Journal of Agricultural and Crop Research
Vol. 9(11), pp. 250-263, November 2021
doi: 10.33495/jacr_v9i11.21.167
ISSN: 2384-731X
Research Paper

Coffee-banana systems in transition: Resource allocation and crop interactions in smallholder farms of Burundi

Anaclet Nibasumba[1]* • Laurence Jassogne[2] • Piet VanAsten[2] • Gilbert Nduwayo[1] • Claudette Nkurunziza[1] • Charles Bielders[3] • Bruno Delvaux[3]

[1]Institut des Sciences Agronomiques du Burundi (ISABU), P.O. Box 795 Bujumbura, Burundi.
[2]International Institute of Tropical Agriculture (IITA), P.O. Box 7878, Kampala, Uganda.
[3]Earth and Life Institute, Université catholique de Louvain, Croix du Sud, Louvain-la-Neuve, 1348, Belgium.

*Corresponding author E-mail: anaclet.nibasumba@hotmail.fr

Accepted 8th November, 2021.

Abstract. This study aimed to analyse interactions between coffee and banana plants in adjunct banana and coffee plots. A diagnostic survey was conducted in 60 farms with adjunct banana and coffee plots selected in a humid plateau ecological zone. Banana plots were divided into two sub-plots, a sub-plot near coffee (NC) and a sub-plot far from coffee (FC). Coffee plots were divided into two sub-plots, sub-plot near banana (NB) and sub-plot far from banana (FB). Results showed that banana yield was higher in sub-plots NC (28.6 Mg ha^{-1} $cycle^{-1}$) than subplots FC (10.4 Mg ha^{-1} $cycle^{-1}$). The coffee yield was not significantly different among sub-plots. The weight of 100 cherries was significantly higher NB. Soils under coffee were significantly richer near banana and banana nutrient leaf content higher NC. Limiting factors in banana sub-plots FC were, in descending order, K > Mg > Corg > P > pH. In banana sub-plots NC, limiting factors were K / (Ca + Mg) > pH > Zn > P and N. In coffee sub-plots NB, limiting factors were Corg > Mulch > Zn > P > K. In sub-plots FB, limiting factors were Zn > N > P > Mulch. The presence of bananas did not affect coffee growth and coffee yield NB while increasing soil characteristics NB. The presence of coffee has significantly increased the yield and growth of banana NC.

Keywords: Banana-coffee, growth-characteristics, nutrient-deficiency, limiting-factor.

INTRODUCTION

In Burundi, it has long been recommended to conduct coffee monocropping without shade trees and annual food crops (Gaie and Flémal, 1988; Ndihokubwayo *et al*., 2021). This practice was recommended because trees used for shade or intercropped crops should compete with coffee trees. However, several benefits of shade in coffee trees have been reported (Perdoná *et al*., 2020). Tree shade: (i) allows moderate temperature variations (Gomes *et al*., 2020), (ii) reduce soil water loss through evaporation by soil moisture conservation (Lin, 2010), (iii) improve soil fertility by providing nutrients, and (iv) limit erosion (Beer, 1987). In some cases, coffee yield is not affected by shade (Rigal, 2020). On the other hand, coffee intercropping with crops other than shade trees ensures optimal land use, increases income and food availability (Daryanto *et al*., 2020).

Under demographic pressure effect, association with some annual crops such as beans is tolerated in Burundi during the first years of young coffee plantation establishment (Gaie and Flémal, 1988). But, special restrictions exist on coffee intercropping with bananas. The reason given was linked to the high potential of competition between the two crops because they have, both banana and coffee, and high demand for N and K, and a superficial root system (Muliele, 2020; Partelli *et al.*, 2020). To avoid any competition between banana and coffee, a buffer distance of a minimum of 3m was required between banana plots and coffee plots (discussions with coffee growers before data collection). However, in the Burundian cropping system, banana and coffee crops are

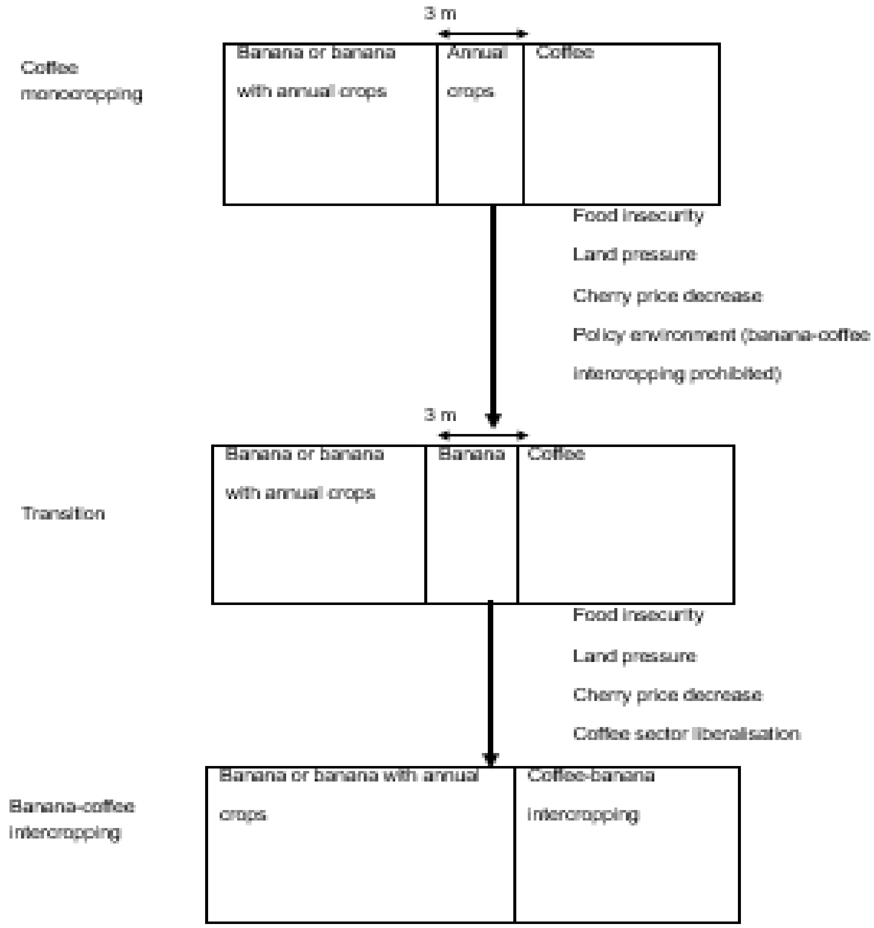

Figure 1. Banana-coffee systems evaluation according to coffee sector organization.

closely linked through the practice of mulching. Banana residues are the most available biomass at the farm level (Gambart *et al.*, 2020) and these residues are used for mulching coffee plots (Cochet, 1996). Mulch supply recommendation is a thickness of 10 to 12 cm, which is equivalent to 48-58 Mg ha^{-1} of dry matter (DM) (Bizimana, 2018). This intensive mulching considerably enriches the coffee plots by restoring nutrients (Nzeyimana *et al*., 2020). Thus, coffee plots are more fertile compared to the surrounding plots. Gradually, some coffee growers extended banana crop into the 3 m of a buffer zone with rows of bananas starting directly after rows of coffee trees. The objectives were (i) to produce banana for home consumption in the restricted area and ii) to have residues to be used as mulch in adjunct coffee plantations in the context of prohibited banana and coffee intercropping. Thus, the contact zone between banana plants (3 m) and the coffee trees (2 rows most affected by banana plants) is subject to several interactions that must be understood and highlighted to make recommendations on this system. Possible interactions are linked to competition for water, nutrients and light as well as the recycling of banana residues in coffee plots. With its root system, banana plants can uptake nutrients from the richer coffee plots because their primary roots have a length greater than 4 m (Sebuwufu *et al*., 2004) and can reach beyond the buffer distance of 3 m. Furthermore, banana height is higher than coffee height and banana leaves provide shade on the coffee canopy. Thus, light availability for coffee should be affected by banana leaves which can reach 2 m in length (Nyombi *et al.*, 2009). As banana is a dominant crop, the latter is more competitive than coffee because of its growth rate (Li *et al.*, 2020). With the presence of bananas, coffee tree morphology and coffee yield in the interaction zone should be affected as coffee under shade. In return, the coffee plots benefit from banana residues, which restore a large part of K, N, Ca and Mg through mulching (Sebatta *et al*., 2020) preferentially in the rows of coffee trees closer to banana plots.

This system is therefore a transition towards an intercropping system between the two crops which is limited by a policy that encourages coffee monocropping.

Thus, the evolution of coffee growing systems in Burundi is detailed below (Figure 1). This evolution shows that coffee monocropping system with a buffer zone of 3 m for banana restriction, which is disappearing towards a system of banana and coffee adjunct, plots. This system may be viewed as a transition system from monocropping, viable under conditions of low land pressure and high mulch availability, towards banana-coffee intercropping under conditions of intense land pressure.

