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Banana leaf pruning to facilitate annual legume intercropping as an intensification strategy in the East African highlands

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ABSTRACT

Banana leaf pruning is a common practice to facilitate intercropping with legumes on farmers' fields. It is however not clear if this practice improves farmers land-use and economic efficiency, especially after full canopy formation. To analyze pruning effects, three legumes viz. bush bean (*Phaseolus vulgaris L*), climbing bean (*Phaseolus vulgaris L*) and soybean (*Glycine max*), were planted under three banana leaf pruning levels in which four, seven and all fully grown leaves were retained. Sole banana or legume plots served as controls. Each treatment combination was replicated three times. Banana growth and yield attributes were measured for the plant and first ratoon crops while legume biomass and yields determined over five consecutive cropping seasons. Significant ($P < 0.001$) reductions in banana growth and yield were associated with leaf pruning. Banana yield reductions of 31% and 10% for the four- and seven-leaf retention treatments, respectively occurred. The vigorous intercrops (climbing beans and soybeans) more often depressed the growth and yield of banana. Legume grain and biomass yields increased with leaf pruning levels. Weed biomass and associated management costs increased with decline in shade intensity. The land-use efficiency measured using the land equivalence ratio (LER) was far lower in the treatment with four-leaves (1.10) compared to when all leaves were retained (1.4) but higher (1.54) for the seven-leaf treatment. Severe banana leaf pruning could thus be detrimental to banana performance and inefficient. Moderate banana leaf pruning could however be promoted were land is limiting and farmers want to maximize diversity/nutrition. However, the highest values for gross revenue and benefit-cost ratio were realized for sole banana-all-leaf retention treatment due to a higher labor productivity and lower input costs attributed to the perennial nature of banana. The higher economic efficiency in sole banana plots suggests that reliance on LER only may be insufficient for guiding intercropping decisions.

1. Introduction

Banana-legume intercropping is important in several countries of the African Great Lakes region (AGLR) including Uganda, Rwanda, Burundi, Democratic Republic of Congo (DR Congo) and north-western Tanzania (Wortmann and Sengooba, 1993; Nzawele et al., 2009; Ntamwira et al., 2013a, b; 2014). Banana-legume intercropping is widely practiced due to high population pressure on the land. The region is characterized by high population densities estimated at between 300 and 350 inhabitants per km^2 (DSRP, 2005; CIALCA, 2010), with each household typically living on less than 0.5 ha of land. The incorporation of food and/or fodder legumes into banana cropping systems in AGLR could increase the use efficiency of land (Sileshi et al., 2007) and other resources in smallholder banana farms (Ouma, 2009).

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It is aimed at maximizing productivity and minimizing risks related to, for example, climate change, pests and diseases (Nyabyenda, 2006; Dapaah et al., 2003; Zinsou et al., 2004) and helps in suppression of weeds (Amanullah et al., 2007). Furthermore, intercropping with nitrogen-fixing legumes may also be a strategy to offset the depletion of soil nitrogen (Chakeredza et al., 2007), thereby contributing to increasing productivity of the system. For example, intercropping with grain legumes (common beans, cowpea, groundnut, pigeon pea or soybean) has been reported to increase productivity with land equivalent ratios of 1.2–1.9 (Pypers et al., 2010).

Wortmann and Sengooba (1993) compared the performance of 16 non-climbing bean genotypes intercropped with East African highland banana with that in their respective sole crop systems. Intercropping reduced the bean yields to only 50% of the sole bean yields yet the intercrop bean density was 68% of the sole crop. This incongruous response to reduction in the bean density in the intercrop compared with that in the sole crop suggests that the banana-bean intercrops were affected by competition for light, water and nutrients, which if well understood can guide the optimization of the system for productivity. Below ground competition for moisture and nutrients in the banana-bean intercrop probably limits bean productivity since both banana and bean species are shallow-rooted (Wortmann and Sengooba, 1993) and require large amounts of nitrogen (N), phosphorus (P) and potassium (K) for growth and development (Maria et al., 2002; Ganeshamurthy et al., 2011; Marschner, 2011; McGrath et al., 2013). Above ground shading of the shorter legume plants by the banana canopy could reduce light interception, growth and yield of the legumes (Nyambo et al., 1982; Davis et al., 1987). Consequently, farmers e.g. in eastern Democratic Republic of Congo, often prune banana leaves to enhance sunlight penetration to the understory component crop so as to improve their growth and yield (Mirindi, 2011; Ntamwira et al., 2013a, b; 2014; Ocimati et al., 2013; Blomme et al., 2017). However, leaf pruning perpetuates the spread of the bacterial wilt disease of banana (Blomme et al., 2017) and is potentially detrimental to the banana yield (Robinson et al., 1992), hence the need to analyze the leaf pruning effects in banana-legume intercrop systems.

Ntamwira et al. (2013a; 2014) observed no significant differences in banana yield when leaves of fully-grown plants were reduced to seven on farmers' fields and five in controlled field experiments compared with non-pruned controls over four annual cropping seasons. In these experiments, leaves were only cut once when plants were at the flowering stage. In contrast, significant declines in banana plant crop growth and yield were observed when leaves were reduced to four or 7 leaves starting from the third month of planting in controlled field experiments (Ntamwira et al., 2013b). The different legume species (soybeans, bush and climbing beans) performed better when banana leaves were pruned across the three experiments. The Ntamwira et al. (2013b) study reported findings of two bean cropping seasons and the banana plant crop (i.e. first crop established from plantlets or suckers) planted at a spacing of 2 m x 2 m. Our work builds on Ntamwira et al. (2013b) taking into account the significantly higher growth vigor and canopy cover of the banana ratoon crops (new shoots in a banana stool retained for the following crops) compared to those of the plant crop (e.g. Robinson et al., 1993). This study analyzed the interaction of the annual crops with the banana crop under different pruning levels over a three years period (i.e. two banana cropping seasons). Higher shade and competition levels were anticipated in additional season compared to those observed by Ntamwira et al. (2013b).

The specific objective of this study was to determine the requisite banana leaf pruning intensity to optimize productivity of the intercrops. It was hypothesized that there is no effect of banana leaf pruning intensity on the overall land use efficiency and net returns from banana-legume intercropping regardless of banana crop cycle and component legume species. The findings of this study could be relevant for guiding farmers' decisions on banana intercropping and leaf pruning practices.

2. Materials and methods

2.1. Study location description

This study was conducted at the Institut National d'Etudes et Recherches Agronomiques (INERA), Mulungu research station in the South Kivu Province in eastern Democratic Republic of Congo. Banana is an important food and cash crop in eastern DR Congo, accounting for 70% of the total crop production landscape (Bakelana and Ndungo, 2004). In this region, the crop is predominantly cultivated on smallholdings and in mixtures, with bush beans and taro as the predominant intercrops. To integrate the shorter annual crops such as beans, different levels of leaf pruning (retaining 4 to 7 leaves) is a common practice on farms in the wet seasons (J. Ntamwira personal communication, 2013). The experiments were located at 02°20.042′ S, 028°47.311′ E, and an altitude of 1,707 m above sea level. The soils are volcanic Andosols with: pH 8.5 (read from a 1:2.5 soil:water extract), soil organic matter content 4.9%, N 0.25% (using salicylate method (Kempers and Zweers, 1986)), P 126 ppm, exchangeable K 748.8 ppm, exchangeable Ca 23.85 cmol(+)/kg and exchangeable Mg 1.41 cmol(+)/kg. P, K, Ca and Mg were extracted using the Mehlich 3 extraction method (Mehlich, 1984). The mean annual rainfall at the site is 1500 mm distributed over two rainy seasons (February to May and September to December). The experimental field had been under banana cultivation for three years. All banana mats were uprooted and plant debris spread out as mulch across the field one week prior to establishing the intercropping experiment.

2.2. Experimental design and management

The treatments consisted of combinations of three different banana leaf pruning levels i.e. maintaining i) four, ii) seven and iii) all fully expanded leaves per plant applied to banana monocrops and banana-legume intercrops. On average, the 'all leaves' treatment had nine leaves per plant, while four leaves represented the worst-case scenarios often observed on farmers' fields during intercrops. For the intercrops three different legume species were used: bush bean (cv. MLB49), climbing bean (*Phaseolus vulgaris L*, cv. AND10) and soybean (*Glycine max*, cv. SB24). The monocrops of banana and the three legumes served as controls. The banana plants of the East African highland cooking cultivar 'Barhabesha' (genome AAA) were planted on the 13th December 2009. The legume crops were planted among the banana plants at 3 (8th March 2010), 9 (9th Sept. 2010), 15 (12th March 2011), 21 (12th Sept. 2011) and 27 (9th March 2012) months after banana planting and data were collected during five consecutive legume cropping seasons starting with the March-June 2010 season and ending with the March-June 2012 season.

A total of 15 treatments were randomized within four blocks resulting in a randomized complete block design with four replications per treatment and a total of 60 plots. Each plot (120 m^2) contained 30 banana mats, in five rows of six mats each, spaced at 2 m × 2 m. Legumes were planted in lines 50 cm apart, thus giving 20 lines of legumes per plot. Each line of legumes was 12 m long and the intra-line spacing was 20 cm for bush bean, 25 cm for climbing bean and 10 cm for soybean plants. Senesced banana leaves were removed regularly from legume planting until legume harvest. No banana leaf cutting was carried out during the dry seasons, to mimic farmers practice. Leaf cutting is mainly done during the rainy season to allow for adequate sunlight to reach the shorter crops planted within banana fields (Ntamwira et al., 2012, 2013a, 2013b). Weeding was carried out monthly, while de-suckering was done at the beginning of the annual cropping season. Farmyard manure was only applied for banana in the planting hole at planting. No additional fertilizer was applied.

