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Nutrient imbalance and yield limiting factors of low input East African highland banana (*Musa* spp. AAA-EA) cropping systems

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ABSTRACT

Low yields of East African highland bananas (*Musa* spp. AAA-EA) are often attributed to poor and declining soil fertility, which outweighs other biophysical factors and management practices. We investigated the influence of planting density on nutrient mass fractions and nutrient imbalance indices in bananas under small-scale, low-input systems using the compositional nutrient diagnosis (CND) approach. Boundary line functions were developed to identify yield limiting factors and quantify their contribution to the yield gap. Soil, plant, yield and water data were collected in plant density experiments conducted in three contrasting agro-ecological sites of Rwanda (i.e. Kibungo low rainfall with medium soil fertility, Rubona high rainfall but low soil fertility and Ruhengeri high rainfall with high soil fertility). Effects of site × cultivar and site × density on bunch yield were significant ($p < 0.05$). Annual yields ($\mathrm{t\,ha^{-1}\,yr^{-1}}$) ranged from 6.1 to 9.2 at Kibungo, 9.5 to 21.5 at Rubona and 7.0 to 25.0 at Ruhengeri. Similar trends were registered for the above ground dry matter yield. CND indices showed that K, Mg and P were the most deficient elements in areas with low inherent soil fertility (Kibungo and Rubona). The yield gap analysis also confirmed that K was the most limiting factor, contributing to a predicted yield gap of 55.3% at Kibungo while P and Mg collectively contributed to a 35% yield gap at Rubona. An increase in plant density resulted in an increase in average yield gap from 45.6 to 70.2% at Kibungo, whilst the average yield gap decreased significantly with increases in plant density from 47.5 to 30.2% at Rubona and 76.6 to 53.7% at Ruhengeri. The study confirmed that soil fertility is a more limiting factor than water, but both CND norms and boundary line analysis showed that predicted yield gaps seem to be higher for plant density than soil fertility. Therefore, plant density management is an entry point to optimize yield of East African highland bananas.

1. Introduction

East African highland bananas (*Musa* spp., AAA-EA genome) are both a staple and a cash crop in the highlands of east and central Africa (Gowen, 1995). Total banana production is estimated at 2.7 million tonnes per year in Rwanda, 9.7 in Uganda and 1.5 in Burundi (CIALCA, 2008). The yields reported in national statistics of Rwanda range between 6.0 and 8.0 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ (FAO, 2008), which is considerably lower than attainable yields of 37.0 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ and potential yields exceeding 100 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ (Wairegi and van Asten, 2010). The potential yield can be defined as maximum yield that can be achieved in a given agro-ecological zone whilst attainable yield is the maximum yield observed in a given agro-ecological zone with a given management intensity (Fermont et al., 2009). Several studies on constraints to banana production in the East African highland region have shown that poor banana yields are mostly attributed to declining soil fertility (van Asten et al., 2005; Okumu et al., 2011), pests and diseases (Gold et al., 1999; Tushemereirwe, 2006) and inadequate water supply (Okech et al., 2004; van Asten et al., 2011).

However, the importance of each factor may differ geographically from one site to another, depending on prevailing biophysical conditions. It is generally observed that pest and disease pressure declines with rising altitude (which implies low temperature and high humidity) and this contributes to higher yields per crop cycle (CIALCA, 2008). Compared with biotic constraints, abiotic factors such as declining soil fertility and drought contribute to poor

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banana yields (Okumu et al., 2011). For instance, compared with other factors, Wairegi and van Asten (2010) concluded that low soil fertility was the most important limitation to banana yield in smallholder farms in Uganda. Okumu et al. (2011) reported similar results in central Kenya.

In the East African highland region, researchers have evaluated soil fertility status using indicators such as crop yield levels and soil chemical analysis (Bekunda et al., 2004), to derive limiting nutrients and expressing the level of yield gap (Wairegi et al., 2010). In low input systems, where the lack of nutrients often limits banana yields (Nyombi et al., 2010), yield improvement can be achieved by the use of fertilizers. However, the high cost of inorganic fertilizers limits their use by smallholder farmers (Camara and Heinmann, 2006; van Asten et al., 2010). Therefore, fertilizer recommendations, with N and K as major elements for banana growth and fruit production, should be based on the most yield-limiting nutrient and/or on site-specific nutrient deficiencies, rather than on blanket recommendations for the whole region (Wairegi and van Asten, 2011). Farmers are still applying different management practices without knowledge of soil nutrient status, which may result in nutrient imbalances and may limit their ability to achieve high yields. As bananas are a high nutrient-demand crop (Jones, 1998), the diagnosis of nutrient imbalance under managerial practices (e.g. different scenarios of plant densities) across distinct agro-ecological zones (with low, medium and high soil fertility) is of importance. Yet, an in-depth analysis of the influence of planting density on nutrient mass fraction in banana plantations under low input management has not been investigated, and nutrient imbalance indices under such low input systems have not been explored.

This study aimed to (i) assess the effect of plant density on nutrient deficiencies and imbalances in distinct agro-ecological zones, (ii) identify the most yield-limiting factors in relation to site characteristics (e.g. soil nutrients and water) under different plant density treatments and (iii) advise on fertilizer recommendations, based on the most deficient elements. We hypothesize that (i) high plant density mines the soil more quickly than lower density, so that influences foliar nutrient concentrations and that indices for nutrient imbalances are site-specific and (ii) as banana is a high nutrient-demand crop, soil fertility is a more important yield-limiting factor than water.

2. Materials and methods

2.1. Experimental sites

Plant density experiments were established in three Rwandan agro-ecological sites (Kibungo, Rubona and Ruhengeri), that differed distinctly in terms of altitude, temperature, annual rainfall and soil fertility levels (Table 1). The Rubona site is of low soil fertility, followed by Kibungo, then Ruhengeri. All soils have an optimum pH for banana nutrition, ranging from 5.7 to 6.2. Average soil organic matter and total N values were higher at Kibungo than at Rubona and Ruhengeri.