The monocropping transition system currently observed in Burundi has not hitherto been studied. Besides providing insight into farmers' resource allocation strategies, it provides an opportunity to study the interactions between the two crops. The objectives of the study were, therefore, i) to document the allocation of resources involved in fertility management; ii) to analyze the resulting interactions between coffee and banana and the impact of these interactions on bananas and coffee yields and iii) to identify limiting factors affecting coffee and banana yield in this system.

MATERIALS AND METHODS

Farm selection, plot subdivision and banana/coffee variety choice

Farms selected for this study were located in the humid plateau ecological zone of Burundi. The average annual rainfall is between 1200 and 1300 mm and the average annual temperature is between 19.1 and 19.6°C (Institut Géographique du Burundi, 2015). A total of 60 farms with coffee plot adjunct banana plots were selected and geo-referenced (Figure 2). Farms selected were those with coffee and banana plots well established, mature and in production. Each banana plot was divided into two sub-plots: the sub-plot near coffee (NC) with a width of 3 m after the last line of coffee and the sub-plot far from coffee (FC) which was beyond the width of 3 m. Similarly, each coffee plot had been divided into two sub-plots: the sub-plot near banana (NB), with a width of 2.5 m corresponding to two rows of coffee plants and the sub-plot far from banana (FB) beyond these two rows.

Banana and coffee growth and yield characteristics had been taken on the same varieties to avoid inter-varietal differences. For bananas, data has been taken on the Igitsiri variety because it was widely present in all banana sub-plots. For coffee, data has been taken on the same variety in sub-plots NB and FB for each plot confirmed using a coffee descriptor. Agronomic and yield data, leave and soil samples have been collected between November 2008 and April 2009.

Coffee and banana morphological characteristics

Banana plant height and girth were measured on 5 plants at the flowering stage randomly selected in each banana sub-plot. For coffee, measurements were taken on 10 trees randomly selected in each coffee sub-plot. Height and base girth was measured for each coffee tree, and branch length, the number of nodes, and leaves per branch were determined from three branches selected at the bottom, the middle and the top of each coffee plant.

Coffee and banana yield estimation

Banana

Yield components were taken on 5 banana plants randomly selected in each sub-plot, the same as those selected for morphological characteristics. Bunch weight was estimated using the allometric model developed by Wairegi *et al*. (2009) incorporating the pseudo-stem girth at 0 and 1 m, the number of hands and the number of fingers in the lower row of the second-lowest hand (Equation 1).

$$ln\,(BW) = -\,6.795 + 0.755\,ln\,(G0m) + 1.059\,ln\,(G1m) + 0.569\,ln\,(NH) + 0.478\,ln\,(NF) \quad (1)$$

With BW: bunch weight (kg); G0m: Girth at 0 m (cm); G1m: Girth at1 m (cm); NH: number of hands and NF: number of fingers in the lower row of the second-lowest hand. Banana yield per hectare and per cycle (BY ha^{-1} $cycle^{-1}$) was determined by multiplying the average bunch weight with the density. The density of banana (plants ha^{-1}) was determined for each sub-plot by measuring the area of the sub-plot and counting the number of plants located inside the sub-plot.

Coffee

Coffee cherries production per plant was estimated using Equation 2.

$$CP = NC/B * NFB * P100C/100 \quad (2)$$

Where CP: cherry weight per plant (g), NC/B: the average number of cherries per branch; NFB: total number of fruiting branches and P100C: weigh of 100 Cherries (g).

For this, data on yield components (NC/B, NFB and P100) were collected on 10 coffee trees randomly selected in each coffee sub-plot just before harvest. For each coffee tree, the total number of fruiting branches was recorded. Then, 5 fruiting branches were selected randomly on each coffee stem. On each branch, the total number of live cherries was recorded. The number of cherries obtained on the five branches has been used to have the average number of cherries per branch. Finally, the weight of 100 randomly selected cherries was determined using a field electronic scale (± 0.1 g).

Coffee cherry yield per hectare (CCY ha^{-1} $year^{-1}$) was obtained by multiplying the yield per plant by the density of coffee. Coffee planting density was determined by an average of 5 measured distances between rows and 5

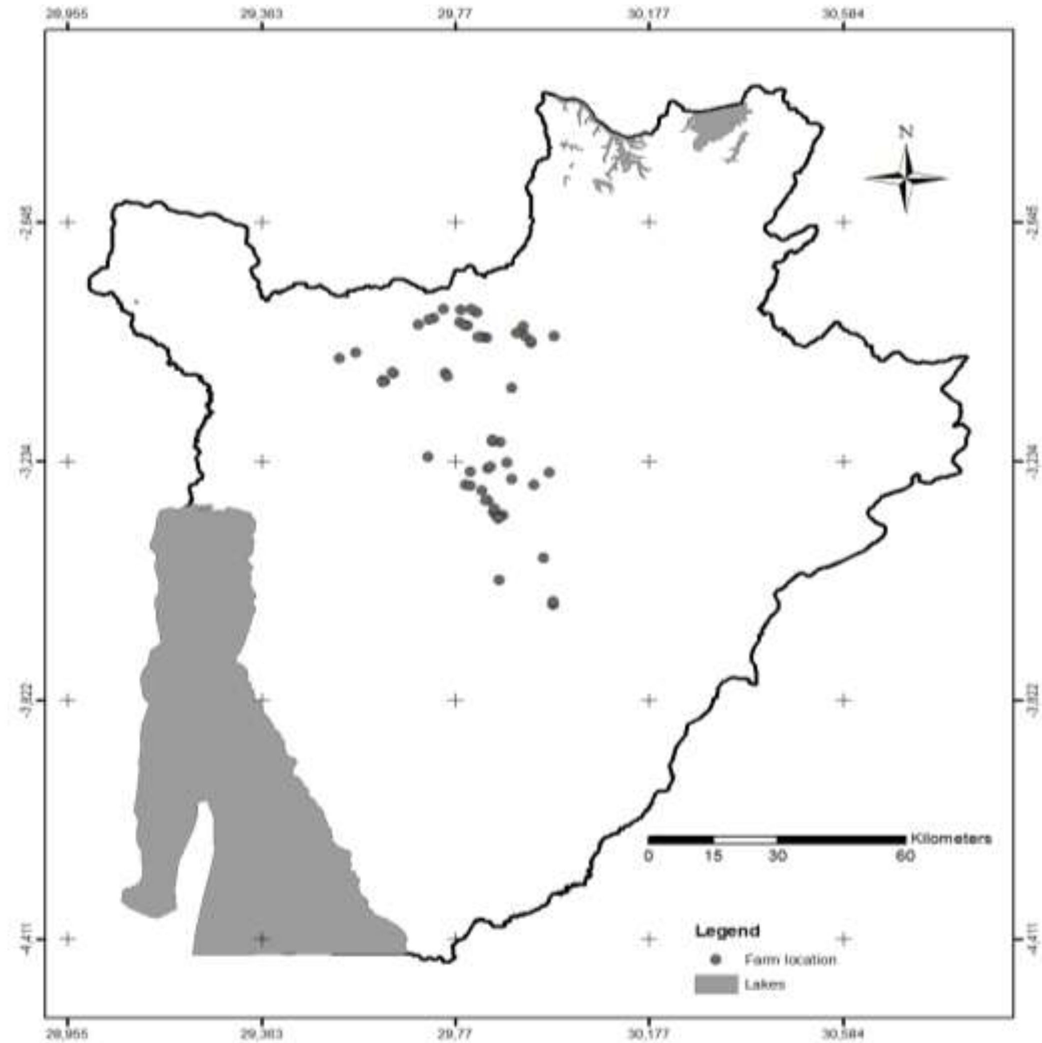

Figure 2. Farm location.

distances in rows. As the coffee density was the same across the entire coffee plots, its determination was done without the separation of sub-plots (Equation 3).

$$CD = ((100/SBR) + 1)) \times ((100/SIR) + 1)) \quad (3)$$

Where CD: coffee density (plants ha^{-1}) SBR: average spacing between rows (m) SIR: average spacing in rows (m).

Banana aboveground biomass

The Aboveground biomass of the banana plant was determined using the equation developed by Nyombi *et al*. (2009) obtained in Uganda on highland banana (Eq. 4)

$$BAB = 9.29 * 10^{-6} * BH^{2.301} \quad (4)$$

With BAB: banana aboveground biomass per plant (kg) and BH: plant height (cm). Banana aboveground biomass per hectare (BAB ha^{-1}) was obtained by multiplying the average biomass per plant by the density obtained above.