2.3. Data collection and measurements

Data were collected during two banana crop cycles, i.e. the plant crop (first crop cycle or crop resulting from plantlets used to establish plantation) and the first ratoon crop cycle (first suckers allowed to grow to maturity), equivalent to 5 legume crop cycles. Banana and legume data were collected in centrally-located net plots, which comprised 12 banana plants and a 6×4 m^2 section of legume crop. Measurements on banana plants for both the plant and first ratoon crop were conducted at flowering and harvest. At flowering stage, data collected included pseudostem circumference (PCSL) at soil level, number of hands and fingers on the second lowest hand.

At banana bunch harvest, data were collected on the weight of the second lowest hand (kg) of the bunch, the length of the middle finger of the second lowest hand, time to harvest (days) and bunch weight (kg). Bunches were harvested when the fruits were deep green, full and rounded (Dadzie and Orchard, 1997). Yield (Mg/ha/year) was computed from the bunch weight (kg) and time to harvest (days), using a cropping density of 2500 banana plants per hectare (i.e. 2 m × 2 m spacing). Time to harvest for the plant crop was considered as the time from planting to harvest, whereas the time to harvest for the first ratoon crop was calculated as the time from harvest of the plant crop bunch to harvest of the first ratoon crop bunch. Bunch yield (Y; Mg/ha/year) was determined using a modification of the formula described by Gaidashova et al. (2008) as below:

$$Y = \frac{W}{T} \bullet D \bullet P \bullet c \tag{1}$$

Where:

W = bunch weight (kg/plant);
T = time to harvest (days);
D = number of days in a year (365 days/year);
P = plant density (2500 plants per ha);
c = conversion factor from kg to Mg (1/1000).

Legume biomass yield was assessed when 50% of legumes had formed pods, in a 1 m × 1 m section located in a corner of each legume net plot, while legume grain yield was assessed in the net plot of 23 m^2. Legume biomass was not returned to the plots to mimic the common practices of the smallholder farmers in the study location.

Weed biomass was also assessed during the third (when banana plants were 15 months old) and fourth legume cropping cycle (21st month) under the different banana leaf pruning and legume treatments. Weed biomass was assessed before legume planting (coinciding with the time of land preparation) and at legume flowering in a 1 m × 1 m section located in a corner of each legume net plot. In the banana monocrop plots, weed biomass was similarly assessed in a corner of the banana net plot.

An ACCUPAR photometer probe (Model LP-80, Decagon Devices, Pullman, WA, USA; Decagon Devices, 2004) was used to measure the photosynthetically active radiation (PAR, μmol/m^2/s) received by the leguminous crops under the different treatments. The PAR measurements were taken, from the second to the fifth legume cropping seasons, on clear days between mid-day and 2 pm, when (i) 50% of legumes had flowered, (ii) 50% of legumes had formed pods and (iii) 50% of legumes had reached full maturity. Twelve light measurements were taken below the banana canopy at 50 cm height in the legume net plot for each legume treatment and at each of the three legume physiological stages. The legume monocrop and intercrop plots were also visually monitored for the presence and severity of common diseases such as leaf spots and viruses.

Banana and grain legume yields across all treatments were compared using the land equivalent ratio (LER) (Willey, 1985), defined as the amount of mono-cultured land needed to produce the same yield as the specified intercrops. For each crop, the relative yield (RY) was calculated to determine the partial LER for that crop and then the partial LERs were summed to give the total LER for the intercrop (Mazaheri et al., 2006).

$$LER = RY_1 + RY_2 = \frac{I_1}{M_1} + \frac{I_2}{M_2} \tag{2}$$

Where:

RY_1 = partial LER of crop 1 (-);
RY_2 = partial LER of crop 2 (-);
I_1 = Yield of crop 1 grown as intercrop (kg/ha/year);
M_1 = Yield of crop 1 grown as monocrop (kg/ha/year);
I_2 = Yield of crop 2 grown as intercrop (kg/ha/year);
M_2 = Yield of crop 2 grown as monocrop (kg/ha/year).

An LER value of 1.0 indicates no difference in relative yield between the intercrop and the collection of monocultures. A total LER greater than 1.0 indicates the presence of positive interactions among the varieties or crops in the mixture and means that any negative interaction that exists in the mixture is not as great as may occur in the monocultures (Mazaheri et al., 2006).

Banana and bean net revenues, i.e. net present value (NPV, US$/ha) were calculated as the difference between the revenues from legume grain and banana bunch sales and the input costs (labor cost for field preparation, digging planting holes, manure application, banana and legume planting, weeding, banana leaf pruning, banana de-suckering, cost of propping banana and staking climbing beans, and cost of harvesting and post-harvest handling) for the period of the study. Legume gross revenues were estimated using the local market prices for grains (i.e. 1.0 U$/kg while banana gross revenue was estimated using the market price for cooking banana bunches at the closest market to Mulungu research station i.e. 0.15 US$/kg. Revenues for the different cropping cycles were adjusted upwards or downwards from the computed annual yields/ha using the duration to harvest for the respective treatments. High quality legume seeds and banana suckers were bought at the INERA research station, respectively at 2.5 US$/ kg and 1 US$ per sucker. Land preparation or weeding was costed at a wage of 1.33 US$ per 100 m^2, while digging a banana planting hole of 60 × 60 × 60 cm was costed at 0.11 US$. The stakes for propping climbing beans were bought at 2.22 US$ per bundle of 100 sticks. A benefit cost ratio (BCR) and the labor productivity for the cropping options were also computed as indices of risk to investment and guidelines for investment decisions. BCR is the ratio of the value of a project to the money spent in undertaking it. BCR provides a value of benefits and costs in actual dollars spent and gained and was computed using the net present values (NPV) of the cropping options. The labor productivity was computed as the ratio of the net present values (NPV) to the cost (US$) of labor invested in a cropping option (US$).

2.4. Statistical analysis

The R statistical software (R Core Team, 2018) and *lmer* function from the *lme4* package (Winter, 2013; Bates et al., 2015) were used to perform a linear mixed model analysis of the relationship between banana/ legume growth and yield parameters and the management options. The linear mixed model was used due to the presence of random effects within the experimental treatments. The random effects were attributed to the blocks (4 levels) and the banana crop cycles (2 levels). The differences between and within the blocks were predominantly significant ($p < 0.05$) following preliminary analysis of variance using the GenStat v. 12 statistical software (VSN International Ltd, 2009). In contrast, the crop cycles were set as random effects because of potential variations in the environment within the different years of experimentation and influence from the remains of mother plants and other attached shoots in the ratoon crop. The remains of the banana mother plants in a mat following harvest have been reported to support the growth and development of the ratoon crops (Walmsley and Twyford, 1968), an effect lacking for the plant crop. The random effects were entered as nested random effects with intercepts. The fixed effects include banana leaf pruning (3 leaf pruning levels), intercrop options (4 treatment levels), and the interaction term between the two effects. The above full model and its null and reduced forms were fit to the same data using the maximum likelihood criterion and compared using combinations of the model-fit statistics. The model fit by maximum likelihood generates several model-fit statistics that include the Akaike's Information Criterion (AIC) (Sakamoto et al., 1986); Bayesian Information Criterion (BIC) (Schwarz, 1978); the log-likelihood and deviance of the parameter estimates; chi-square and p-values. The model with smaller values of BIC, AIC and deviance are recommended. For this study, models with the smallest BIC were selected for subsequent analysis. Where two or more models had more or less the same values of BIC, the AIC, deviance and p-values values were also considered. P values were considered significant when < 0.05. The best model was subsequently refit with the restricted maximum likelihood criterion (REML) which is default for *lmer* (Bates, 2010) to determine the random and fixed effects in the model. The lmerTest package was used to give the lmer4 package an extended output of the summary consisting of degrees of freedom using the Satterthwaite's (Kenward-Roger's) approximations for the *t*-test and corresponding p-values (Kuznetsova et al., 2017). These p-values jointly with the treatment effects were used for comparison of the fixed effects.

For the legumes, the blocks had a zero variance and thus only the seasons that accounted for a greater part of the variance were retained as random effects. The banana canopy levels increased with subsequent seasons and legume performance was thus expected to be affected by this seasonal variation in canopy. Differences were also anticipated for other environmental variables such as nutrient levels, moisture and cloud cover of the different seasons. Only banana leaf pruning levels were considered as the fixed effect. A comparison between the legumes and legume interaction with the banana leaf pruning levels were not considered relevant given the inherent differences between the legume species. Further analysis was as for the banana crop above.

Data visualization was attained using the R statistical software (R Core Team, 2018) and statistical packages devtools (Wickham and Chang, 2018), ggplot2 (Wickham, 2016), ggpubr (Kassambara, 2018) and patchwork (Pedersen, 2017) were used. The residual plots were visually inspected for obvious deviations from linearity, homoscedasticity or normality, and when necessary log transformed. GenStat v. 12 was also used to compute linear regressions with groupings (with the bush bean as the reference level) between PAR and legume grain or biomass yield.

3. Results

3.1. Banana plant characteristics at flowering and harvest

Table 1 shows that the reduced model was the best predictor for the banana plant characteristics (i.e. the lowest value for BIC and $p < 0.05$ for significance of difference with the null model), and was thus used in the subsequent determination of the fixed effects. The fixed effects did not profoundly affect the time to harvest in banana plants (Table 1). Despite this observation, a lower mean time to harvest was observed in banana plants in which four leaves had been retained (Fig. 1a) while the banana monocrop relative to the intercrop treatments had a lower median and mean score (Fig. 1b).