2.2. Trial set up and management

Three East African highland banana cultivars, including two cooking cultivars (“Ingaju” and “Injagi”) and one beer cultivar (“Intuntu”) were used in this study. Banana plants were young (< 1.0 m height) and healthy sword suckers. The experiment had a randomized complete block design with five densities (plants ha^{-1}): 1428 at a spacing of 3.5 m × 2.0 m, 2500 at 2.0 m × 2.0 m, 3333 at 1.5 m × 2.0 m, 4444 at 1.5 m × 1.5 m and 5000 at 1.0 m × 2.0 m. There were three replicates per site. Neither external mulch nor inorganic inputs were applied. Throughout the experimentation period, desuckering was done to maintain a maximum of three plants per mat; i.e. one plant crop, one follower as first ratoon and one follower as second ratoon. Weeded grass, old banana leaves and split pseudostems of harvested plants were left as self mulch in all treatments.

Table 1
Biophysical characteristics of the Kibungo, Rubona and Ruhengeri trial sites.

Variables	Site		
	Kibungo	Rubona	Ruhengeri
Altitude (m) above sea level	1572	1727	1875
Rainfall distribution	Bimodal	Bimodal	Bimodal
Total annual rainfall (mm)			
2007	929	1196	1432
2008	895	1213	1392
2009	970	707	1275
Average annual temperature (°C)			
2007	19.4	19.1	16.2
2008	19.1	18.9	16.0
2009	19.7	19.1	16.6
[*]Dry period (days): mean and (range)	86 (31–123)	59 (0–123)	15 (0–62)
Topography (% slope)	Gentle (2%)	Gentle (3%)	Gentle (1%)
Soil textural classification	Clay loam (71.3% clay)	Sandy clay (64.4% sand)	Sandy clay loam (50.4% sand)
[**]Soil types/parent material	Nitisol/shale	Acrisol/granitic rocks	Andosol/volcanic ash
Soil chemical properties: mean and (range)			
Soil pH (1:2.5)	5.7 (5.5–5.9)	5.8 (5.6–5.9)	6.2 (6.1–6.2)
Organic matter (%)	6.1 (3.5–7.5)	2.2 (2.1–2.4)	2.4 (2.4–2.4)
Total soil nitrogen (%)	0.30 (0.20–0.35)	0.15 (0.15–0.16)	0.16 (0.16–0.17)
Extractable P (ppm)	4.42 (4.00–5.14)	9.91 (7.10–11.77)	37.7 (34.0–41.5)
Exchangeable Ca ($\text{cmol}_c\ \text{kg}^{-1}$)	3.30 (3.10–3.69)	2.42 (2.02–3.15)	3.04 (2.90–3.19)
Exchangeable Mg ($\text{cmol}_c\ \text{kg}^{-1}$)	1.16 (1.02–1.35)	0.67 (0.48–1.00)	0.55 (0.54–0.57)
Exchangeable K ($\text{cmol}_c\ \text{kg}^{-1}$)	0.34 (0.27–0.44)	0.10 (0.02–0.18)	0.23 (0.21–0.26)
Ratio K to Mg	0.30 (0.20–0.40)	0.14 (0.05–0.19)	0.42 (0.36–0.49)
[*]Fertility rating (agricultural value)	Moderate-good	Poor-moderate	Good-excellent

Bimodal refers to March–May and October–December.

[*] Data adapted from Verdoodt and Van Ranst (2003).

[**] Soil type classification by FAO (1987).

2.3. Data collection

2.3.1. Leaf area index

During the growth period, the number of functional (considered as >50% green) and dead leaves were recorded, as well as the length and width of the middle leaf of each banana plant in inner plot. The total plant leaf area was then calculated following Nyombi et al. (2009). The leaf area index (LAI) was computed for each density as the total leaf area per plant divided by the land area per plant.

2.3.2. Soil and plant analyses

Prior to establishment of the experiment, three soil subsamples were collected at 0–30 cm depth from each plot and composited. Before flowering of the plant crop, three soil subsamples were also collected at the same depth for each plant density treatment and composited. Soil samples were oven dried at 105 °C for 48 h, ground and passed through 2 mm sieve and analyzed for soil pH (1:2.5 sediment–water suspension), particle size distribution (hydrometer method), soil organic carbon (Walkley–Black procedure), total N (micro-Kjeldhal digestion), available P (Mehlich-3 solution), exchangeable Ca, Mg and K (ammonium acetate solution) (Okalebo et al., 2003). To analyze for nutrient mass fraction, foliar subsamples of 10 by 10 cm were collected from both sides of the midrib in the midpoint of the lamina from the third most fully expanded leaf of three randomly selected flowering plants (Lahav, 1995) and they were composited for each density treatment. Foliar samples were oven dried at 72 °C for 48–96 h, ground, sieved to < 2 mm particle size, and digested in a sulphuric acid and selenium mixture (Okalebo et al., 2003). Nitrogen and P were determined colourimetrically, while K, Ca and Mg were determined using an atomic absorption spectrophotometer.

2.3.3. Banana production

The total fresh weights of bunch, pseudostems and leaves were measured using a field balance (±0.5 kg). Fresh weight subsamples of fingers, pseudostems and leaves were oven-dried at 70 °C for 72 h for dry matter determination. The bunch yield ($\text{t ha}^{-1}\text{ yr}^{-1}$) was calculated from the mean bunch mass, the number of plants per ha and the crop cycle (in months). Total above ground dry matter yields (bunches + leaves + pseudostems) (ABG) were expressed as $\text{t ha}^{-1}\text{ cycle}^{-1}$.