Leaf, soil sampling and compositional nutrient diagnosis (CND) analysis

Banana leaf sampling was performed using a method proposed by Lahav (1995) on 5 banana plants for each sub-plot; the same plants were used for yield calculation. Foliar sub-samples of 20 cm were collected from both sides of the midrib in the midpoint of the lamina from the third most fully expanded leaf of a flowering plant and composited for each plot. Coffee leaf sampling was made on the third pair counted from the last expanded pair (Wrigley 1988). In each coffee sub-plot, 10 trees were randomly selected and 5 pairs of leaves were randomly collected on each coffee tree. Leaves from the same sub-plot were mixed to get a composite sample. After sampling, banana and coffee leaves were cleaned manually to remove traces of dust and dried in an oven at a temperature of 60°C for 96 h. Foliar analyses had been conducted at the National Agricultural Research Laboratory of Kawanda in Uganda. Analyzed elements were nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and zinc (Zn). The samples were oven-dried at 72°C for 48 to 96 h, ground to <2 mm, digested in a mixture of sulphuric and selenium acid. The samples were analysed colorimetrically for N and P while K was analysed using a flame photometer and Ca, Mg and Zn were analysed using atomic absorption spectrophotometer. CND indexes were determined using norms proposed by Wairegi *et al.* (2011) for banana and Wairegi *et al.* (2012) for coffee. Each element is deficient when the index is less than 0, excess when greater than 0 and balanced when closer to 0.

Soil sampling was carried out using an auger on a depth of 30 cm in each coffee and banana sub-plots. Soil from 10 random points has been mixed to get a composite sample. After sampling, the soil was dried in the open and covered room for three to four days to reduce soil moisture. Soil analysis was performed at the National Laboratory for Agricultural Research of Kawanda in Uganda. Soil pH was measured in 1:2.5 sediment-water suspensions. Soil organic matter (*SOM*) was determined using the Walkley-Black method. Total N was determined using Kjeldahl digestion with sulphuric acid and Selenium as a catalyser, and measured colorimetrically. Available P and extractable cations (K, Ca, Mg and Zn) were extracted using Mehlich-3 extraction solution (Mehlich, 1984). Available P was measured colorimetrically using the molybdenum blue method, K was measured using a flame photometer, and the other cations were determined using atomic absorption spectrophotometer.

Data collection on crop management

For each banana and/or coffee sub-plot, mineral fertilizers, manure and compost supply were noted according to the response of the farmer. Measurements on mulch were performed only in coffee sub-plots because this practice was not observed in banana sub-plots. To determine the characteristics of mulching, three transects of 10 m each were randomly selected in each coffee sub-plot. For each transect at each one meter, the depth of mulch and mulching dominant material was determined.

Bound lines analysis and limiting factors

The relationship between coffee/banana yield and soil characteristics on one hand, and between yield and management factors of banana and coffee, on the other hand, have been developed using the average bunchy weight or coffee cherries weight per plant for each sub-plot. The average production per plant was used rather than the yield per hectare because the latter has been calculated from production per plant.

With the Spearman test, correlations between the various factors and the average of cherries weight per plant in coffee sub-plots and the average bunch weight in banana sub-plots have been determined. Functional relationships between yield and those factors have been developed for significant correlations ($P \leq 0.05$) with Spearman's test, or for those variables for which the upper boundary points in the scatter plot suggested a functional relationship (Fermont *et al.*, 2009). Outlier values were removed using the box plot method. Upper boundary points were built from scatter plots using the boundary line development system (BOLIDES) developed by Schnug *et al.* (1996). For factors positively correlated with the production per banana/coffee plant, the logistic model was used to fit up boundary points (Equation 5).

$$YI = \frac{Y\max}{((1+(K\exp(-R\cdot x_n))} \quad (5)$$

With YI: Mean cherries per plant or bunchy weight; Ymax: maximum weight of cherries per plant or bunchy; x_n: the n^{th} independent variable; K and R are constants.

For relations that are not significant but show a polynomial function, and quadratic model was fitted on upper points.

For each coffee or banana sub-plot, assuming responses according to von Liebig's law of the minimum (Lark *et al*., 2020), the minimum predicted yield (*Ymin*) was identified (Equation 6).

$$Ymin = Min\ (Yx1,\ Yx2,\ \ldots\ldots,Yxn) \quad (6)$$

For each factor, the number of plots in which it was identified as the most limiting was calculated in each sub-plot type. This allowed the ranking of most limiting factors per sub-plot (NC, FC, NB, FB) with the most important constraint being the factor that was most often identified as corresponding to *Ymin*.

Statistical analysis

Data used were the average of the different variables at the sub-plot level (near banana (NB), far from banana (FB), near coffee (NC) and far from coffee (FC)) and the ANOVA I was used after the normality test. Statistical analysis and graphics were performed using MS Excel and means ranked with Tukey's test. The level of significance was $p \leq 0.05$.

RESULTS

Yield, yield components and morphological characteristics

Banana yield per cycle far from coffee and near coffee was

Table 1. Minimum, Maximum and means (± standard error of mean (s.e.m)) of coffee and banana yield and coffee and banana yield components (N = 60) according to banana and coffee sub-plots location (FC: far from coffee, NC: near coffee; FB: far from banana, NB: near banana).

	Min	Max	Mean ± s.e.m	Min	Max	Mean ± s.e.m
Banana		**FC**			**NC**	
BY[1] ($Mg\ ha^{-1}$)	3.1	42.6	10.4 ± 0.8^{a}	6.5	69.0	28.6 ± 1.8^{b}
BW[2] (kg)	3.4	16.0	8.0 ± 0.3^{a}	3.7	26.6	15.1 ± 0.6^{b}
Density (plants ha^{-1})	535	3077	1321 ± 77^{a}	504	3546	1949 ± 100^{b}
BAB[3] ($Mg\ ha^{-1}$)	2.70	27.19	10.1 ± 0.7^{a}	2.49	36.0	15.5 ± 1.0^{b}
Coffee		**FB**			**NB**	
CCY[4] ($Mg\ ha^{-1}$)	1.6	10.5	4.9 ± 0.3^{a}	1.92	8.35	4.8 ± 0.2^{a}
CP[5] (kg $plant^{-1}$)	0.7	3.4	2.01 ± 0.1^{a}	0.98	3.45	1.98 ± 0.01^{a}
P100[6] (g)	127.4	174.3	152.2 ± 2.4^{a}	120.1	187.1	161.6 ± 3.4^{b}

[1] BY: banana yield, [2] BW: bunch weight [3] BAB: banana aboveground biomass; [4] CCY: coffee cherries yield, [5] CP: cherry production, [6] P100: weigh of 100 cherries. Means with the same letter in the lines are not significantly different at p ≤ 0.05.

Table 2. Minimum, Maximum and means (± standard error of mean (s.e.m)) of coffee and banana morphological characteristics (N = 60) according to banana and coffee sub-plots location (FC: far from coffee, NC: near coffee; FB: far from banana, NB: near banana).

	Min	Max	Mean ± s.e.m	Min	Max	Mean ± s.e.m
Banana		**FC**			**NC**	
BH[1] (m)	2.5	4.7	3.2 ± 0.1 a	3	4.7	3.8 ± 0.1 b*
BBG[2] (cm)	45.6	72.2	58.4 ± 0.8 a	57.8	88.8	72.7 ± 0.9 b
Coffee		**FB**			**NB**	
CH[3] (m)	1.3	4.2	2.9 ± 0.07 a	1.3	4	3.0 ± 0.07 a
CBG[4] (cm)	7	20	13.1 ± 0.4 a	5.8	18.3	12.6 ± 0.4 a
NN[5]	6	17	11 ± 0.3 a	6	15	10.1 ± 0.3 a
B-LN[6] (cm)	27.0	51.1	37.9 ± 0.7 a	26.0	63.6	40.6 ± 1.0 b
NL[7]	1	7	5.0 ± 0.2 a	3	12	6.0 ± 0.2 b

[1] BH: Banana plant height; [2] BBG : banana plant girth at 0 m ; [3] CH : Coffee plant height ; [4] CBG : coffee plant girth at 0 m ; [5] NN : number of nodes; [6] B-LN: Branch length ; [7] NL : number of leaves; * : means with the same letter in rows are not significantly different at
p ≤ 0.05.

significantly different ($p < 0.001$) with an average of 10 Mg ha^{-1} far from coffee and 29 Mg ha^{-1} near coffee (Table 1). Similarly, the average of bunch weight, density and aboveground biomass were significantly higher near coffee, with values equal to 189, 148 and 153% of values observed far from coffee for bunchy weight, density and aboveground biomass, respectively.

For coffee, the average cherry yield per hectare and the average cherry weight per plant were not significantly different between coffee sub-plots (Table 1). Though the weight of 100 cherries was significantly higher near banana with an increase of 7% compared to far from banana sub-plots and those weights were 152 and 163 g far from banana and near banana respectively.

Banana morphological characteristics were significantly higher near coffee. Thus, banana height was 4 m near coffee and 3 m far from coffee and girth at 0 m was 58 cm and 73 cm far from coffee and near coffee respectively (Table 2). Coffee plant height, stem base girth and the number of nodes per branch were not different between coffee sub-plots (Table 2). However, the branch length and the number of leaves per branch were significantly higher near banana. Branch length was 38 cm far from banana and 41 cm near banana. The number of leaves per branch was 5 and 6 far from banana and near banana respectively. Consequently, the internodes length and the number of leaves per node were significantly higher near banana with respective values of 4.1 cm and 0.5 cm near banana and 3.7 cm and 0.4 far from banana.