The fixed effects (i.e. banana leaf pruning levels and intercrop options) generally had profound effects on banana pseudostem circumference at soil level, the number of hands on bunch and the number of fingers on the second lowest hand (Table 2). Banana leaf pruning significantly ($p < 0.001$) reduced all the above parameters measured at flowering, with higher effects realized for the severe banana leaf pruning (i.e. to four leaves) treatment (Table 2, Fig. 2a-c). For example, the intercepts of pseudostem circumference were 3.2 and 8.8 cm smaller in the seven and four-leaf treatments, respectively, compared to the situation without banana leaf pruning (Table 2). Bush and climbing bean intercrops resulted in larger pseudostems compared to the banana

Table 1
The Bayesian Information Criterion (BIC) for null, reduced and full linear mixed models fit on the same banana growth and yield data. The model fixed effects include three levels of banana leaf pruning and four banana-legume intercrop treatments while the random effects are the blocks and banana crop cycles. For a given dependent variable, the best fit model is the one with the lowest BIC value.

Dependent variable	Null model	Reduced model	Full model
Pseudostem circumference at soil level	6763.1	6456.0	6476.9
Number of hands on bunch	2565.8	2448.5	2469.1
Fingers on second hand	2150.6	2089.1	2091.5
Time to harvest	10089.0	10104.0	10133.0
Finger length	4507.1	4282.9	4310.9
Bunch weight	5445.1	5069.2	5092.6
Yield	−492.6	−682.1	−673.6

Null model: $y \sim 1 + (1|block/cycle)$; reduced model: $y \sim x_1 + x_2 + (1|block/cycle)$; and full model: $y \sim x_1 * x_2 + (1|block/cycle)$. 'y' is the dependent variable (i.e. measured parameter), 'x_1' and 'x_2' respectively, the de-leafing treatments and the intercrop option that are the fixed effects. Block (treatment blocks) and cycle (crop cycles) are the random effects of the model.

monocrop whereas soybean intercrop depressed the size of the pseudostem (Table 2, Fig. 2b). However, the effect of climbing beans and soybean did not result in pseudostem circumferences that were significantly ($P > 0.05$) different from that of the banana monocrop. The intercrops negatively affected the number of hands, though this was only significant ($P = 0.0235$) for the climbing beans. Similarly, the number of fingers on the second lowest hand of the bunch were depressed by all intercrops, though only significantly in the bush ($P = 0.0010$) and climbing beans ($P = 0.0134$) (Table 2).

Leaf pruning and the legume intercrops also affected the finger length, bunch weight and overall banana yield measured at harvest (Table 3, Fig. 3a, c, e). Finger length, bunch weight and yield significantly decreased ($P < 0.01$) with the increasing level of leaf pruning (Table 3, Fig. 3a, c and e). For example, the finger length intercepts for the seven and four-leaf treatments dropped by 0.56 and 2.93 cm, respectively, from an intercept of 20.68 cm in the all leaf treatment.

The intercrops, except for the bush bean crop that resulted in increased finger length ($P = 0.0005$), generally depressed finger length, bunch weight and banana yield (Table 3, Fig. 3b, d, e). Significant negative effects were however only caused by the climbing bean intercrop on bunch weight ($P = 0.0038$) and banana yield ($P < 0.0001$) and by soybean on banana yield ($P < 0.0001$) (Table 3).

3.2. Light interception, weed biomass, legume grain and biomass yields

Retaining a larger number of banana leaves adversely affected light transmission to the underlying legumes in the intercrop systems. The amount of PAR intercepted at 1 m height significantly increased with the level of leaf pruning (Fig. 4a). However, PAR under the four-leaf treatment was significantly ($P < 0.001$) lower than that above the sole legume crop (Fig. 4a).

The effect of PAR was clearly visible on the growth of weeds. Weed biomass yields were significantly higher ($P < 0.05$) in the legume monocrop fields compared with the fields that had banana, irrespective of the intercrop legume component crop or the number of leaves retained on the banana plants (Fig. 4b). For fields with banana, weed biomass significantly ($P < 0.05$) increased with a decline in the number of leaves retained on the banana plants (Fig. 4b).

The cycle (seasonal) effects accounted for 52–55% of the variance in the random effects on the legume biomass and grain yield while the blocks accounted for 0% of the variance. Leaf pruning significantly ($P < 0.01$) affected legume biomass and grain yields. Consistently the

Fig. 1. Mean time to harvest banana bunches under different leaf pruning levels (a) and intercrop options (b). "4", "7" and "All", respectively, denote four, seven and all fully open leaves retained on the banana plants. The horizontal line within each box is the median while the red diamond shape is the mean. The lower and upper boundaries of the boxes are respectively, the 25th and 75th percentile; the bars/whiskers below and above the box the 10th and 90th percentile and points beyond 10th and 90th percentiles are outliers (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

legume biomass and grain yields were significantly lower in the banana-legume intercrop fields compared with the legume monocrops, and increased with increasing leaf pruning levels (Table 4, Fig. 5). The leaf pruning effects on legume biomass and grain yield did not however profoundly differ between the 7-leaf and the all-leaf treatments. Regression analysis showed that the PAR accounted for about 72% and 78% of the observed variation in biomass and grain yields, respectively.

Septoria brown spot caused by the fungus *Septoria glycines* and angular leaf spot caused by *Phaeoisariopsis griseola* were observed on soybean and bush/climbing beans, respectively. The severity of these two diseases was higher in the legume monocrop plots, while in the intercropped plots, legume disease severity increased with increasing level of leaf pruning.

3.3. The land equivalent ration (LER), income and risk of investment analysis

Agronomic yield advantage measured in terms of LER (i.e. LER > 1), was observed for all the banana-legume intercrops (Table 5). LER values varied between 1.54 in the banana-seven-leaf soybean intercrop and 1.10 in the banana with four leaves intercropped with climbing bean. In all cases, a higher LER value was obtained in the seven-leaf treatment when compared with the treatment in which all banana leaves were retained. In contrast, the four-leaf treatments under-performed in comparison to the all-leaf treatment (Table 5).

The gross revenue calculations revealed a high gap between the four, seven and all-leaf treatments across the banana monocrop and the banana-legume intercrops. For a given legume intercrop, gross revenues consistently declined with increasing level of leaf pruning. The banana monocrop average gross revenue varied between 8,788 and 11,429 US $/ha for the period of study (i.e. 30 months) in the sole banana four-leaf and all-leaf treatments respectively, while it varied between 9,212 and 13,042 US$/ha/annum in the banana-legume intercrop treatments (Table 5). The gross revenues from the sole banana and banana-intercrops were far higher than those from the sole legume crops (2,907–4,615 US$/ha) due to the higher production per ha and monetary value of banana in the market. However, input and the labor costs where higher for the banana-legume intercrops compared to the sole banana crop resulting in lower net revenues for the banana-legume intercrops. The net revenue for the sole banana crop varied between

Table 2
Experiment to understand the effect of banana leaf pruning to integrate legumes on the performance of the component crops. Fixed effects of three banana leaf pruning levels (i.e. retaining 4, 7 and all fully open leaves) and intercrops of bush bean (cv. MLB49), climbing bean (cv. AND10) and soybeans on pseudostem circumference at soil level (cm), number of hands on bunch and fingers on second lowest hand. The experiment was established under controlled conditions at the Institut National d'Etudes et Recherches Agronomiques, Mulungu research station in eastern Democratic Republic of Congo.

Banana parameter	Effects	Estimate	S. E	t value	Pr(> |t|)
Pseudostem circumference at soil level	(Intercept)	80.83	1.17	68.80	1.5E-13
	7 leaves	−3.22	0.45	−7.13	1.9E-12
	4 leaves	−8.81	0.45	−19.53	< 2.0E-16
	Banana-climbing bean intercrop	0.75	0.52	1.45	0.1483
	Banana-bush bean intercrop	1.19	0.51	2.33	0.0203
	Banana-soybean intercrop	−0.96	0.51	−1.87	0.0622
Number of hands on bunch	(Intercept)	7.80	0.09	83.96	3.5E-13
	7 leaves	−0.12	0.06	−1.90	0.0582
	4 leaves	−0.75	0.06	−11.66	< 2.0E-16
	Banana-climbing bean intercrop	−0.17	0.07	−2.27	0.0235
	Banana-bush bean intercrop	−0.10	0.07	−1.40	0.1610
	Banana-soybean intercrop	−0.08	0.07	−1.09	0.2753
Number of fingers on the second lowest hand	(Intercept)	7.94	0.08	103.18	< 2.0E-16
	7 leaves	−0.11	0.05	−2.04	0.0415
	4 leaves	−0.47	0.05	−8.90	< 2.0E-16
	Banana-climbing bean intercrop	−0.15	0.06	−2.48	0.0134
	Banana-bush bean intercrop	−0.20	0.06	−3.31	0.0010
	Banana-soybean intercrop	−0.09	0.06	−1.41	0.1585