2.3.4. Rainfall, evapotranspiration and soil water content

Rainfall was recorded hourly throughout the experimental period by automatic micro weather stations installed at each trial site. Due to off-site data on irrigation, drainage and runoff, an estimate on an "effective water supply was calculated using available rainfall and simulated evapotranspiration data during the experimentation period (April 2007–December 2009). Data on monthly evapotranspiration (mm) at the experimental sites were simulated using the LocClim estimator (FAO, 2006). The later was found to provide reliable rainfall and evapotranspiration estimates, for a mean annual rainfall < 5000 mm yr^{-1} (Mokany et al., 2006). The LocClim software estimates mean monthly rainfall and evapotranspiration for a location based on past rainfall and evapotranspiration records of nearby meteorological stations using input coordinates (altitude, latitude and longitude) of the study location. Previous studies (e.g. Wairegi et al., 2010) showed that LocClim estimator can be used to estimate rainfall and evapotranspiration for East African highland banana systems. Water demand (mm yr^{-1}) by bananas was calculated by multiplying the reference evapotranspiration by the crop factor (which is 0.9 for bananas for Rwanda). The difference between rainfall and water demand by bananas was roughly calculated to account for the surplus or deficit water supply at each experimental site. Correlations were calculated to illustrate the relationship between the overall average bunch yield ($\text{t ha}^{-1}\text{ yr}^{-1}$) and ABG ($\text{t ha}^{-1}\text{ cycle}^{-1}$) surplus/deficit water supply.

To measure soil water content, a subplot was made in each plant density plot by selecting four mats in a rectangular arrangement and one access tube was installed in the centre of the four mats. Soil water content from the soil surface to a depth of 1.60 m, at 0.10 m intervals, was measured using a Diviner 2000 instrument, which is a portable soil moisture monitoring system, comprised by a data display unit and a portable probe, which measures soil moisture content at regular intervals of 10 cm down through the soil profile. Readings were taken through the wall of a PVC access tube. In one swipe and go action, Diviner 2000 records data from all levels in the soil profile to the depth of the probe, i.e. 0.7, 1 or 1.6 m. At a single depth level, the probe records moisture from a soil volume outside the access tube, which has a sphere of influence of 10 cm vertical height and 5–10 cm radial distance from the outer wall of the access tube. Each reading is a snapshot of the soil moisture content at a specific depth in a particular soil profile. Before measurements, the instrument was calibrated (i.e. establishing relationship between real volumetric water content (%) and water readings (mm) for a soil profile). Measurements were taken at monthly intervals, starting from six months after planting.

2.4. Analytical approach

2.4.1. Yield data and diagnosis of nutrient imbalances

Using JMP statistical discovery software version 10.0 (SAS Institute Inc., NC, USA), yield data were subjected to general analysis of variance with a factorial model to capture all interaction effects and the mean values were separated using Duncan's multiple range test at $p < 0.05$. All data were firstly analyzed at the site × cultivar × density level and then data were presented based on the significance of specific interactions.

To identify the most limiting nutrients to the attainment of optimal yield, nutrient imbalances within the plant leaves were determined by computing compositional nutrient diagnosis (CND) indices (Parent and Dafir, 1992; Raghupathi et al., 2002; Wairegi and van Asten, 2011). The CND approach is based on row-centred log ratios where each nutrient is adjusted to the geometric mean of all nutrients and to a filling value (Rd) (Parent and Dafir, 1992). To compute norms, the iteration procedure of Cate–Nelson (Nelson and Anderson, 1977; Khiari et al., 2001) was followed to get an optimum partitioning into low and high yield subpopulations. Foliar nutrient mass fractions (%) and bunch yield ($\text{t ha}^{-1}\text{ yr}^{-1}$) data were used to compute CND norms and derive indices. A negative value of the nutrient indices denoted the magnitude of deficiency and the excess for the positive value. Computation of norms was done by Microsoft Office Excel 2007. A principal components analysis (PCA) was carried out to explore possible patterns between variables (N, P, K, Ca and Mg indices) under density treatments. In the PCA, the original variables were transformed into a few new variables, designated as principal components.

2.4.2. Yield gap analysis

The boundary lines approach or maximum line determination technique (Schnug et al., 1996) was used to explore in more detail the contribution of site characteristics to bunch annual yield and total above ground dry matter yield (ABG) gaps. Using SAS for Windows (version 9.2), we performed Pearson correlation analysis of bunch yields and total above ground dry matter yields with biophysical variables. Those factors were: (i) soil chemical properties (pH, soil organic matter, N-total, P, K, Ca, and Mg), (ii) leaf area index (LAI), (iii) monthly rainfall (mm), (iv) cumulative rainfall (mm) in the 12 months before harvest of the plant crop, (v) cumulative soil water content (mm) at 40 and 60 cm rooting zone in plant density treatment during the wet (March, April and May) and dry (June and

August) months of the years 2008 and 2009, and (vi) plant density. Variables that correlated significantly with bunch yield or ABG (i.e. $r > 0.25$, $p < 0.05$) were retained for further analyses (Fermont et al., 2009).

Following the procedure of Fermont et al. (2009), boundary functions were fitted by regression lines by plotting yields on the *Y*-axis and the explanatory variables on the *X*-axis. The upper boundary points were built of a data cloud. In this analysis, the boundary lines represented the maximum attainable yield response (i.e. the highest attained yield in each site) to the various independent variables. For each independent variable, an individual boundary function was used to calculate the maximum bunch and ABG yields that could have been obtained if other independent variables are not limiting (Fermont et al., 2009). The difference between the attainable yield (i.e. the maximum yield achieved) and actual yield is referred as the yield gap and is expressed as the percentage of attainable yield. Based on Liebig's law of the minimum as adapted by Shatar and McBratney (2004), the minimum of the predicted maximum yields were considered as the actual attainable yield. The difference between the attainable yield and the minimum yield referred to the explainable yield gaps whilst unexplainable yield gaps was the difference between observed yield and minimum yield (Wairegi et al., 2010).