Leaf analysis and compositional nutrient diagnosis (CND)

In banana sub-plots, foliar analysis results showed that the values recorded near coffee were significantly higher for

Table 3. Minimum, Maximum and means (± standard error of mean (s.e.m)) of coffee and banana leaf nutrients content (N = 60) according to banana and coffee sub-plots location (FC: far from coffee, NC: near coffee; FB: far from banana, NB: near banana).

	Min	Max	Mean ± s.e.m	Min	Max	Mean ± s.e.m
Banana		**FC**			**NC**	
N (%)	1.50	3.21	2.41 ± 0.05[a]	1.96	3.51	2.74 ± 0.04[b] *
P (%)	0.10	0.31	0.19 ± 0.01[a]	0.13	0.42	0.21 ± 0.01[b]
K (%)	1.67	4.02	3.06 ± 0.07[a]	2.43	4.08	3.47 ± 0.04[b]
Ca (%)	0.49	1.85	0.99 ± 0.04[a]	0.92	1.40	1.21 ± 0.02[b]
Mg (%)	0.18	0.58	0.35 ± 0.01[a]	0.23	0.52	0.34 ± 0.01[a]
Zn (ppm)	1.99	11.36	6.57 ± 0.27[a]	4.19	12.57	8.66 ± 0.21[b]
Coffee		**FB**			**NB**	
N (%)	1.20	3.13	2.65 ± 0.04[a]	1.99	3.23	2.77 ± 0.04[b]
P (%)	0.07	0.29	0.17 ± 0.01[a]	0.09	0.26	0.16 ± 0.01[a]
K (%)	0.95	3.85	2.29 ± 0.08[a]	1.64	4.3	2.70 ± 0.07[b]
Ca (%)	0.22	1.18	0.71 ± 0.03[a]	0.17	1.5	0.99 ± 0.03[b]
Mg (%)	0.15	0.77	0.41 ± 0.01[a]	0.03	0.75	0.38 ± 0.02[a]
Zn (ppm)	0	3.05	1.33 ± 0.11[a]	0	4.58	1.56 ± 0.20[a]

*means with the same letter in rows are not significantly different at p ≤ 0.05.

all analyzed elements except for Mg for which there was no difference between banana sub-plots (Table 3). In coffee sub-plots, leaf analysis showed significantly higher values for N, K and Ca near banana compared to far from banana. For other nutrients, there was no difference between coffee sub-plots.

In banana plots, deficiencies of K and Mg had been observed in the two banana sub-plot types (Figure 3a) when Ca was in excess. The indexes of N and P were not significantly different to 0, when K and Mg indexes were significantly lower than 0, and Ca was significantly higher than 0 ($p < 0.001$). The deficiency of Mg and excess of Ca were significantly higher near coffee. 97% of sub-plots near coffee were deficient in Mg when this percentage was 90% in sub-plots far from coffee. 100% of sub-plots near coffee had an excess of Ca against 85% in sub-plots far from coffee. For other nutrients, higher indexes were observed near coffee although not significant.

Coffee plots had an excess of N and deficiency of P (Figure 3b). Sub-plots near banana were significantly deficient in P. In those sub-plots, P deficiency was observed in 93% of them when the frequency of deficiency was 78% for sub-plots far from banana. For cations, excess of K and Ca had been observed near banana and excess of Mg far from banana. The deficiency of K and Ca had been registered in sub-plots far from banana. In those sub-plots, 62% of them were deficient in K and 78% in Ca. The indexes of Mg near banana were not different to 0. For all cations, the differences between sub-plots were significant.

Fertility management and soil results

In visited coffee plots, there was no application of neither manure nor mineral fertilizers. Similarly, mulch was not supplied in banana plots. However, manure was applied in 53% of sub-plots far from coffee and in 25% of sub-plots near coffee. Chemical fertilizers were applied only in 22% of sub-plots located far from coffee.

In coffee sub-plots, the depth of mulch was significantly higher near banana, with a thickness average of 5.4 cm near banana and 3.6 cm far from banana. Banana residues were the most used as mulching material because those residues were dominant in 50% of sub-plots far from banana and 71% near banana. The second most important source of mulch were wild grasses which were dominant in 18% of coffee sub-plots located far from banana and 1% of coffee sub-plots located near banana.

Soil physicochemical characteristics were significantly higher in coffee sub-plots for all nutrients except for P and Zn where the highest values were observed in banana sub-plots (Table 4). In coffee sub-plots, significantly higher values of Corg, N, P and Mg were obtained near banana compared to far from banana. In banana sub-plots, the highest values of Mg and N were observed far from coffee while the values of K were higher near coffee.

Limiting factors

In near coffee banana sub-plots, significant correlations with Spearman's test between bunchy weight in one hand, and soil and crop management factors in the other hand were observed for Corg ($r = 0.30$), N ($r = 0.29$), Zn ($r = 0.39$), pH ($r = -0.28$) and banana density ($r = -0.29$). Other factors (P, K, Mg and K / (Ca + Mg) ratio) were selected because the scatter plots showed a functional relationship with the bunchy weight (Figure 4a). In far from coffee

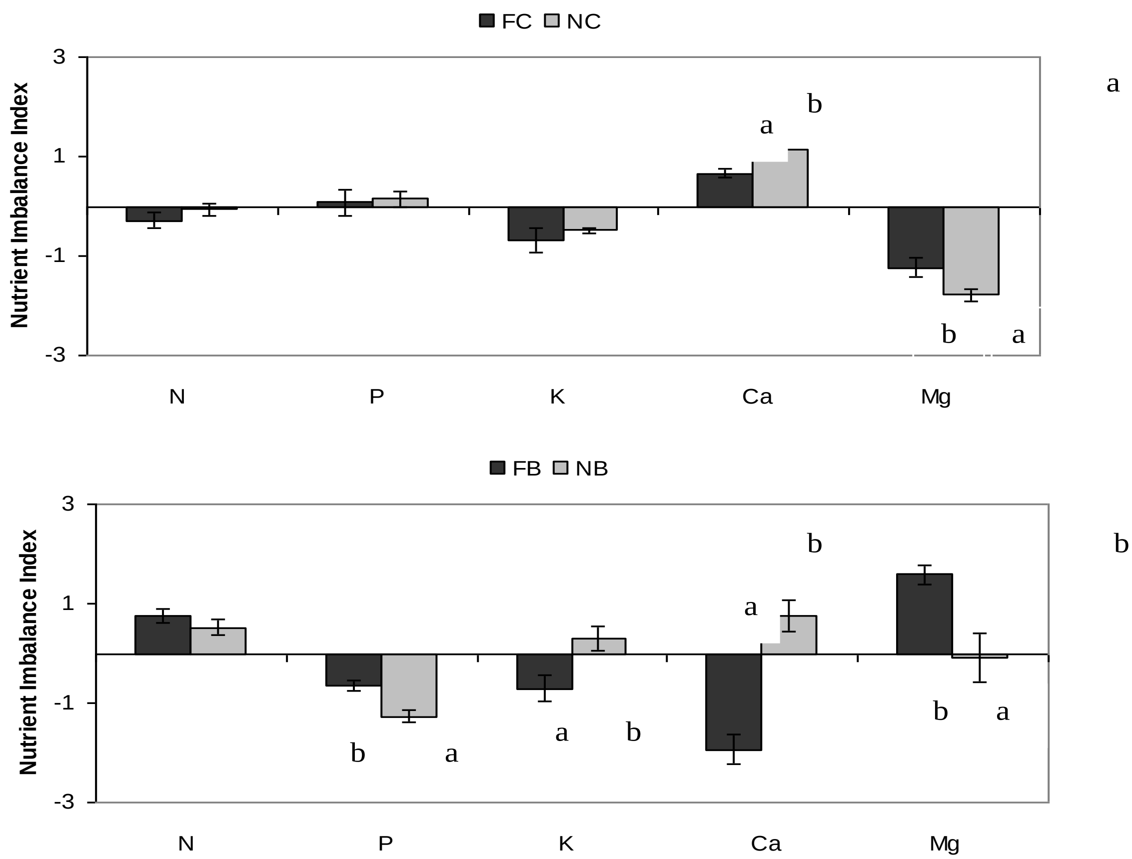

Figure 3. CND index of N, P, K, Ca, Mg according to coffee and banana sub-plots location (FC: far from coffee, NC: near coffee; FB: far from banana, NB: near banana). The bars represent standard deviations. The values with different letters between banana sub-plots or coffee sub-plots are statistically different at $p \leq 0.05$. There is no letter for no significantly different values.

Table 4. Minimum, maximum and means (± standard error of mean (s.e.m)) of soil characteristics (N = 60) according to banana and coffee sub-plots location (FC: far from coffee, NC: near coffee; FB: far from banana, NB: near banana).