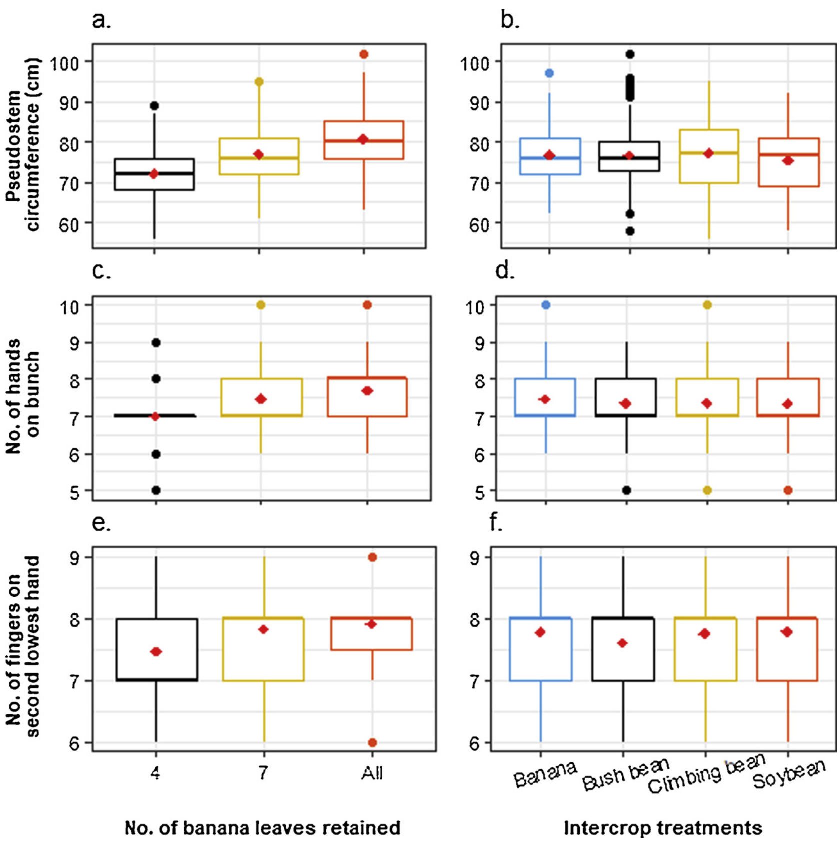

Fig. 2. Banana pseudostem circumference at soil level, number of hands on the bunch and number of fingers on the second lowest hand of bunch for different leaf pruning levels and intercrop options. "4", "7" and "All", respectively, denote four, seven and all fully open leaves retained on the banana plants. The horizontal line within each box is the median while the red diamond shape is the mean. The lower and upper boundaries of the boxes are respectively, the 25th and 75th percentile; the bars/whiskers below and above the box the 10th and 90th percentile and points beyond 10th and 90th percentiles are outliers (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

5,432 US$/ha for the four-leaf and 8,103 US$/ha for all-leaf treatments over a 30 months period compared with 3,504 and 7,366 US$/ha for the four-leaf and all-leaf banana-climbing bean and banana-bush bean intercrops, respectively (Table 5). For the intercrop treatments, the banana-bush bean intercrop was more profitable than the banana-soybean and -climbing bean intercrops (Table 5). A benefit cost ratio (BCR) revealed a higher return for every unit cost invested in the banana monocrop plots (1.6–2.4) compared with the intercrops (0.6–1.4) (Table 5). Higher returns were also realized for the all-leaf treatments (1.2–1.4) compared with 1.0–2.2 for the seven-leaf and 0.6–1.6 for the four-leaf treatments. A higher return for labor (i.e. 9.8–15.4 US$/ unit labor cost) was also observed for the banana monocrop fields compared to the sole legume (0.3-0.9) and legume-banana intercrop (1.6–3.6) fields (Table 5).

4. Discussion

Intercropping of bananas in East Africa has increased due to the currently increasing land pressure (Bekunda and Woomer, 1996; Bekunda, 1999; Ntamwira et al., 2013b; Ocimati et al., 2013; Tittonell and Giller, 2013). To intercrop shorter crops such as the legume crops within banana fields, pruning banana leaves is one of the intensification

Table 3

Experiment to understand the effect of banana leaf pruning to integrate legumes on the performance of the component crops. Fixed effects of three levels of banana leaf pruning (i.e. retaining 4, 7 and all leaves) and legume intercrops (i.e. bush bean (cv. MLB49), climbing bean (cv. AND10) and soybean) on finger length, bunch weight and yield of banana. The experiment was established under controlled conditions at the Institut National d'Etudes et Recherches Agronomiques, Mulungu research station in eastern Democratic Republic of Congo.

Banana parameter	Effect	Estimate	S. E.	t value	Pr(> |t|)
Finger length	(Intercept)	20.68	0.31	66.10	< 2.0e-16
	7 leaves	−0.56	0.19	−2.97	0.0031
	4 leaves	−2.93	0.19	−15.52	< 2e-16
	Banana-climbing bean intercrop	−0.12	0.22	−0.56	0.5781
	Banana-bush bean intercrop	0.75	0.21	3.52	0.0005
	Banana-soybean intercrop	−0.31	0.22	−1.44	0.1504
Bunch weight	(Intercept)	18.23	0.70	25.88	< 0.0001
	7 leaves	−1.37	0.27	−5.00	6.8E-07
	4 leaves	−5.87	0.27	−21.48	< 2.0E-16
	Banana-climbing bean intercrop	−0.91	0.31	−2.90	0.0038
	Banana-bush bean intercrop	−0.14	0.31	−0.44	0.6575
	Banana-soybean intercrop	−0.58	0.32	−1.83	0.0675
$\log_{10}$ (Yield)	(Intercept)	1.626	0.08	21.61	6.4E-08
	7 leaves	−0.048	0.01	−3.66	0.0003
	4 leaves	−0.190	0.01	−14.51	< 2.0e-16
	Banana-climbing bean intercrop	−0.063	0.01	−4.26	2.3E-05
	Banana-bush bean intercrop	−0.022	0.01	−1.49	0.1374
	Banana-soybean intercrop	−0.058	0.01	−3.94	9.0E-05

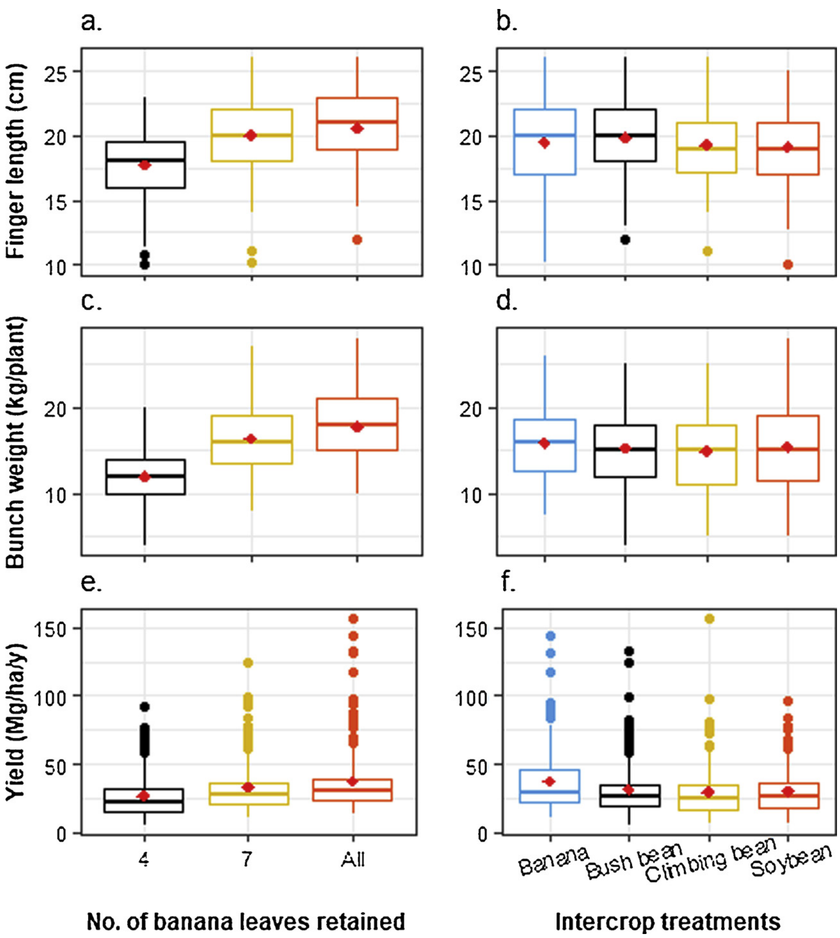

Fig. 3. Banana finger length, bunch weight and yield for different leaf pruning levels and intercrop options. "4", "7" and "all", respectively, denote four, seven and all fully open leaves retained on the banana plants. The horizontal line within each box is the median while the red diamond shape is the mean. The lower and upper boundaries of the boxes are respectively, the 25th and 75th percentile; the bars/whiskers below and above the box the 10th and 90th percentile and points beyond 10th and 90th percentiles are outliers (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

practices applied by smallholder farmers, mainly to meet their household food security and nutritional needs. This practice is aimed at increasing the efficiency of using the limited area of available land. Despite its role in the spread of the Xanthomonas wilt (XW) disease of banana (Blomme et al., 2017) it persists, especially in the eastern part of DR Congo. This study explored the effect of this practice on the performance of the component crops and overall productivity and profitability of the system.