3. Results

3.1. Bunch yield and total above ground dry matter yield

The effects of the interactions site × cultivar and site × plant density on bunch yield (t ha^{-1} yr^{1}) and the total above ground dry matter yield (ABG) (t ha^{-1} cycle^{-1}) were highly significant ($p < 0.05$) and yields increased consistently with plant density at both Rubona and Ruhengeri (Table 2). Ruhengeri registered higher bunch annual yields (7–25 t ha^{-1} yr^{-1}) than Rubona (9.5–21.5 t ha^{-1} yr^{-1}) or Kibungo (6.1–9.2 t ha^{-1} yr^{-1}). ABG were significantly larger at Ruhengeri (53.3–143.9 t ha^{-1} cycle^{-1}) than Rubona (31.9–118.4 t ha^{-1} cycle^{-1}) and Kibungo (21.5–73.8 t ha^{-1} cycle^{-1}). At Rubona, greater bunch yields were found for cultivar "Intuntu" compared with "Ingaju" and "Injagi" whilst ABG were significantly higher for cultivar "Injagi" than for "Intuntu" and "Ingaju" at Kibungo and Ruhengeri (Table 2).

3.2. Leaf nutrient contents and compositional nutrient diagnosis (CND) indices

At all sites, the CND analysis of foliar nutrient contents showed that indices of nutrients did not differ significantly ($p > 0.05$) between cultivar and plant density treatments (data not shown). However, some indices were larger than others and there were possible partners between indices and density treatments (Fig. 1). At Kibungo, K and P imbalances were associated with densities of 2500, 3333, 4444 and 5000 plants ha^{-1} whilst a density of 1428 plants ha^{-1} was associated with N, Ca, Mg and the total nutrient imbalances. At Rubona, high densities of 4444 and 5000 plants ha^{-1} were associated with Ca, Mg, K and the total nutrient imbalances while densities of 1428 and 3333 plants ha^{-1} correlated with indices of N and P. At Ruhengeri, the density of 3333 plants ha^{-1} correlated with N, K, P indices and the densities of 1428 and 5000 plants ha^{-1} correlated with Ca and Mg. Bunch yield cutoff for the high-yield subpopulation was 11.7 t ha^{-1} yr^{-1} at Kibungo, 24.2 at Rubona and 18.5 at Ruhengeri (Table 3). The values of CND r^2 suggested that the global nutrient imbalance (N, P, K, Ca, Mg) at yield cutoff was much higher at Ruhengeri (CND $r^2 = 13.42$ at 18.5 t ha^{-1} yr^{-1}) compared with Kibungo (CND $r^2 = 1.19$ at 11.7 t ha^{-1} yr^{-1}) and Rubona (CND $r^2 = 3.15$ at 24.2 t ha^{-1} yr^{-1}) (data not shown).

Table 2
Mean values for the effect of site × cultivar and site × plant density interactions on bunch yield and above ground dry matter yield (ABG) at the trial sites.

Interaction site × cultivar		Bunch yield (t ha^{-1} yr^{-1})	ABG (t ha^{-1} cycle^{-1})
1	1	7.8c	47.9cd
1	2	8.6bc	52.1cd
1	3	7.5c	40.3d
2	1	11.6b	64.9bc
2	2	15.3a	71.5b
2	3	17.9a	75.8b
3	1	16.9a	129.6a
3	2	15.1a	130.8a
3	3	17.1a	115.7a
SE	±1.1	±6.7	
p	0.0153*	0.0393*	
Site × density			
1	1428	8.7fg	21.5j
1	2500	6.1g	30.8ij
1	3333	8.6fg	50.4ghi
1	4444	9.2efg	57.4gh
1	5000	7.0g	73.8fg
2	1428	9.5efg	32.0ij
2	2500	11.4ef	48.6hi
2	3333	13.1bcde	52.8ghi
2	4444	21.5ab	118.4cd
2	5000	19.2bc	101.9de
3	1428	7.0g	53.3ghi
3	2500	11.9ef	86.4ef
3	3333	16.2cd	127.3c
3	4444	21.8ab	133.9b
3	5000	25.0a	143.9a
SE	±1.5	±8.7	
p	<0.0001*	<0.0001*	

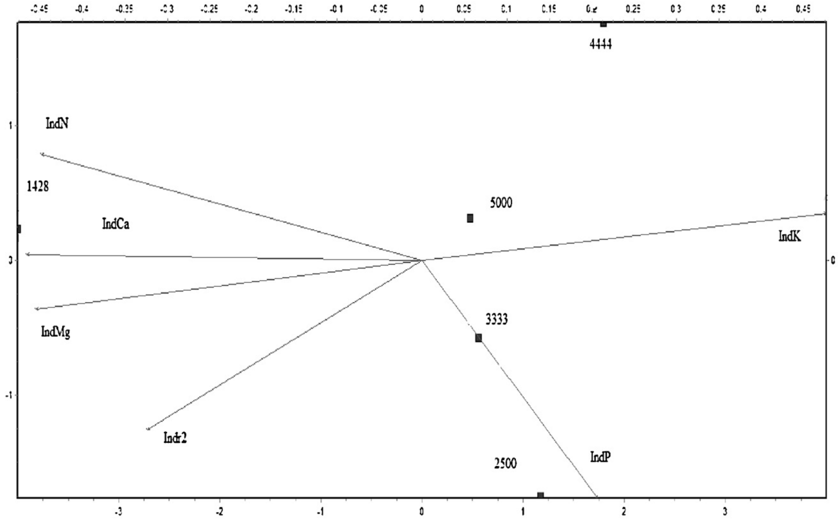
Site 1 = Kibungo, site 2 = Rubona and site 3 = Ruhengeri. Cultivar 1 = "Ingaju", cultivar 2 = "Injagi" and cultivar 3 = "Intuntu".
Mean values with the same letter within the column are not significantly different at $p = 0.05$. SE = standard error.
* Significant effect (Pr > *F*, $p < 0.05$) for site × cultivar and site × density interactions.