	Banana		Coffee	
	FC	NC	FB	NB
	Mean ± s.e.m	Mean ± s.e.m	Mean ± s.e.m	Mean ± s.e.m
pH	5.88 ± 0.1 a (a)	5.90 ± 0.1 a (a)	6.18 ± 0.07 b (a)	6.16 ± 0.1 b (a)
Corg (%)	2.96 ± 0.10 a (a)	2.71 ± 0.08 a (a)	3.11 ± 0.08 ab (a)	3.71 ± 0.11 b (b)
N (%)	0.26 ± 0.01 a (b)	0.24 ± 0.01 a (a)	0.28 ± 0.01 ab (a)	0.31 ± 0.01 b (b)
P (ppm)	3.53 ± 0.68 ab (a)	3.87 ± 0.94 b (a)	1.67 ± 0.16 a (a)	2.65 ± 0.14 ab (b)
K (cmolc kg^{-1})	0.18 ± 0.01 a (a)	0.23 ± 0.01 a (b)	0.45 ± 0.03 b (a)	0.46 ± 0.04 b (a)
Ca (cmolc kg^{-1})	7.33 ± 0.30 a (a)	7.41 ± 0.34 a (a)	9.35 ± 0.64 b (a)	9.73 ± 0.39 b (a)
Mg (cmolc kg^{-1})	1.01 ± 0.04 b (b)	0.7 ± 0.03 a (a)	0.98 ± 0.07b (a)	1.15 ± 0.05 c (b)
Zn (ppm)	6.78 ± 0.21 b (a)	6.04 ± 0.46 b (a)	4.42 ± 0.14 a (a)	4.16 ± 0.32 a (a)

Means with the same letter in the lines are not significantly different at $p \leq 0.05$. The letters in parenthesis indicate comparisons between coffee and banana sub-plots; letters out of parenthesis show the comparisons within coffee sub-plots or banana sub-plots.

banana sub-plots, significant correlations with Spearman's test between bunchy weight and soil and crop management factors were observed for Corg (r = 0.30), N (r = 0.29), Ca (r = 0.33) and Zn (r = 0.39). Other factors (P, K, Mg and K / (Ca + Mg) ratio) were selected because the scatter plots showed a functional relationship with the

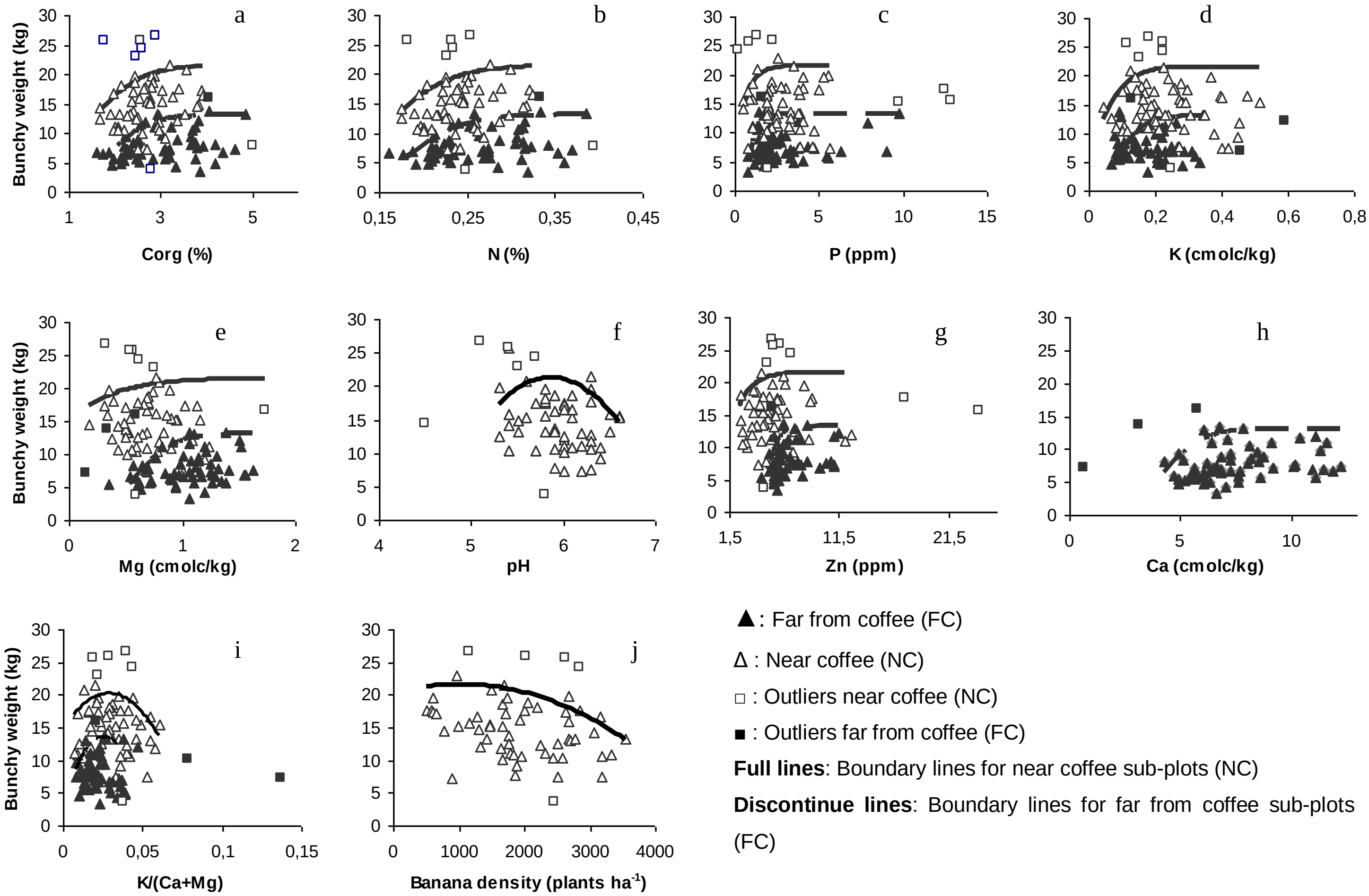

Figure 4a. Relationship between soil and management factors and bunch weight in banana sub-plots.

bunchy weight.

For coffee sub-plots near banana, all factors (Corg, N, P, K, Mg, depth of mulch, the K/(Ca + Mg) ratio, pH, Zn) were selected because the scatter plots showed a functional relationship with the cherry weight per plant (Figure 4b). In coffee sub-plots far from banana, the only significant correlation with cherry weight per plant was Mg (r = 0.29). Corg, N, P, K, the depth of mulch, pH, and Zn were chosen because the scatter plots showed a functional relationship with cherry weight per tree.

In banana sub-plots near coffee, the most limiting factor was K / (Ca + Mg) ratio observed in 28% of sub-plots, followed by pH with 22% of sub-plots, Zn in 13%, P and N in 12% of the sub-plots (Figure 5). In sub-plots FC, the most limiting factor was K observed in 22% of sub-plots, followed by Mg in 17%, Corg in 15%, pH and P in 12% sub-plots each and Zn observed in 10% of sub-plots.

In coffee sub-plots near banana, the Corg was the most limiting in 18% of the sub-plots, followed by mulch depth in 17% of the sub-plots, Zn in 15% of sub-plots, P and K in 12% of sub-plots near banana (Figure 5). Other factors were liming in less than 10% of these sub-plots. In coffee sub-plots far from banana, Zn was the most limiting factor in 28% of the sub-plots, followed by N in 20% of sub-plots, mulch depth in 13%, P in 12% and Mg in 10% of those sub-plots.

DISCUSSION

Yield of banana and coffee and morphological characteristics

Banana yield per hectare, bunch weight and plant density were higher near coffee banana sub-plots (Table 1). The high yield per hectare near coffee was therefore due to the highest of the bunch weight and banana density. The bunchy weight recorded in these two sub-plots was lower than the bunchy weight of 17 kg registered in Uganda (Wairegi *et al*., 2009). Morphological characteristics of banana (height, the girth at 0 m) were significantly higher near coffee than far from coffee (Table 2). Morphological characteristics are also well correlated with bunch weight (Wairegi *et al*., 2009). The highest yield, biomass and morphological characteristics of banana recorded near coffee are due to banana plants that uptake water and