In the current study, with exception of the time to harvest, negative effects on banana growth and yield attributes occurred with increasing levels of banana leaves pruned. The time to harvest was not significantly ($P > 0.05$) affected by both the banana leaf pruning treatments and the intercrops. This is consistent with finding by Ntamwira et al. (2013a, 2013b) for banana-legume intercrops in which banana leaves were reduced to 5 and 7. The reduced performance of the banana crop attributes with the subsequent reduction in number of functional

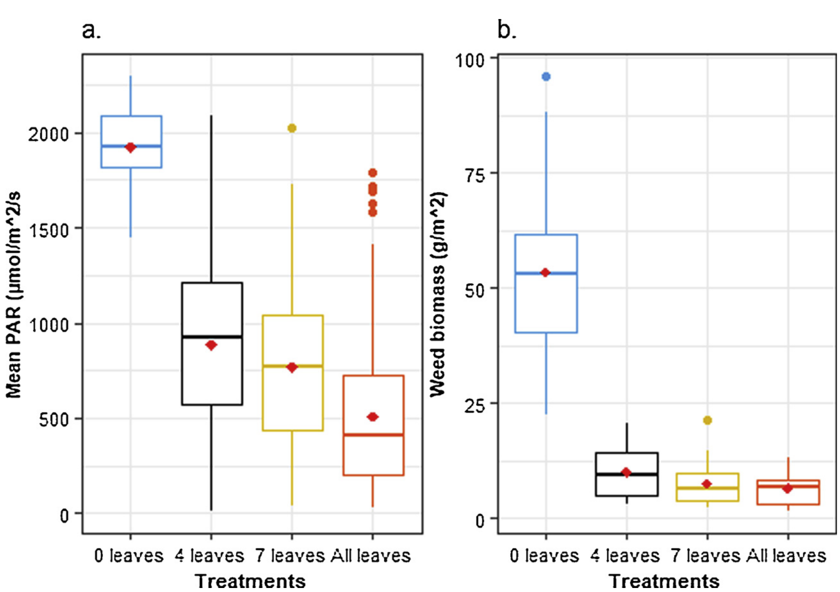

Fig. 4. Photosynthetically active radiation (PAR) (a) and weed biomass (b) above/in legume monocrop field (i.e. 0 leaves) and under banana at three leaf pruning levels. "4 leaves", "7 leaves" and "All leaves", respectively, denote four, seven and all fully open leaves retained on the banana plants. The horizontal line within each box is the median while the red diamond shape is the mean. The lower and upper boundaries of the boxes are respectively, the 25th and 75th percentile; the bars/whiskers below and above the box, the 10th and 90th percentile and points beyond 10th and 90th percentiles are outliers (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Table 4
Experiment to understand the effect of banana leaf pruning to integrate legumes on the performance of the component crops. Fixed effects of three levels of banana leaf pruning (i.e. retaining 4, 7 and all leaves) and a control of legume monocrops on legume biomass and grain yield. The experiment was established under controlled conditions at the Institut National d'Etudes et Recherches Agronomiques, Mulungu research station in eastern Democratic Republic of Congo.

Legume parameters/ Effects	Estimate	S. E.	t value	Pr(> |t|)
Legume biomass yield (kg/ha)				
(Intercept)	2252.5	443.6	5.08	0.0057
4 leaves	−957.0	144.8	−6.61	2.6E-10
7leaves	−1226.7	144.8	−8.47	2.8E-15
All leaves	−1410.0	144.8	−9.74	< 2.0E-16
Legume grain yield (kg/ha)				
(Intercept)	748.4	120.6	6.20	0.0024
4 leaves	−332.0	44.3	−7.50	1.4E-12
7leaves	−452.2	44.1	−10.26	< 2.0E-16
All leaves	−500.8	44.1	−11.36	< 2.0E-16

leaves could be primarily due to the reduced photosynthetic capacity and production of assimilates for growth and partitioning into the storage organs, and increase in evapotranspiration with declining canopy cover. Leaf area is often used to estimate the photosynthetic capacity and to predict the performance of a banana crop (Stover and Simmonds, 1987; Echeverry, 2001). A strong positive relationship between leaf area and bunch weight has been reported for east African *Musa* spp. genotypes (Mukasa et al., 2005). Leaf pruning could have also led to a reduced root mass, leading to a lower supply of water and nutrients for photosynthesis, growth and development. A significant reduction in root system and above ground plant growth following leaf pruning in banana has been reported (Blomme et al., 2001). In this study, the retention of four leaves on banana plants mimicked the worst case scenario observed commonly on some farms in the annual cropping season. This practice severely depressed bunch weights, yields and the overall performance of plants (cf. Fig. 3c, f and Table 3). In contrast, the performance of the banana plants with seven leaves were profoundly different from those with all leaves. Robinson et al. (1992) reported a 35% increase in CO_2 uptake and a greater photosynthetic efficiency in retained leaves after pruning banana leaves of cv. Williams. This could explain the lower yield depression in the banana plants when mildly pruned (e.g. to seven leaves). Krishnamoorthy et al. (2004) reported seven to eight functional leaves as a requirement for optimal bunch formation and fruit filling at flowering. In contrast, Balbín and Zapata (2001) also reported five healthy leaves at flowering to be sufficient for bunch development. Retention of five and seven leaves were also confirmed not to significantly depress the yield of banana by Ntamwira et al. (2013a, b and 2014).

The banana yields obtained in this study (32–46 Mg/ha/year) were comparable to yields reported for banana-legume intercrops on farmers' fields (31–42 Mg/ha/year) in this region by Ntamwira et al. (2014) but higher than those on farmers' fields (6–42 Mg/ha/year) in other regions in the AGLR (e.g. Okumu et al., 2011; Ndabamenye et al., 2013; van Asten et al., 2011). This performance is however still lower than the achievable yields of 60–70 Mg/ha/year under recommended practices (Tushemereirwe et al., 2001; Smithson et al., 2001). The relatively good performance of banana plants even when leaves had been pruned in the current study despite not adhering to recommended soil input levels can be attributed to the high fertility level at the site. Different responses could potentially have been obtained for these treatments under varying soil fertility conditions. For example, in Rwanda, Ndabamenye et al. (2013) observed Ca, Mg and K to limit plant density at Rubona that had a lower soil fertility while increasing plant density did not always result in nutrient imbalance at Ruhengeri that had a high soil fertility level.

In general, the intercrops reduced the performance of banana, though often non-significantly at P = 0.05. The bush beans (cv. MLB49) that have a smaller stature and biomass had the least effect on bunch weight and yields, suggesting a potential effect of competition for the below ground resources from the more robust climbing beans (cv. AND10) and soybeans. Similar observations were reported by McIntyre et al. (2001) and Ntamwira et al. (2012; 2013a, 2013b, 2014) for banana-legume intercrops.

Nitrogen is one of the key yield-limiting nutrients for banana (Nyombi et al., 2010; Taulya, 2013) and the integration of legumes that biologically fix N into the soil has often been recommended as a strategy for offsetting soil N balance and improving yields of other component crops. However, the heavy shading under the all- and seven-leaf treatments do not seem to offer conducive conditions for N fixation by the legumes, as such this benefit may not be fully harnessed and needs to be further explored. Shading has been reported to cause a marked loss of roots and nodules, and subsequently biological nitrogen fixation by different legume species (Butler et al., 1959; Fujita et al., 1992). Dry matter (DM) allocation plasticity suggests that more DM gets allocated to the shoots when light or carbondioxide is limiting and to the roots when water or nutrients are limiting (Bloom et al., 1985; McCarthy and Enquist, 2007). In the current situation, more DM in the

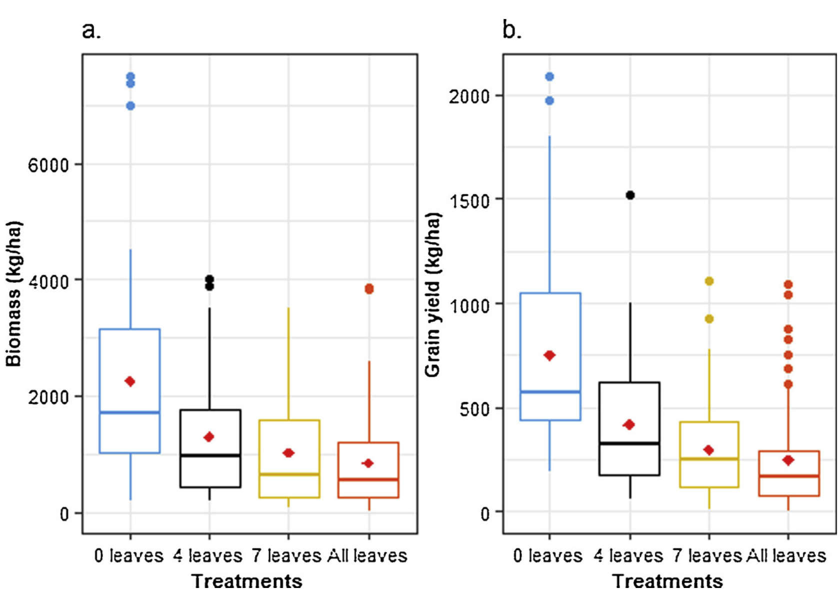

Fig. 5. Legume biomass (a) and grain yield (b) in a legume monocrop (i.e. 0 leaves) and under three banana leaf pruning levels (i.e. 4, 7 and All leaves). "4 leaves", "7 leaves" and "all leaves", respectively, denote four, seven and all fully open leaves retained on banana plants. The horizontal line within each box is the median while the red diamond shape is the mean. The lower and upper boundaries of the boxes are respectively, the 25th and 75th percentile; the bars/whiskers below and above the box, the 10th and 90th percentile and points beyond 10th and 90th percentiles are outliers (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Table 5
Land Equivalent Ratio (LER) and revenue analysis (labor and input costs; gross revenue and net present value (NPV); benefit cost ratio (BCR) and labor productivity (LP)) for banana-legume intercropping/ monocropping options and different banana leaf pruning treatments over a period of 30 months. Data was collected over two banana cropping cycles (plant crop and first ratoon cycle) and five legume cropping cycles. NA denotes not applicable. The mean number of leaves for the treatments with all leaves was nine.