3.3. Yield gap and limiting factors

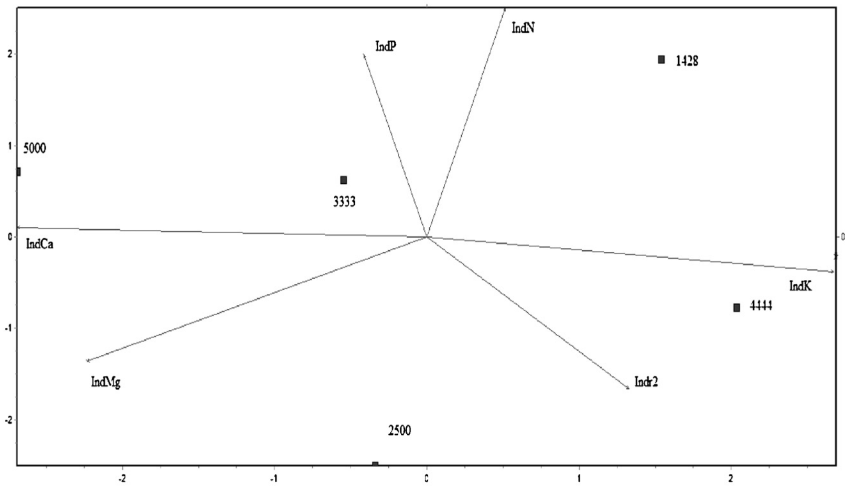
Bunch yield correlated positively with soil nutrient contents at Kibungo and Rubona (Table 4). At Kibungo, significant positive correlations were found for soil pH ($r = 0.34$) and K ($r = 0.53$), and P ($r = 0.46$), K ($r = 0.58$) and Mg ($r = 0.40$) at Rubona where the LAI correlated with P, K and Mg. At Ruhengeri, yield correlated negatively with soil pH ($r = -0.30$). The average bunch yield was positively correlated with water balance (i.e. difference between rainfall and water demand by bananas) ($r^2 = 0.97$), with highest yield (16.4 t ha^{-1} yr^{-1}) found in high rainfall areas (>1200 mm yr^{-1}) with positive water balance (382 mm yr^{-1}) and lowest bunch yield (7.9 ha^{-1}) found in lower rainfall areas (900–1000 mm yr^{-1}) with negative water balance (−135 mm yr^{-1}) (Fig. 2). The similar trends were found for the ABG. For both rooting zones (at 40 and 60 cm soil depths), significant correlations between bunch yield and soil water content were found at Rubona and Ruhengeri but not at Kibungo (Table 5). At Rubona, those correlations were negative, while positive at Ruhengeri, implying that high yield is associated with high water content in wet areas (Ruhengeri).

The boundary lines showed that, at Kibungo, initially the bunch yield and the ABG increased linearly with exchangeable soil K content and then flattened at the attainable yield, whilst a larger scatter of boundary points was found at Rubona (Fig. 3). At Ruhengeri, the boundary line points showed that bunch yield and ABG did not increase significantly after the LAI = 4 (Fig. 3).

a) Kibungo



b) Rubona



b) Ruhengeri

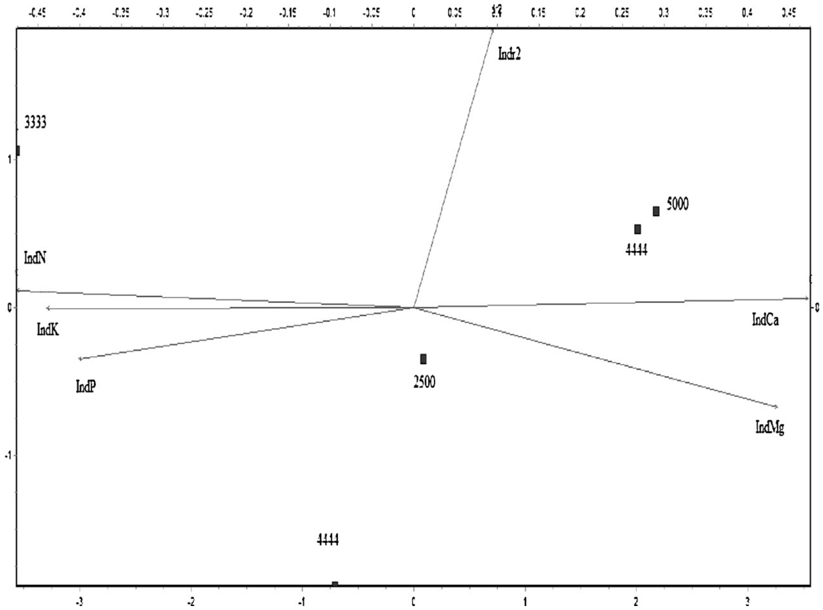


Fig. 1. PCA score plot of PC1 and PC2 of derived CND indices at the Kibungo, Rubona and Ruhengeri sites. 1428, 2500, 3333, 4444 and 5000 are plant densities (plants ha^{-1}). Ind denotes indice and r^2 refers to r^2 which is the global nutrient imbalance.

Table 3
Cumulative variance function $[F_i^c V_x]$ for row-centred ratios and bunch yield (t ha^{-1} yr^{-1}) at inflection point (optimum partition) at the Kibungo, Rubona and Ruhengeri sites.