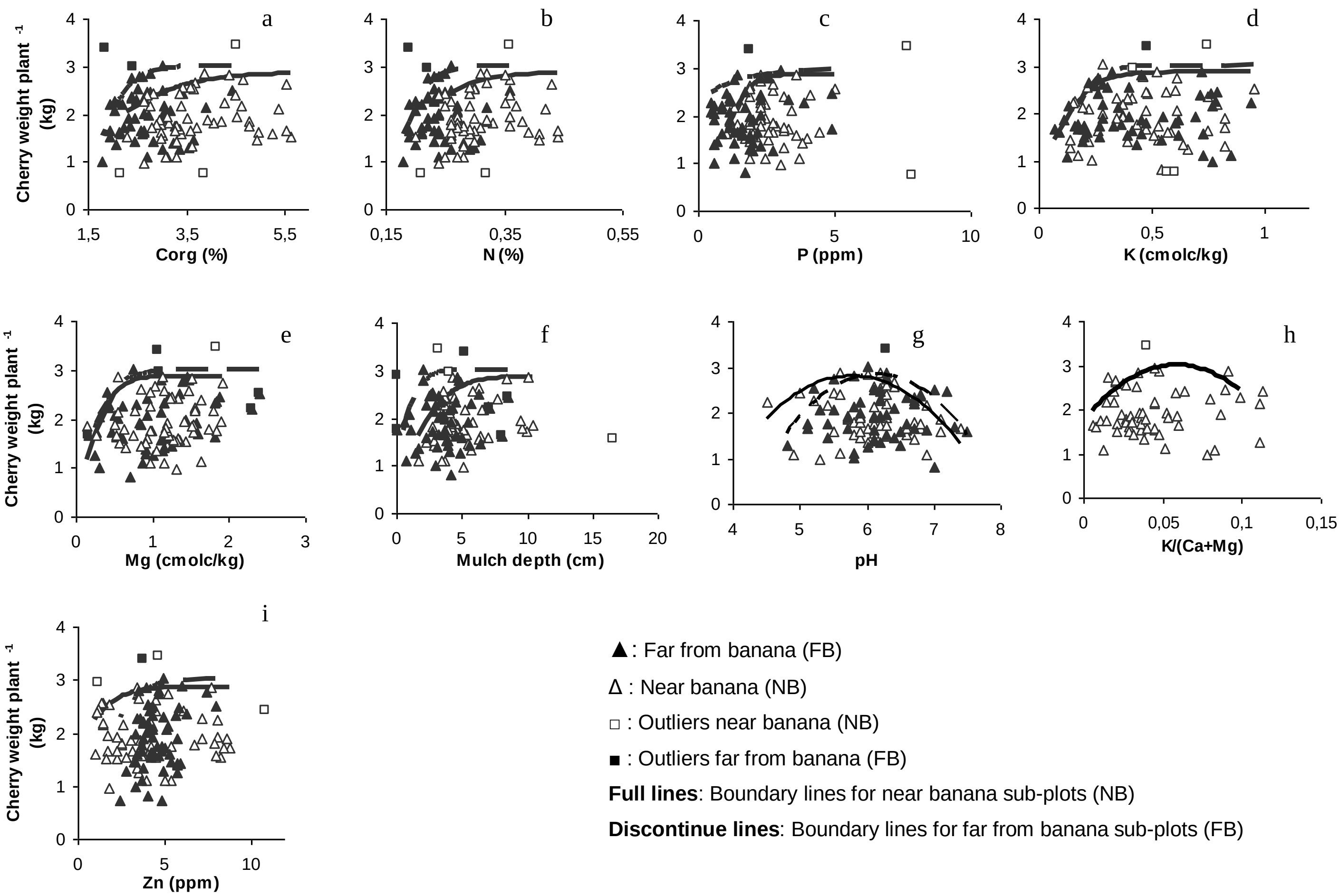

Figure 4b. Relationship between soil and management factors and cherry weight per plant in coffee sub-plots.

nutrients in coffee sub-plots because the characteristics of the soils were similar near coffee and far from coffee but higher in coffee sub-plots (Table 4). The length of the banana roots can reach more than 4 m (Avilán *et al.*, 1982; Sebuwufu *et al*., 2004) and can explore coffee sub-plots near banana which are richer in N, K, Ca and Mg (Table 4), the uptake of the main element by a banana plant (Lahav 1995). Additionally, banana near coffee can benefit from the advantages of mulch observed in coffee sub-plots near banana such as the soil moisture conservation (Chakraborty *et al*., 2008). A plot of 3 m thick may seem insignificant. But, under food production deficit (Zoyem *et al*., 2008) and land scarcity, banana harvested in this plot can mitigate food insecurity.

Coffee yield per hectare and cherry production per hectare were not different between sub-plots (Table 1). The yield of cherries per hectare was higher than the average yield observed in other studies which was less than 3 Mg ha^{-1} (Office du Café du Burundi, 2009). This could suggest that coffee plots near banana plots have soil relatively richer than the average. Coffee yields near banana and far from banana were the same while soil characteristics were higher in coffee sub-plots near banana (Table 4). This suggests that the presence of banana has negatively affected coffee production because without banana and conditions remaining the same, the yield of coffee would be higher in coffee sub-plots near banana. The weight of 100 cherries was higher near banana (Table 1). The weight of 100 cherries is one of the indicators of coffee quality (Muschler, 2001; Steiman *et al.*, 2011.). This difference in weight of 100 cherries is due to the shade of coffee by banana, higher K content in coffee leaves (Table 3) and the number of leaves which was higher near banana (Table 2). Muschler (2001) showed that the weight of 100 cherries was higher in coffee plots under shade. The same researcher also showed that the weight of green beans was higher under shade, meaning that the difference of weight recorded in cherries is maintained for green beans. Bosselmann *et al.* (2009) found that the percentage of large grains (size > 16 mm) increased with shade. Additionally, potassium fertilization increases the cherry weight. Cong *et al.* (2001) showed that nitrogen fertilization increased coffee yield while potassium fertilization increased the weight of cherries. Thus, K content in the coffee leaves near banana was higher (Table 3), meaning that coffee plots near banana

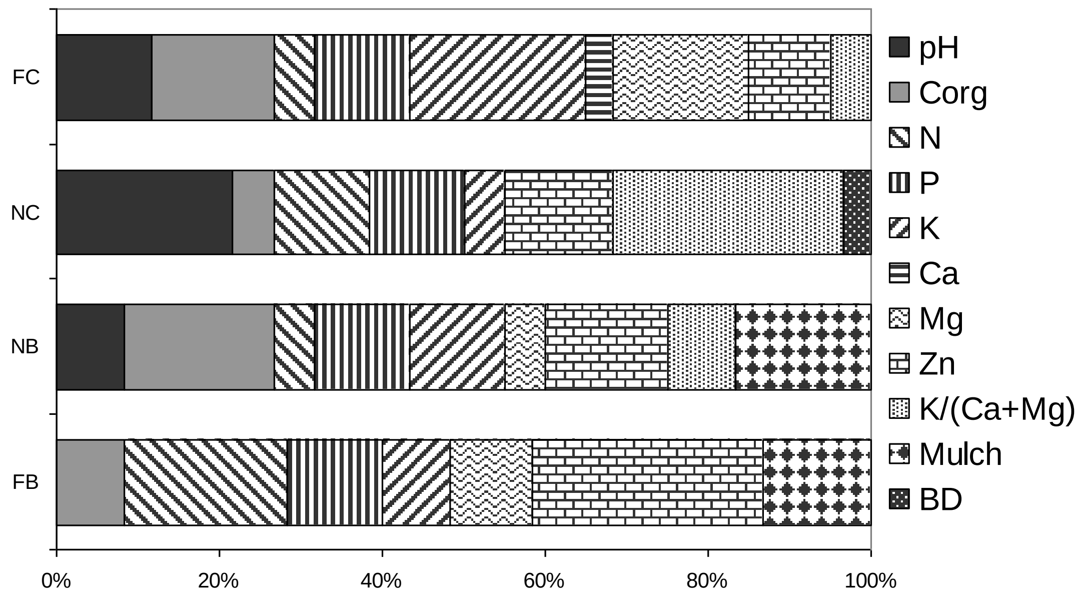

Figure 5. Limiting factors identified with boundary line method and the corresponding percentage in which these factors were most limiting, depending on banana and coffee sub-plots location (far from coffee (FC), near coffee (NC), near banana (NB), far from banana (FB). BD: Banana density; Corg: organic carbon in soil.

have good K nutritional status comparatively to coffee plots far from banana. Because the cherry filling is made from leaves, cherry weight is higher for branches with a high number of leaves (Lima Filho and Malavolta, 2003). This was the case in this study where the number of leaves was higher in sub-plots near banana (Table 2).

The branch length and the number of leaves per branch were significantly higher near banana (Table 2). Branch length was higher due to longer internodes not to the increase of the number of nodes per branch (Table 2) because the number of nodes remained the same in the two coffee sub-plots. Thus, the presence of banana affected some morphological characteristics of coffee near banana. The increase of internodes length and the number of leaves in shaded coffee had also been observed by Campanha *et al.* (2004). According to Morais *et al.* (2009), when the shading is intense, plant height increases and girth decreases. This was not observed in this study (Table 2) maybe because the shade was from one side.

Impact of cultural practices on the nutrient levels in soil and leaves

Compared with near coffee banana sub-plots, far from coffee banana sub-plots were preferentially fertilized with organic and mineral fertilizers. This led to an increase of soil N and Corg in sub-plots far from coffee.