Treatment	Retained banana leaves	LER	Mean Labor cost (US$)	Mean cost of other inputs (US$)	Mean gross revenue (US$/ ha)	Mean net revenue (NPV) (US$/ha)	BCR	LP (US$/ ha)
Soybean (cv. SB24) monocrop	NA	NA	1774	357	3653	1522	0.7	0.9
Climbing bean (cv. AND10) monocrop	NA	NA	1774	1013	4615	1828	0.7	1.0
Bush bean (cv. MLB49) monocrop	NA	NA	1774	532	2907	601	0.3	0.3
Banana monocrop	4	NA	556	2800	8788	5432	1.6	9.8
	7	NA	546	2800	10,809	7463	2.2	13.7
	All	NA	526	2800	11,429	8103	2.4	15.4
Banana-soybean (cv. SB24) intercrop	4	1.22	2127	3157	9612	4328	0.8	2.0
	7	1.54	2102	3157	12,003	6744	1.3	3.2
	All	1.41	2052	3157	12,403	7194	1.4	3.5
Banana-climbing bean (cv. AND10) intercrop	4	1.10	2127	3813	9444	3504	0.6	1.6
	7	1.46	2102	3813	11,733	5818	1.0	2.8
	All	1.45	2052	3813	13,042	7177	1.2	3.5
Banana-bush bean (cv. MLB49) intercrop	4	1.26	2127	3332	9212	3753	0.7	1.8
	7	1.52	2102	3332	12,339	6905	1.3	3.3
	All	1.40	2052	3332	12,750	7366	1.4	3.6

legumes under the heavily shaded plots would be allocated to the shoots resulting into poorly developed and less competitive legume-root systems and thus a depression in the activity of the symbiotic bacteria (Bloom et al., 1985). Similar situations of dry matter plasticity have been reported in vines (Grechi et al., 2007), *Cryptomeria japonica* (McCarthy and Enquist, 2007) and *Lindera melissifolia* seedlings (Lockhart et al., 2012). Grechi et al. (2007) observed that vine leaves under shade had an increased specific leaf area (i.e. thinner leaves); a significantly reduced dry weight and a low root to shoot biomass ratio. In the above situation, the banana plants with four-leaves would possibly not also benefit from the increased N fixation arising from the increased light penetration and improved legume root development due to a poorly developed root system and reduced photosynthetic capacity. Apart from N fixation, plants also compete for water and other essential minerals such as potassium and phosphorus. Integration of legumes would thus be effective when these other resources are not limiting in the system.

Legume grain and biomass yields as expected increased with leaf pruning levels and amount of PAR received by the legume crops, PAR accounting to over 70% of the observed variation in legume yield. The PAR values declined by approximately 36% in the four leaf treatments and 74% in the all leaf treatments compared to the legume monocrops. Akyeampong et al. (1999) showed a 27% decrease in PAR not to affect bean yields in a banana-tree-bean experiment, although a further decrease to 42% of total PAR decreased dry bean grain yield by 27% compared with the control. The current decline in PAR values are above the 27% in Akyeampong et al. (1999) and result in yield declines varying between 56 and 86% in the four and all-leaf treatments, respectively. In contrast, increasing the amount of light penetration to the annual crops under the banana canopy, led to increased weed growth and frequency of weeding and thus raising the labor costs for weed management. Weeds also increase competition for water and nutrients.

Higher severities of septoria brown spot and angular leaf spot were observed in the legume monocrop plots, and to increase with increasing levels of leaf pruning in the banana-legume intercrop plots. This suggests a positive effect of the banana canopy on reducing their spread. The role of crop or cultivar mixtures in disease and pest suppression has been reported in several studies (Boudreau, 2013; Vidal et al., 2017; Li et al., 2018; Mulumba et al., 2012; Ocimati et al., 2018). The mechanisms for disease suppression in mixtures include: a change in the microclimate, vector population and behavior; pathogen dispersal rate; host alteration; dilution effect due to decrease in the susceptible host; and pathogen inhibition (Boudreau, 2013; Vidal et al., 2017). Septoria brown spot and angular leaf spot are mainly favored by presence of infested plant debris, volunteer crops and infected seed (Celetti et al., 2006; Allen et al., 2017). Rainfall events help to splash their spores from plant debris into the plant canopies, leading to infection (Celetti et al., 2006; Allen et al., 2017). The observed trend in the severity of these two diseases in the current study could be attributed to the increasing impact of rain drops with declining leaf canopy levels. Understanding the potential influence of banana-legume intercropping on the prevalence of pests and diseases in a system is thus also important.

The agronomic advantage for banana-legume intercrop combinations measured as LER, was greater than one across all leaf pruning treatments but highest for intercrops in which seven leaves had been retained. This suggests a higher land use efficiency in intercrops compared with sole crops (Prasad and Brook, 2005). The LER values suggest that area planted to monocultures would need to be larger than the current area planted to the intercrops by 10 to 54% to produce the same value as realized from the intercrops. The observed LER values agree with values (1.2–1.9) reported by Pypers et al. (2010) for banana-grain legume intercrops. LER in banana-based systems may thus be increased by incorporating food and/or fodder legumes within the banana fields. High LER values of 1.5 and 2.5 reported for banana intercrops with Robusta and Arabica, respectively (van Asten et al., 2011) also offer a good case for improving the productivity of banana systems through intercropping of banana with other species. In all cases in the current study, a higher LER value was obtained in the seven-leaf treatment when compared with the treatment in which all banana leaves were retained. In contrast, the four-leaf treatment was less efficient compared to the all-leaf treatment. This practice also increased weed growth and labor costs needed for weeding. Extreme cutting of leaves also negatively affected the quality of the banana bunch and fruits as shown by the reduced number of hands, fingers and finger length (cf. Tables 2 and 3), and this could potentially lead to lower prices in the markets. The observed potential negative effect of severe leaf pruning (e.g. to four) on the agronomic efficiency of the system offers a good basis for discouraging this practice that currently also plays a big role in the spread of the XW disease of banana in the study region.

Despite a higher LER for the intercrops, higher profit, benefit cost ratio and labor productivity were realized for the sole banana and all leaf treatments compared with the sole annual crops and banana-legume intercrops. This can be attributed to the high market value of banana fruits compared with that for the grain legumes. Labor costs for banana production are also only high at establishment. Given its perennial nature plantations are not frequently re-established, with plantations in areas with low disease and pest pressure lasting even for decades. For example, plantations that are over 30 years old are common in East Africa (Bekunda, 1999). The investments are often low in the first and subsequent ratoon crops compared with the plant crop because of lower input costs, lack of costs associated with banana seed purchase, land preparation and weeding. The large canopy after full establishment suppresses weed growth and labor associated with weed management is therefore reduced. This can be shown by the higher weed biomass in the monocrop plots especially at the start of the season (cf. Fig. 4b). In contrast, for the intercrops, costs associated with the intercrops such as land preparation, weeding, staking, de-leafing are incurred seasonally. Of the intercrops, the banana-bush bean intercrops were more profitable than other legumes across all leaf pruning treatments. This could be because they offered less competition compared with soybean and climbing beans. Ntamwira et al. (2012) also reported a banana-bush bean intercrop as giving a larger net revenue compared to banana-climbing bean intercrop. Careful selection of intercrops will also be helpful for realizing optimal benefits from banana-legume/annual crop intercrops.

Despite the higher benefits from banana monocrops, few farmers cultivate these monocrops due to a very high population pressure on the land (estimated at 300–350 inhabitants per km^2) given the small land holdings (less than 0.5 ha per household) in the study region. Most production is thus focused on ensuring diversity for nutrition and insurance of food security against production risks. The observed trends could also be due to farmers' lack of knowledge of the performance of the monocrops in comparison to the intercrops. Armed with knowledge on the performance of the monocrops in comparison with the intercrops, farmers' choice to intercrop and/or prune would need to be consciously balanced out with farmers' production objectives and access to land. Possible objectives could include maximization of income; farm/crop diversity and nutrition; and soil fertility improvement. Farmers aiming at maximizing profits could allot all or a large portion of their land to banana monocrop and lesser to annual crops, whereas those aiming at nutritional security could differently apportion their land to other crops/intercrops. Farmers with large parcels of land in contrast can afford to grow banana or legumes as monocrops on large areas without affecting their nutritional and food security needs. Model-based approaches that integrate biophysical and socio-economic aspects of production are recommended for tailoring such management decisions to farm types, production goals and resource endowments.

This study was however, conducted over a short period of time i.e. two production cycles (i.e. 4 years) and at a single experimental site with a single replication in time. Longer term environmental effects such as changes in soil fertility, buildup of pests and diseases and changes in the weather and climate conditions on banana leaf pruning and intercrops could thus not be ascertained. Interactions of the treatments with site conditions (e.g. different soils, environmental and management and biotic scenarios) could not be assessed, whereas could have varied with site conditions. Thus, the application of the study findings in other context needs to be done with caution.

5. Conclusions

Banana leaf pruning despite its current role in the spread of XW disease of banana, is a common practice to allow for banana-legume intercropping and mainly driven by the small land/farm sizes. Leaf pruning improved light penetration to legumes and their yield while it negatively affected the growth and yield of the banana crop. More severe yield reductions occurred when only four leaves were retained, a practice that also resulted in the least land use efficiency compared to when all leaves are retained. Moderate leaf pruning (7 leaves) however, did not in most cases significantly depress yields and resulted in a higher land use efficiency than the banana monocrop all-leaf treatment. However, higher net revenues and labor productivity realized for sole banana and all leaf retention treatments suggests that growing banana as a sole crop is more profitable and moderate leaf- pruning, preferably bending the older leaves to avoid spread of XW could promoted when intercropping is necessary. Intensification decisions should thus go beyond the assessment of the land use efficiency of the systems to determining economic value (net revenues) of the systems. Depending on farmers' production objectives they can decide whether to diversify their farms or target higher incomes. Given the findings of this study, it is recommended for a farmer interested in fostering food security, diversity and nutrition to go for moderate leaf pruning (7 leaves), preferably through manually bending leaves. In contrast, a farmer interested in improving immediate incomes could go for a sole banana crop. Intensification decisions (e.g. pruning banana leaves to integrate legumes) should also look at a broader range of production constraints. For example, where land is not limiting, it is recommended to cultivate the banana and the legumes as sole crops. Where land is limiting, minimal pruning to e.g. seven leaves can be applied with minimal damage. In the current study, annual crops were labor intensive compared to the banana crop, and as such a farmer constrained by labor could go for the sole banana crop. Taking such intensification decision is knowledge intensive, thus rigorous/regular knowledge extension to farmers will be crucial. Bio-economic models (e.g. FarmDESIGN, Groot et al., 2009) that address multiple constraints, decision variables and objectives would be handy in guiding farmers' decision with respect to such intensification options.