Site		$[F_i^c V_x] = ax^3 + bx^2 + cx + h$	R^2	Bunch yield at inflection point = −b/(3a)
Kibungo	V_N	$0.033x^3 - 0.445x^2 - 9.390x + 131.6$	0.987	4.5
	V_P	$0.016x^3 - 0.295x^2 - 5.606x + 118.9$	0.974	6.1
	V_K	$-0.100x^3 + 3.528x^2 - 40.84x + 167.4$	0.952	11.7[a]
	V_{Ca}	$-0.030x^3 + 1.663x^2 - 28.87x + 171.7$	0.979	18.5
	V_{Mg}	$-0.095x^3 + 3.352x^2 - 39.14x + 162.4$	0.934	11.8
	V_{Rd}	$0.075x^3 - 1.373x^2 - 5.624x + 132.1$	0.966	6.1
Rubona	V_N	$-0.005x^3 + 0.494x^2 - 16.63x + 190.6$	0.994	32.9
	V_P	$-0.000x^3 + 0.124x^2 - 7.623x + 146.0$	0.992	−4.1
	V_K	$-0.018x^3 + 1.304x^2 - 29.71x + 222.7$	0.964	24.2[a]
	V_{Ca}	$-0.016x^3 + 1.204x^2 - 29.96x + 249.6$	0.992	25.0
	V_{Mg}	$-0.012x^3 + 0.959x^2 - 24.59x + 216.9$	0.992	26.6
	V_{Rd}	$-0.006x^3 + 0.480x^2 - 14.12x + 173.8$	0.994	26.7
Ruhengeri	V_N	$-0.009x^3 + 0.705x^2 - 19.52x + 204.8$	0.987	26.1
	V_P	$-0.011x^3 + 0.643x^2 - 15.25x + 181.0$	0.983	19.5
	V_K	$0.002x^3 - 0.257x^2 + 2.764x + 91.61$	0.983	42.8
	V_{Ca}	$-0.013x^3 + 0.721x^2 - 15.64x + 180.1$	0.984	18.5[a]
	V_{Mg}	$0.000x^3 + 0.048x^2 - 4.963x + 86.78$	0.825	−16.0
	V_{Rd}	$-0.009x^3 + 0.600x^2 - 15.07x + 173.2$	0.979	22.2

[a] Value was retained as yield cutoff by the iteration procedure of Cate–Nelson (Nelson and Anderson, 1977) described by Khiari et al. (2001). N, P, K, Ca, and Mg are the nutrient proportions (% dry matter leaves) and Rd is the filling value computed as: $R_d = 100 - (N + P + K + Ca + Mg)$. V_N, V_P, V_K, V_{Ca}, V_{Mg}, and V_{Rd} are the CND row-centred ratio expressions for nutrients and Rd.

The average bunch yield gaps for soil pH, K, Ca and Mg content in soil did not differ significantly for all cultivars and plant density treatments at Kibungo and Rubona (data not shown). Plant densities differed significantly for the LAI yield gap at Rubona and Ruhengeri. Predicted average yield gap explained by the plant density differed significantly ($p < 0.05$) between sites (Fig. 4). An increase in plant density resulted in an increase in average bunch yield gap from 45.6 to 70.2% at Kibungo whilst average yield gap decreased significantly from 47.5 to 30.2% at Rubona and 76.6 to 53.7% at Ruhengeri (Fig. 4). The distribution of predicted yield gap showed that the yield gap median was higher for soil pH (57.3%) compared with K (55.3%) at Kibungo. The yield gap median was about 35% for all soil nutrient concentrations at Rubona whilst it was about 32% for soil pH and LAI at Ruhengeri (Fig. 5).

For soil pH and K, the explained average bunch yield gap was 23.4 t ha^{-1} yr^{-1} at Kibungo, 20.6 at Rubona and 23.7 at Ruhengeri, and the unexplained yield gap was 0.5 at Kibungo, 6.7 at Rubona and 0.0 at Ruhengeri (Fig. 6). The explained average ABG gap was 65.8 t ha^{-1} cycle^{-1} at Kibungo, 113.6 at Rubona and 108.3 at Ruhengeri with the unexplained yield gap was 2.7 t ha^{-1} cycle^{-1} at Kibungo, 60.0 at Rubona and 1.6 at Ruhengeri.

Explained average bunch yield gaps for planting density alone were 21.7 t ha^{-1} yr^{-1} at Kibungo, 20.0 at Rubona and 30.7 at Ruhengeri and the unexplained yield gaps were 1.2, 7.2 and 7.0 in Kibungo, Rubona and Ruhengeri respectively. Explained average bunch yield gap for soil nutrient concentration was higher at Kibungo (23.4 t ha^{-1} yr^{-1}) and Ruhengeri (23.7 t ha^{-1} yr^{-1}) compared with Rubona (20.6 t ha^{-1} yr^{-1}). The explained average bunch yield gap

Table 4
Pearson correlation coefficients ($n = 45$, $Pr > |r|$) for soil nutrient concentrations, LAI, bunch yield (t ha^{-1} year^{-1}) and above ground dry matter yields (ABG) (t ha^{-1} cycle^{-1}) at the Kibungo, Rubona and Ruhengeri sites.

Site	Parameter	pH soil	P soil	K soil	Ca soil	Mg soil
Kibungo	N soil	0.41*				
	P soil	0.38*				
	K soil	0.55*	0.42*			
	Ca soil	0.53*	−0.01 NS	0.11 NS		
	Mg soil	0.68*	0.16 NS	0.23 NS	0.78*	
	Bunch yield	0.34*	0.09 NS	0.53*	0.09 NS	0.14 NS
	ABG	0.268 NS	0.21 NS	0.37*	−0.12 NS	0.06 NS
Rubona	P soil	0.27 NS				
	K soil	0.11 NS	0.59*			
	Ca soil	0.55*	0.26 NS	0.02 NS		
	Mg soil	0.47*	0.71**	0.58*	0.64**	
	Bunch yield	−0.05 NS	0.46*	0.58*	−0.08 NS	0.40*
	ABG	−0.03 NS	0.36 NS	0.41*	−0.06 NS	0.35*
	LAI	−0.03 NS	0.52*	0.41*	0.03 NS	0.37*
Ruhengeri	P soil	0.73**				
	K soil	0.36*	0.34*			
	Ca soil	0.38*	0.09 NS	0.654**		
	Mg soil	0.41*	0.20 NS	0.754**	0.94**	
	Bunch yield	−0.30*	−0.19 NS	−0.24 NS	−0.18 NS	−0.21 NS
	ABG	−0.13 NS	−0.17 NS	−0.18 NS	0.02 NS	−0.05 NS
	LAI	−0.17 NS	−0.14 NS	−0.11 NS	−0.18 NS	−0.17 NS

NS = not significant ($p > 0.05$).