In coffee sub-plots, the depth of mulch was significantly higher near banana. In all sub-plots, the mulch depth was less than 10-12 cm proposed by Gaie and Flémal (1988) in Burundi, but the values were close to the optimal depth of 4 cm given by Wairegi and van Asten (2010) for highland banana. The higher depth of mulch near banana coffee sub-plots had positively affected the physicochemical characteristics of the soil. Higher levels of Corg, N, P and Mg were observed near banana where mulch depth was higher compared to far from banana sub-plots. Mulch is the principal source of organic matter (C, N) and cations (Rodrigo *et al.,* 2001) of coffee plots in Burundi because no manure is applied. In a study done by Youkhana and Idol (2009), mulch helped to increase significantly soil N and Corg content over a period of 4 years. Corg, N, K, Ca and Mg were higher in coffee plots compared to banana plots (Table 4). This can be explained by the export of banana residues to coffee plots. Fertility transfer from banana plots through mulching might provide cations mainly K (Pozy and Dehareng, 1996). The difference between coffee sub-plots was not due to the difference of mulch depth observed during this study, but the preferred application of mulch near banana which had been carried out regularly over a long period.

Foliar analysis showed that banana sub-plots near coffee had a better nutritional status compared to banana sub-plots far from coffee (Table 3). By comparing the values obtained with the critical values of N, Mg and Zn proposed by Wortmann *et al.* (1992), these elements were deficient in all banana sub-plots. This was confirmed by CND indexes analysis for N and Mg (Figure 3). K leaf content was equal or greater than the critical value of 3% (Table 3) in the two banana sub-plots, although CND indexes showed that this element was deficient. In both sub-plots near and far from coffee, Ca values were above the critical value of 0.54% proposed by Delstanche (2011). This was confirmed by analysis of CND indexes which showed that Ca was excess in banana sub-plots. Wairegi and van Asten (2010) had also showed that Ca was not a constraint in highland banana in Uganda.

The values obtained by coffee foliar analysis were significantly higher in sub-plots near banana for N, K and Ca. For other factors such as P, Mg and Zn, the differences between sub-plots location were not significant (Table 3). According to norms values proposed by Snoeck and Lambot (2009), deficiency is only observed for Zn. Zn deficiency was higher because the values obtained were 10 times less than the critical values. Sometimes, it was a contradiction between the proposed standards to identify deficiencies of nutrients in leaves and CND indexes. Nutrients in normal leaves can appear deficient with CND indexes analysis. This is due to CND indexes considering the balance of all nutrients (van Asten and Wairegi, 2010; Wairegi and van Asten, 2012) when norms are established for each nutrient separately.

Limiting factors

Far from coffee, limiting factors were of importance in order; K, Mg, Corg, P, pH, Zn, K / (Ca + Mg), N and Ca (Figure 5a). For K and Mg, analysis of CND indices showed that these elements were deficient in banana leaves while Ca was surplus and N was close to 0 (Figure 4). In sub-plots near coffee, limiting factors were of importance in order; K / (Ca + Mg), pH, Corg, P, Zn, K, N and density of bananas (Figure 5). In coffee sub-plots, limiting factors far from banana were of importance in order; Zn, N, the depth of mulch, P, Mg, K, pH and Corg. Content Zn was the most limiting factor far from banana coffee sub-plots. The deficiency of Zn has been mentioned in Burundi since 1988 (Gaie and Flémal 1988). The limiting factors were Corg, the depth of mulch, Zn, P and K near banana (Figure 5). The Corg and depth of mulch were the most limiting factors near banana, and even the respective values were higher in those coffee sub-plots (Table 4). This is due to that whenever there is a limiting factor correction, another limiting factor appears. Soil sub-plots near banana is richer in nutrients (Table 4), but management factors such as mulching and organic matter are limited.

Limiting factors observed far from banana coffee sub-plots, far from coffee banana sub-plots and near coffee banana sub-plots are mostly factors related to soil quality (K, Mg, Corg, P, N, K / (Ca + Mg), pH, Zn) and secondarily related to crop management (amount of mulch and banana density). Wairegi and van Asten (2010), van Asten and Wairegi (2012) and Delstanche (2011) found that the same factors were limiting for banana in varying proportions depending upon regions in Uganda and Rwanda. Zn is an important limiting factor for coffee sub-plots far from banana. The ratio of cations (K / (Ca + Mg) was limiting in banana sub-plots near coffee. Imbalance leads to competition between cations in the absorption of these cations and they may be deficient even if they are available in the soil (Boyer 1978).

Banana and coffee interactions in near coffee and near banana sub-plots

Banana residues from sub-plots near coffee brought to coffee sub-plots near banana increased thickness of mulch and improved the physicochemical characteristics of soil (Table 4). Thus, coffee sub-plots near banana are richer than those far from banana. On the other hand, there is no fertility transfer from coffee plots to banana plots and the level of fertility is not different between the two types of banana sub-plots (Table 4). Although the soil characteristics were the same in banana sub-plots, the yields and the yield components were higher in the sub-plots near coffee (Table 1). In addition, the nutrient contents were higher in leaves of banana near coffee (Table 3). The only source of these nutrients that led to high yield in banana sub-plots near coffee was coffee plots that are within 4 m from banana sub-plots near coffee (Sebuwufu *et al*., 2004). Thus, bananas can uptake nutrients and water in the coffee sub-plots near banana enriched by banana residues from banana sub-plots near coffee. In addition, there was no significant difference in yield between coffee sub-plots (Table 1), while the values of the soil characteristics were higher in the subplots closer to banana (Table 4). The presence of bananas did not allow the richness of coffee sub-plots near banana to be expressed in terms of yield. Bananas competed with coffee trees which prevented the latter from yielding better than sub-plots far from the banana.

Certain morphological characteristics show that coffee has been affected by shade provided by banana leaves from banana sub-plots near coffee. This is the case for the length of primary branches, length of internodes and number of leaves per node which were higher in coffee sub-plots near banana (Table 2). Similar results were found by comparing coffee trees under shade and coffee trees without shade (Morais *et al*., 2003; Campanha *et al*., 2004). The main morphological characteristics of coffee trees such as height and circumference at girth were not affected by the presence of bananas (Table 2), because the richness of coffee sub-plots near banana made the coffee plants more vigorous. The fact of having the same main morphological characteristics in the plots which do not have the same soil physicochemical characteristics shows that banana negatively affected the growth of coffee trees.

CONCLUSION

Bananas placed near coffee had a high yield without affecting the production of coffee near banana.

Furthermore, the weight of 1000 cherries, an indicator of coffee quality, was higher near banana. With this banana-coffee system, farmers gain on banana production and coffee quality. Banana affected some morphological characteristics of coffee, but the effect of shade was moderate and the main characteristics of the coffee plant such as height, girth at the base and the number of nodes per branch were not affected. The physical and chemical characteristics of coffee plots were generally higher than those of banana plots. This shows that mulch can significantly improve soil fertility in coffee plots. Applying a higher quantity of mulch in coffee sub-plots located near banana with banana residues had led to the increase of soil characteristics in these sub-plots. The analysis of this system has shown that these two crops benefit from each other in adjunct sub-plots (banana near coffee and coffee near banana), and the competition from banana was not harmful to coffee because they have benefited from banana residues applied as mulch.

ACKNOWLEDGEMENT

The authors are grateful to the host farmers who had welcomed them in their plots where the data was collected. This research was funded by DGCD, Belgium and IITA through Consortium for Improving Agriculture-based Livelihoods in Central Africa (CIALCA).

Conflict of interest statement

Anaclet Nibasumba, Laurence Jassogne, Piet VanAsten, Gilbert Nduwayo, Claudette Nkurunziza, Charles Bielders and Bruno Delvaux declared that they have no conflict of interest.

REFERENCES

Avilán RL, Meneses RL, Sucre RE (1982). Distribución radical del banano bajo diferentes sistemas de manejo de suelos. Fruits, 37(2):103-110.

Beer J (1987). Advantages, disadvantages and desirable characteristics of shade trees for coffee, cacao and tea. Agrofor. syst. 5(1):3-13. http://dx.doi.org/10.1007/BF00046410.

Bizimana S (2018). L'agriculture de conservation peut-elle améliorer la fertilité des sols et la productivité des systèmes bananiers en Région des Grands Lacs? (Doctoral dissertation, UCL-Université Catholique de Louvain).

Bosselmann AS, Dons K, Oberthur T, Olsen CS, Ræbil A, Usma H (2009). The influence of shade trees on coffee quality in small holder coffee agroforestry systems in Southern Colombia. Agric. Ecosyst. Environ. 129:253-260.

Boyer J (1978). Le calcium et le magnésium dans les sols des régions tropicales humides et sub-humides. Initiations - Documentations Techniques no 35. ORSTOM, Paris, p. 173.

Campanha MM, Silva Santos RH, Bernardo de Freitas G, Martinez HEP, Garcia SLR, Finger FL (2004). Growth and yield of coffee plants in agroforestry and monoculture systems in Minas Gerais, Brazil. Agrofor. Syst. 63:75-82. http://dx.doi.org/10.1023/B:AGFO.0000049435.22512.2d.

Chakraborty D, Nagarajan S, Aggarwal P, Gupta VK, Tomar RK, Garg RN, Kalra N (2008). Effect of mulching on soil and plant water status, and the growth and yield of wheat (*Triticum aestivum* L.) in a semi-arid environment. Agric. Water Manag. 95(12):1323-1334.