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References

Akyeampong, E., Hitimana, L., Torquebiau, E., Munyemana, P.C., 1999. Multistrata agroforestry with beans, bananas and *Grevillea robusta* in the highlands of Burundi. Exp. Agri. 35, 357–369.
Allen, T.W., Bradley, C.A., Sisson, A.J., Byamukama, E., Chilvers, M.I., Coker, C.M., et al., 2017. Soybean yield loss estimates due to diseases in the United States and Ontario, Canada, from 2010 to 2014. Plant Health Prog. 18 (1), 19–27.
Amanullah, M.M., Somasundaram, E., Vaiyapuri, K., Sathyamoorthi, K., 2007. Intercropping in cassava. Agric. Rev. 28, 179–187.
Balbín, L.A.G., Zapata, J.C., 2001. Integrated management of black and yellow Sigatoka diseases in plantain cv. Africa. InfoMusa 10 (2), 3–7.
Bakelana, K., Ndungo, V., 2004. La maladie de Bwere: une bactériose dévastatrice de la culture de la banane dans la province du Nord Kivu en République Démocratique du Congo. Rapport de mission FAO 1 pp.
Bates, D.M., 2010. lme4: Mixed-Effects Modeling with R.
Bekunda, M., 1999. Farmers' Responses to Soil Fertility Decline in Banana-Based Cropping Systems of Uganda. Managing Africa's Soils No. 4(Available at: http://pubs.iied.org/pdfs/7397IIED.pdf (Accessed on 24th Nov. 2016).
Bekunda, M.A., Woomer, P.L., 1996. Organic resource management in banana-based cropping systems of the Lake Victoria Basin, Uganda. Agri. Ecosyst. Environ. 59 (3), 171–180.
Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67 (1), 1–48. https://doi.org/10.18637/jss.v067.i01.
Bloom, A.J., Chapin III, F.S., Mooney, H.A., 1985. Resource limitation in plants-an economic analogy. Annu. Rev. Ecol. Syst. 16, 363–392.
Blomme, G., Ocimati, W., Sivirihauma, C., Vutseme, L., Mariamu, B., Kamira, M., van Schagen, B., Ekboir, J., Ntamwira, J., 2017. A control package revolving around the removal of single diseased banana stems is effective for the restoration of Xanthomonas wilt infected fields. Eur. J. Plant Pathol. 149 (2), 385–400.
Blomme, G., Tenkouano, A., Swennen, R., 2001. Influence of leaf removal on shoot and root growth in banana (*Musa* spp.). InfoMusa 10 (2), 10–13.
Boudreau, M.A., 2013. Diseases in intercropping systems. Annu. Rev. Phytopathol. 51, 499–519. https://doi.org/10.1146/annurev-phyto-082712-102246.
Butler, G.W., Greenwood, R.M., Soper, K., 1959.). Effects of shading and defoliation on the turnover of root and nodule tissue of plants of *Trifolium repens*, *Trifolium pratense*, and *Lotus uliginosus*. New Zeal. J. Agr. Res. 2 (3), 415–426.
Celetti, M.J., Melzer, M.S., Boland, G.J., 2006. Angular Leaf Spot of Snap Beans. Ministry of Agriculture, Food and Rural Affairs, Ontario.
Chakeredza, S., Hove, L., Akinnifesi, F.K., Franzel, S., Ajayi, O.C., Sileshi, G., 2007. Managing fodder trees as a solution to human–livestock food conflicts and their contribution to income generation for smallholder farmers in southern Africa. Nat.