* r values are significant at $p = 0.05$ levels.

** r values are significant at $p = 0.01$ levels.

Table 5
Pearson correlation coefficients ($n = 45$, $Pr > |r|$) for bunch yield (t ha^{-1} year^{-1}) and cumulative soil water content (mm) at 40 and 60 soil depths (i.e. banana rooting zone) at different time intervals during a 12-month period before harvest at the experimental sites.

Site		Soil depth (cm)	Cumulative soil water content							
			2008					2009		
			12 MAP (April)	13 MAP (May)	14 MAP (June)	16 MAP (August)	20 MAP (December)	21 MAP (January)	23 MAP (March)	24 MAP (April)
Kibungo	Bunch yield	40	−0.095 NS	−0.083 NS	−0.015 NS	−0.073 NS	−0.013 NS	0.046 NS	0.085 NS	0.003 NS
		60	−0.082 NS	−0.048 NS	−0.071 NS	−0.097 NS	−0.099 NS	−0.042 NS	−0.032 NS	−0.087 NS
Rubona	Bunch yield	40	−0.254 NS	−0.530**	−0.373*	−0.279*	−0.456**	−0.362*	−0.350*	−0.313*
		60	−0.402**	−0.526**	−0.384**	−0.236 NS	−0.453**	−0.326*	−0.387**	−0.394**
Ruhengeri	Bunch yield	40	–	–	0.222NS	0.386**	0.372*	0.417**	0.324*	–
		60	–	–	0.258 NS	0.419**	0.374*	0.422**	0.343*	–

NS = not significant ($p > 0.05$).
Empty cases mean that no data collected.
MAP = months after planting.
* r values are significant at $p = 0.05$ levels (2-tailed).
** r values are significant at $p = 0.01$ levels (2-tailed).

for plant density was higher at Ruhengeri (30.6 t ha^{-1} yr^{-1}) compared with Kibungo and Rubona (20.6 t ha^{-1} yr^{-1}).

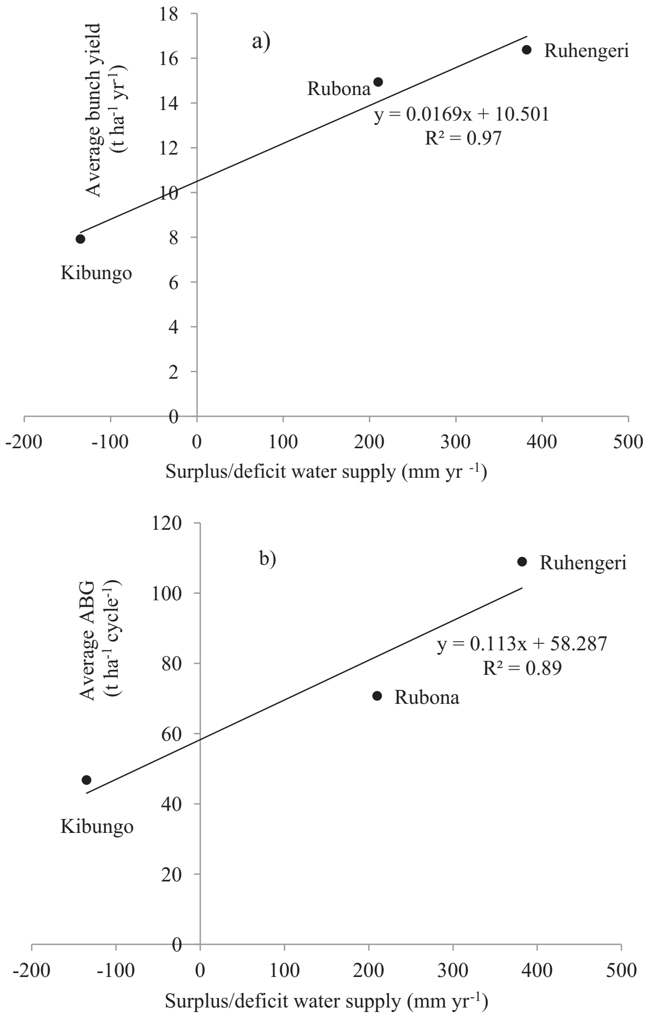


Fig. 2. (a) Relationship between surplus/deficit of water supply (mm yr^{-1}) and bunch yield (t ha^{-1} yr^{-1}) and above ground dry matter yield (t ha^{-1} cycle^{-1}) (b) at the Kibungo, Rubona and Ruhengeri sites. Surplus/deficit (i.e. difference between rainfall and water demand by bananas) refers to positive/negative balance respectively.

4. Discussion

4.1. *Influence of plant density on nutrient imbalances and yields*

Relationships between yield and biophysical variables confirmed that there was variability in nutrient deficiencies between sites. The fact that the effects of cultivar and density on nutrient imbalance did not differ significantly within sites suggests that plant nutrition was sub-optimal across all plant density treatments. Negative nutrient indices were found with an increase in plant density, suggesting that nutrient imbalances are higher in more densely planted than lower densities, therefore lower yields. Higher association between K and P indices and the densities of 2500, 3333, 4444 and 5000 plants ha^{-1} suggests that K and P are more limiting compared with N, Ca and Mg at Kibungo, and an increase in plant density would result in lower yield per plant due to lower K concentration. K are essential nutrients for banana fruit filling, therefore substantial limitation of K requires particular attention for sustainable soil fertility management by taking soil fertility-replenishing measures. Indices of Ca, Mg and K that showed high association with high plant density at Rubona implies that Ca, Mg and K are more limiting elements compared with N, while at Ruhengeri, an increase in plant density did not always result in nutrient imbalance due to its high soil fertility levels.