Cochet H (1996). Gestion paysanne de la biomasse et développement durable au Burundi. Cah. Sci. Hum. 32:133-151.

Cong P, Sat C, Härdter R (2001). Response of selected crops to K fertilization on major soil types in South Vietnam. Plant nutrition – Food security and sustainability of agro-ecosystems. http://dx.doi.org/10.1007/0-306-47624-X_399.

Daryanto S, Fu B, Zhao W, Wang S, Jacinthe PA, Wang L (2020). Ecosystem service provision of grain legume and cereal intercropping in Africa. Agric. Syst. 178:1027-61. http://dx.doi.org/10.1016/j.agsy.2019.102761.

Delstanche S (2011). Drivers of soil fertility in smallholder banana systems in the African Great Lakes Region. PhD thesis Université Catholique de Louvain, Louvain-la-Neuve, Belgium.

Fermont AM, van Asten PJA, Tittonell P, van Wijk MT, Giller KE (2009). Closing the cassava yield gap: an analysis from smallholder farms in East Africa. Field Crops Res. 112:24-36. http://dx.doi.org/10.1016/j.fcr.2009.01.009.

Gaie W, Flémal J (1988). La culture du cafeier d'arabie au Burundi. ISABU–Administration Générale de la Coopération au Développement. Publication du Service Agricole, (14).

Gambart C, Swennen R, Blomme G, Groot JC, Remans R, Ocimati, W (2020). Impact and opportunities of agroecological intensification strategies on farm performance: A case study of banana-based systems in central and south-western Uganda. Front. Sustain. Food Syst. 4:87.

Gomes LC, Bianchi FJJA, Cardoso IM, Fernandes RBA, Fernandes Filho EI, Schulte RPO (2020). Agroforestry systems can mitigate the impacts of climate change on coffee production: a spatially explicit assessment in Brazil. Agric. Ecosyst Environ. 294:106858.

Institut Géographique du Burundi (2015). Internal data.

Lahav E (1995). Banana nutrition in Banana and plantains. INIBAP, Chapman & Hall. Glasgow, Weinheim, New York. 259-316.

Lark RM, Gillingham V, Langton D, Marchant BP (2020). Boundary line models for soil nutrient concentrations and wheat yield in national-scale datasets. Eur. J. Soil Sci. 71(3):334-351.

Li C, Hoffland E, Kuyper TW, Yu Y, Li H, Zhang C, van der Werf W (2020). Yield gain, complementarity and competitive dominance in intercropping in China: A meta-analysis of drivers of yield gain using additive partitioning. Eur. J. Agronom. 113:125987.

Lima filho OF, Malavolta E (2003). Studies on mineral nutrition of the coffee plant (*coffea arabica* l. cv. catuaí vermelho): remobilization and re-utilization of nitrogen and potassium by normal and efficient plants. braz. J. boil. 63:481-490. http://dx.doi.org/10.1590/S1519-69842003000300014.

Lin BB (2010). The role of agroforestry in reducing water loss through soil evaporation and crop transpiration in coffee agroecosystems. Agric. For. Meteorol. 150(4):510-518. http://dx.doi.org/10.1016/j.agrformet.2009.11.010.

Mehlich A (1984). Mehlich 3 soil test extractant: A modification of Mehlich 2extractant. Communications in soil science and plant analysis, 15(12): 1409-1416. http://dx.doi.org/10.1080/00103628409367568.

Morais H, Caramori PH, Koguishi MS, Gomes JC, Ribeiro AMDA (2009). Sombreamento de cafeeiros durante o desenvolvimento das gemas florais e seus efeitos sobre a frutificação e produção. Ciência Rural, 39:400-406.

Muliele TM (2020). Effect of Tillage Tools (Hand Hoe and Fork) on Banana Rooting System of the East African Highlands Banana. Int. J. Innov. Appl. Stud. 29(2):236-239.

Muschler RG (2001). Shade improves coffee quality in a sub-optimal coffee-zone of Costa Rica. Agrofor. Syst. 85:131-139.

Ndihokubwayo S, Havyarimana T, Windbühler S, Niragira S, Habonimana B, Kaboneka S, Megerle HE (2021). Farmers' Perception of Coffee Agroforestry Systems in an Area Targeted for Organic Certification in Burundi. East Afr. J. For. Agrofor. 3(1):40-53.

Nyombi K, van Asten PJA, Leffelaar PA, Corbeels M, Kaizzi CK, Giller KE (2009). Allometric growth relationships of East Africa highland bananas (*Musa* AAA-EAHB) cv. Kisansa and Mbwazirume. Ann. Appl. Biol. 155:403-418.

Nzeyimana I, Hartemink AE, Ritsema C, Mbonigaba JJM, Geissen V (2020). Mulching effects on soil nutrient levels and yield in coffee farming systems in Rwanda. Soil Use Manag. 36(1):58-70.

Office du Café du Burundi (2009). Internal data.

Partelli FL, Cavalcanti AC, Menegardo C, Covre AM, Gontijo I, Braun H (2020). Spatial distribution of the root system of Conilon and Arabica coffee plants. Pesquisa Agropecuária Brasileira, p. 55.

Perdoná MJ, Soratto RP (2020). Arabica coffee–macadamia intercropping: Yield and profitability with mechanized coffee harvesting. Agronom. J. 112(1):429-440.

Pozy P, Dehareng D (1996). Composition et valeur nutritive des aliments pour animaux au Burundi. AGCD-ISABU, Publication agricole n° 37:59.

Rigal C, Xu J, Vaast P (2020). Young shade trees improve soil quality in intensively managed coffee systems recently converted to agroforestry in Yunnan Province, China. Plant Soil, 453(1):119-137.

Rodrigo VHL, Stirling CM, Teklehaimanot Z, Nugawela A (2001). Intercropping with banana to improve fractional interception and radiation-use efficiency of immature rubber plantations. Field Crops Res. 69:237-249. http://dx.doi.org/10.1016/S0378-4290(00)00147-7.

Schnug E, Heym J, Achwan F (1996). Establishing critical values for soil and plant analysis by means of the boundary line development system (Bolides). Commun. Soil Sci. Plant Anal. 27:2738-2739. http://dx.doi.org/10.1080/00103629609369736.

Sebatta C, Mugisha J, Bagamba F, Nuppenau EA, Domptail SE, Ijala A, Karungi J (2020). Efficiency and possibilities for Arabica coffee-banana management systems switching in the Mt. Elgon landscape of Uganda. Afr. Crop Sci. J. 28(3):421-439.

Sebuwufu G, Rubaihayo PR, Blomme G (2004). Variability in the root system of East African banana genotypes. Afr. Crop Sci. J. 12(1):85-93. http://dx.doi.org/10.4314/acsj.v12i1.27666.

Snoeck J, Lambot C (2009). Coffee nutrition in: Coffee growing, processing sustainable production. Seconde edition. Willey-vch, Weinheim: pp. 250-273.

Steiman S, Idol T, Bittenbender HC, Gautz L (2011). Shade coffee in Hawai: Exploring some aspects of quality, growth, yield, and nutrition. Scientia Horticulturae, 128(2):152-158.

Wairegi LWI, van Asten PJ (2012). Norms for multivariate diagnosis of nutrient imbalance in arabica and robusta coffee in the East African Highlands. Exp. Agric. 48(3): 448. http://dx.doi.org/10.1017/S0014479712000142.

Wairegi, LWI, van Asten PJA (2012). Norms for multivariate diagnosis of nutrient imbalance in Arabica and Robusta coffee in the East Africa highlands. Expl. Agric. 48:448-460.

Wairegi L, van Asten P (2011). Norms for multivariate diagnosis of nutrient imbalance in the East African highland bananas (Musa spp. AAA). J. Plant Nutr. 34(10):1453-1472.

Wairegi LW, van Asten PJ, Tenywa MM, Bekunda MA (2010). Abiotic constraints override biotic constraints in East African highland banana systems. Field Crops Res. 117(1):146-153.

Wairegi LWI, Van Asten PJA, Tenywa M, Bekunda M (2009). Quantifying bunch weights of the East African Highland bananas (Musa spp. AAA-EA) using non-destructive field observations. Scientia horticulturae, 121(1):63-72. http://dx.doi.org/10.1016/j.scienta.2009.01.005.

Wortmann CS, Sengooba T, Kyamanywa S (1992). Banana and Bean intercropping: factors affecting bean yield and land use efficiency. Expli. Agric. 28:287-294. doi.org/10.1017/S0014479700019888.

Wrigley G (1988). Coffee in Tropical Agriculture Series. New York, p. 639.

Youkhana A, Idol T (2009). Tree pruning mulch increases soil C and N in a shaded coffee agro-ecosystem in Hawaii. Soil Biol. Biochem. 41: 2527–2534.

Zoyem JP, Diang'a, E, Wodon Q (2008). Mesures et déterminants de l'insécurité alimentaire au Burundi selon l'approche de l'apport calorifique. The Afr. Stat. J. 6:35-66.