adequate management of banana biomass.

AUTHOR CONTRIBUTIONS

Anaclet Nibasumba: Conceptualization; data curation; formal analysis; methodology; writing—original draft; writing—review and editing. **Piet VanAsten**: Conceptualization; funding acquisition; methodology; project administration; resources; software; visualization; writing—original draft. **Laurence Jassogne**: Conceptualization, formal analysis, software, validation, visualization, writing—review and editing. **Claudette Nkurunziza**: Data curation; methodology. **Grégoire Nahimana**: Data curation, methodology, writing—review and editing. **Salvator Kaboneka**: Methodology; writing—review and editing. **Bruno Delvaux**: Conceptualization; funding acquisition; methodology; supervision; validation; visualization; writing—review and editing. **Charles Bielders**: Conceptualization; formal analysis; methodology; project administration; software; supervision; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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