Resour. Forum 31, 286–296.
CIALCA, 2010. CIALCA Baseline Survey Report. Consortium for Improving Agriculture-based Livelihoods in Central Africa. 129 p. .
Dapaah, H.K., Asafu-Agyei, J.N., Ennin, S.A., Yamoah, C., 2003. Yield stability of cassava, maize, soya bean and cowpea intercrops. J. Agric. Sci. 140, 73–82.
Davis, J.H.C., Smithson, J.B., Arregoses, O., Maria, L.M., 1987. Principes de la culture du haricot en association avec d'autres espèces. CIAT Series. 04-FB-12.05, 42 p.
Dadzie, B.K., Orchard, J.E., 1997. Routine Post Harvest Screening of Banana/Plantain Hybrids: Criteria and Methods. INIBAP Technical Guidelines 2. International Plant Genetic Resources Institute, Rome, Italy; International Network for the Improvement of Banana and Plantain, Montpellier, France. ACP-EU Technical Centre for Agricultural and Rural Cooperation, Wageningen, The Netherlands.
Decagon Devices, 2004. ACCUPAR Model LP80 Operators Manual. Decagon Devices Pullman, WA, USA.
DSRP, 2005. Document de Stratégie de Réduction de la Pauvreté Province du Sud-Kivu République Démocratique du Congo. Ministère du Plan. Unité de Pilotage de Processus du DSRP Kinshasa 96 p.
Echeverry, N.E., 2001. The production of fire-softened plantain leaves for the agrifood industry. Agro-economics production and use of leaves. InfoMusa 10 (1), 9–12.
Fujita, K., Ofosu-Budu, K.G., Ogata, S., 1992. Biological nitrogen fixation in mixed legume-cereal cropping systems. Plant Soil 141 (1-2), 155–175.
Gaidashova, S.V., Karemera, F., Karamura, E.B., 2008. Agronomic performance of introduced banana varieties in lowlands of Rwanda. Afr. Crop Sci. J. 16 (1).
Ganeshamurthy, A.N., Satisha, G.C., Prakash, P., 2011. Potassium nutrition on yield and quality of fruit crops with special emphasis on banana and grapes. Karnataka J. Agric. Sci. 24 (1), 29–38.
Grechi, I., Vivin, P.H., Hilbert, G., Milin, S., Robert, T., Gaudillère, J.P., 2007. Effect of light and nitrogen supply on internal C:N balance and control of root-to-shoot biomass allocation in grapevine. Environ. Exper. Bot. 59 (2), 139–149.
Groot, J.C.J., Rossing, W.A., Tichit, M., Turpin, N., Jellema, A., Baudry, J., et al., 2009. On the contribution of modelling to multifunctional agriculture: learning from comparisons. J. Environ. Manage. 90, S147–S160.
Kassambara, A., 2018. ggpubr:' ggplot2' based publication ready plots. R package version 0.2.999. http://www.sthda.com/english/rpkgs/ggpubr.
Kempers, A.J., Zweers, A., 1986. Ammonium determination in soil extracts by the salicylate method. Commun. Soil Sci. Plant Anal. 17 (7), 715–723.
Krishnamoorthy, V., Kumar, N., Angappan, K., Soorianathasundaram, K., 2004. Evaluation of new banana hybrids against black leaf streak disease. InfoMusa 13 (1), 25–27.
Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B., 2017. lmerTest package: tests in linear mixed effects models. J. Stat. Softw. 82 (13), 1–26. https://doi.org/10.18637/jss.v082.i13.
Li, X., de Boer, W., Zhang, Y., Ding, C., Zhang, T., Wang, X., 2018. Suppression of soil-borne Fusarium pathogens of peanut by intercropping with the medicinal herb *Atractylodes lancea*. Soil Biol. Biochem. 116, 120–130. https://doi.org/10.1016/j.soilbio.2017.09.029.
Lockhart, B.R., Gardiner, E.S., Stautz, T., Leininger, T.D., 2012. Development and plasticity of endangered shrub *Lindera melissifolia* (Lauraceae) seedlings under contrasting light regimes. Plant Spec. Biol. 27 (1), 30–45.
Maria, C.T.F., David, M.E., Jonathan, P.L., 2002. Lack of evidence for programmed root senescence in common bean (*Phaseolus vulgaris*) grown at different levels of phosphorus supply. New Phytol. 153, 63–71.
Marschner, H., 2011. *Marschner's Mineral Nutrition of Higher Plants*. Academic press.
Mazaheri, D., Madani, A., Oveysi, M., 2006. Assessing the land equivalent ratio (LER) of two corn [*Zea mays* L.] varieties intercropping at various nitrogen levels in Karaj, Iran. J. Cent. Eur. Agr. 7 (2), 359–364.
McCarthy, M.C., Enquist, B.J., 2007. Consistency between an allometric approach and optimal partitioning theory in global patterns of plant biomass allocation. Funct. Ecol. 21 (4), 713–720.
McGrath, C., Wright, D., Mallarino, A.P., Lenssen, A.W., 2013. Soybean Nutrient Needs. Agriculture and Environment Extension Publications. Book 189. (Accessed on: 5th May 2017). http://lib.dr.iastate.edu/extension_ag_pubs/189.
McIntyre, B.D., Gold, C.S., Kashaija, I.N., Ssali, H., Night, G., Bwamiki, D.P., 2001. Effects of legume intercrops on soil-borne pests, biomass, nutrients and soil water in banana. Biol. Fertil. Soils 34, 342–348.
Mehlich, A., 1984. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15 (12), 1409–1416.
Mirindi, J.B., 2011. Contribution a la connaissance des pratiques paysannes dans une association bananier haricot et de l'utilisation de différentes parties du bananier en territoires de Kabare et de Walungu. BSc thesis. Université Catholique de Bukavu, DR Congo 47p.
Mukasa, H.H., Ocan, D., Rubaihayo, P.R., Blomme, G., 2005. Relationships between bunch weight and plant growth characteristics of *Musa* spp. Assessed at farm level. MusAfrica 16, 2–4.
Mulumba, J.W., Nankya, R., Adokorach, J., Kiwuka, C., Fadda, C., De Santis, P., et al., 2012. A risk-minimizing argument for traditional crop varietal diversity use to reduce pest and disease damage in agricultural ecosystems of Uganda. Agri. Ecosyst. Environ 157, 70–86. https://doi.org/10.1016/j.agee.2012.02.012.
Ndabamenye, T., van Asten, P.J.A., Blomme, G., Vanlauwe, B., Uzayisengae, B., Annandale, J.G., Barnard, R.O., 2013. Nutrient imbalance and yield limiting factors of low input East African highland banana (*Musa* spp. AAA-EA) cropping systems. Field Crops Res. 147, 68–78.
Ntamwira, J., Pypers, P., Van Asten, P., Vanlauwe, B., Ndungo, V., Badesire, A., Blomme, G., 2012. Effect of banana leaf pruning on banana and bean yield in an intercropping system in eastern Democratic Republic of Congo. Afr. J. Plant Sci. Biotechnol. 7 (1), 32–35.
Ntamwira, J., Pypers, P., van Asten, P., Vanlauwe, B., Ndungo, V., Badesire, A., Lepoint, P., Blomme, G., 2013a. Effect of banana leaf pruning on banana and bean yield in an intercropping system in Eastern Democratic Republic of Congo. Afr. J. Plant Sci. Biotechnol 7 (1), 32–35.
Ntamwira, J., Pypers, P., van Asten, P., Vanlauwe, B., Ruhigwa, B., Lepointe, P., Blomme, G., 2013b. Effect of leaf pruning of banana on legume yield in banana–legume intercropping systems in eastern Democratic Republic of Congo. In: Blomme, G., van Asten, P., Vanlauwe, B. (Eds.), Banana Systems in the Humid Highlands of Sub-Saharan Africa: Enhancing Resilience and Productivity. CABI, Wallingford, Oxfordshire, UK, pp. 158–165.
Ntamwira, J., Pypers, P., van Asten, P., Vanlauwe, B., Ruhigwa, B., Lepoint, P., Dhed'a, B., Monde, T., Kamira, M., Blomme, G., 2014. Effect of banana leaf pruning on banana and legume yield under intercropping in farmers' fields in eastern Democratic Republic of Congo. J. Hortic. For. 6 (9), 72–80.
Nyabyenda, P., 2006. Les plantes cultivées en régions tropicales d'altitude d'Afrique. Les presses agronomiques de Gembloux, Gembloux. Belgium, pp. 22–24.
Nyambo, D.B., Matimati, T., Komba, A.L., Jana, R.K., 1982. Influence of plant combinations and planting configurations on three cereals (maize, sorghum, millet) intercropped with two legumes (soybean, green-gram). Keswani, C.L., Ndunguru, B.J. (Eds.), Proceedings of the Second Symposium on Intercropping in Semi-Arid Areas 56–62.
Nyombi, K., Van Asten, P.J., Corbeels, M., Taulya, G., Leffelaar, P.A., Giller, K.E., 2010. Mineral fertilizer response and nutrient use efficiencies of East African highland banana (*Musa* spp., AAA-EAHB, cv. Kisansa). Field Crops Res. 117 (1), 38–50.
Nzawele, D.B., Rweyemamu, C.L., Maerere, A.P., 2009. Banana (*Musa* spp.) cropping systems, production constraints and cultivar preferences in eastern Democratic Republic of Congo. J. Anim. Plant Sci. 4, 341–356.
Ocimati, W., Karamura, D., Rutikanga, A., Sivirihauma, C., Ndungo, V., Ntamwira, J., Kamira, M., Kanyaruguru, J.P., Blomme, G., 2013. Agronomic Practices for *Musa* across Different Agro-ecological Zones in Burundi, Eastern Democratic Republic of Congo and Rwanda. Banana Systems in the Humid Highlands of Sub-Saharan Africa, pp. 175.
Ocimati, W., Were, E., Groot, J.C., Tittonell, P., Nakato, G.V., Blomme, G., 2018. Risks posed by intercrops and weeds as alternative hosts to *Xanthomonas campestris* pv. *musacearum* in banana fields. Front. Plant Sci. 9, 1471.
Okumu, M.O., van Asten, P.J.A., Kahangi, E., Okech, S.H., Jefwa, J., Vanlauwe, B., 2011. Production gradients in smallholder banana (cv. Giant Cavendish) farms in central Kenya. Sci. Hortic. 127, 475–481.
Ouma, G., 2009. Intercropping and its application to banana production in East Africa: a review. J. Plant Breed. Crop Sci. 1, 13–15.
Pedersen, T.L., 2017. Patchwork: The Composer of Ggplots. R Package Version 0.0.1. https://github.com/thomasp85/patchwork.
Prasad, R.B., Brook, R.M., 2005. Effect of varying maize densities on intercropped maize and soybean in Nepal. Expl. Agric. 41, 365–382.
Pypers, P., Sanginga, J., Kasereka, B., Walangululu, M., Vanlauwe, B., 2010. Increased productivity through integrated soil fertility management in cassava–legume intercropping systems in the highlands of Sud-Kivu, DR Congo. Field Crops Res. 120 (1), 76–85.
R Core Team, 2018. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.
Robinson, J.C., Fraser, C., Eckstein, K., 1993. A field comparison of conventional suckers with tissue culture banana planting material over three crop cycles. J. Hortic. Sci. 68 (6), 831–836.
Robinson, J.C., Anderson, T., Eckstein, K., 1992. The influence of functional leaf removal at flower emergence on components of yield and photosynthetic compensation in banana. J. Hortic. Sci. 67 (3), 403–410.
Sakamoto, Y., Ishiguro, M., Kitagawa, G., 1986. Akaike Information Criterion Statistics. D. Reidel, Dordrecht, The Netherlands 81.
Schwarz, G., 1978. Estimating the dimension of a model. Ann. Stat. 6 (2), 461–464.
Sileshi, G., Akinnifesi, F.K., Ajayi, O.C., Chakeredza, S., Kaonga, M., Matakala, P.W., 2007. Contributions of agroforestry to ecosystem services in the Miombo eco-region of eastern and southern Africa. Afr. J. Environ. Sci. Technol. 1, 68–80.
Smithson, P.C., McIntyre, B.D., Gold, C.S., Ssali, H., Kashayij, I.N., 2001. Nitrogen and potassium fertilizers vs. nematode and weevil effects on yield and foliar nutrient status of banana in Uganda. Nutr. Cycl. Agroecosyst. 59, 239–250.
Stover, R.H., Simmonds, N.W., 1987. Bananas (3rd Edn), Tropical Agricultural Series. Longman, Essex, UK 468 p.
Taulya, G., 2013. East African highland bananas (*Musa* spp. AAA-EA) 'worry' more about potassium deficiency than drought stress. Field Crops Res. 151, 45–55.
Tittonell, P., Giller, K.E., 2013. When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crops Res. 143, 76–90.
Tushemereirwe, W.K., Karamura, D., Ssali, H., Bwamiki, D., Kashaija, I., Nankinga, C., Bagamba, F., Kangire, A., Ssebuliba, R., 2001. Bananas (*Musa* spp.) In Uganda. In: Mukiibi, J.K. (Ed.), Agriculture, Vol. II: Crops. Fountain Publishers, Kampala, Uganda, pp. 281–321.
van Asten, P.J., Wairegi, L.W.I., Mukasa, D., Uringi, N.O., 2011. Agronomic and economic benefits of coffee–banana intercropping in Uganda's smallholder farming systems. Agr. Syst. 104 (4), 326–334.
Vidal, T., Boixel, A., Durand, B., de Vallavieille-Pope, C., Huber, L., Saint-Jean, S., 2017. Reduction of fungal disease spread in cultivar mixtures: impact of canopy architecture on rain-splash dispersal and on crop microclimate. Agr. For. Meteorol. 246, 154–161. https://doi.org/10.1016/j.agrformet.2017.06.014.
VSN International Ltd, 2009. GenStat 12th Edition. www.vsni.co.uk.
Walmsley, D., Twyford, I.T., 1968. The translocation of phosphorus within a stool of Robusta bananas. Tropical Agriculture (Trinidad) 45, 229–233.

Willey, R.W., 1985. Evaluation and presentation of intercropping advantages. Exp. Agric. 21, 119–133.
Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York.
Wickham, H., Chang, W., 2018. Devtools: Tools to Make Developing R Packages Easier. R Package Version 1.13.6. https://CRAN.R-project.org/package=devtools.
Winter, B., 2013. Linear Models and Linear Mixed Effects Models in R with Linguistic Applications. arXiv:1308.5499. http://arxiv.org/pdf/1308.5499.pdf.
Wortmann, C.S., Sengooba, T., 1993. The banana-bean intercropping systems - bean genotype x cropping systems interactions. Field Crops Res. 31, 19–25.
Zinsou, V., Wydra, K., Ahohuendo, B., Hau, B., 2004. Effects of soil amendments, intercropping and planting time in combination on the severity of cassava bacterial blight and yield in two ecozones of West Africa. Plant Pathol. 53, 585–595.