From our data, larger nutrient deficiencies at Kibungo and Rubona seem be related to the lower inherent soil fertility levels in these areas. This is supported by significant positive correlation between yield and soil nutrient concentration (K, P and Mg) at these sites. Low inherent soil fertility e.g. soil organic matter, total N and the ratio K/(Ca + Mg) has been suggested to limit banana production (Wairegi et al., 2010). High correlation at Rubona highlights that soil fertility is a more limiting factor (i.e. resulting in a decrease in banana yield) compared with other sites. In previous studies (e.g. CIALCA, 2008), P and Mg deficiencies were observed on highly weathered soils and K deficiencies dominate generally on soils that have a slower weathering rate or where it is inherently lacking due to the nature of the parent material (i.e. quartzite and granite) (Gaidashova et al., 2009; Wairegi and van Asten, 2010). Although the K/Mg ratio (0.3:1) was optimal, suggesting that our experimental sites have relatively good soil fertility, therefore suitable to banana growth and production (Delvaux, 1995), K, P and Mg deficiencies were observed. Previous studies in the region also reported K deficiency in banana fields (van Asten et al., 2003).

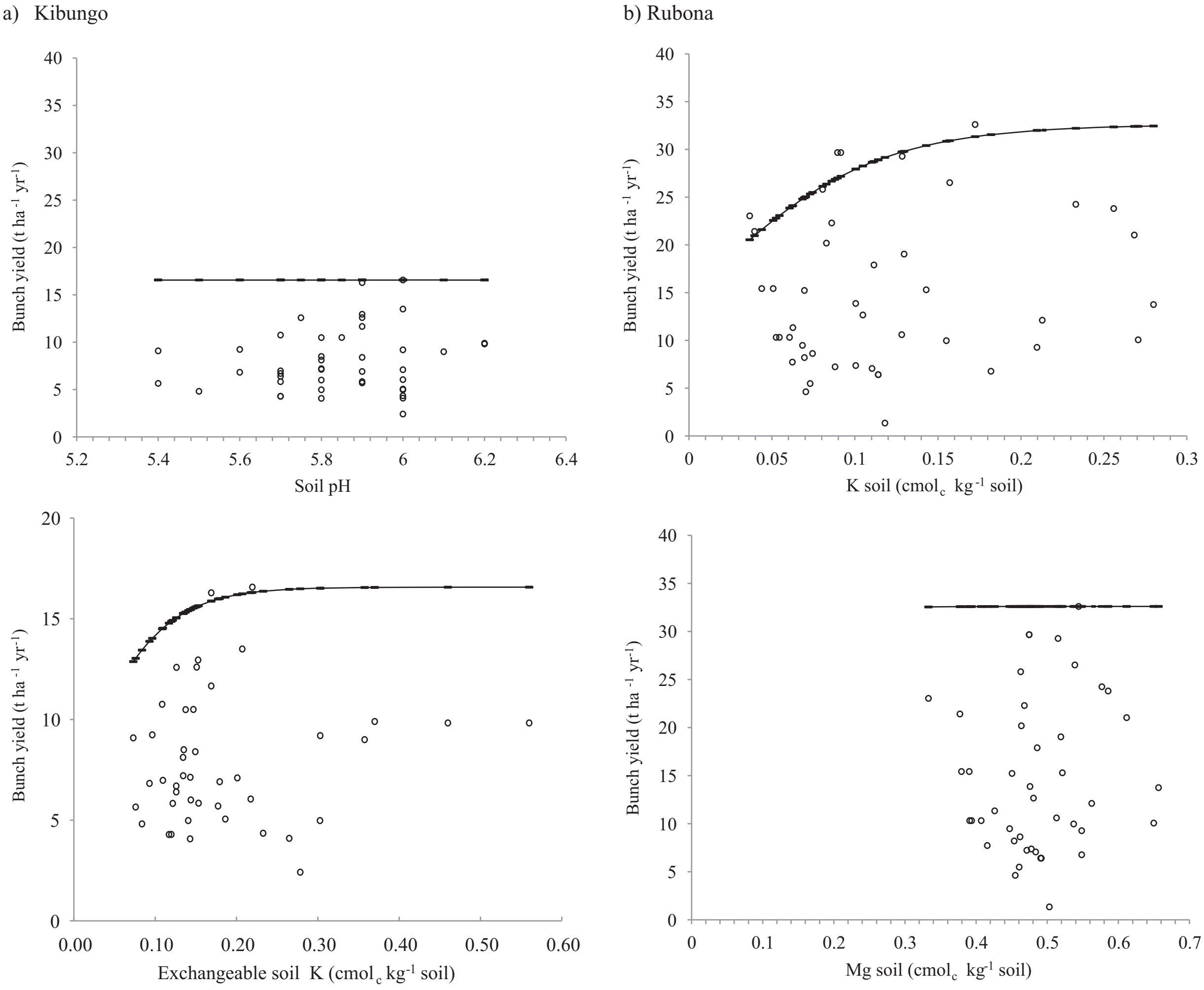


Fig. 3. Relationships between bunch yield (t ha^{-1} yr^{-1}) and soil nutrient contents at the Kibungo, Rubona and Ruhengeri sites. The lines represent the boundary lines. (a and b) refer to variables that correlate with bunch yield ($r > 0.025$, $p < 0.05$) at Kibungo and Rubona respectively.

Significant correlations between soil nutrient concentrations and yield imply the ability of soil to supply the available nutrient in the soil (Havlin et al., 2004). Yield did not correlate significantly with N, P, Ca and Mg at Kibungo and Ruhengeri. This agrees with Gaidashova et al. (2009) who reported higher soil organic carbon, Ca and Mg in a Nitisol at Kibungo, and higher Ca, Mg and P content on the young volcanic soils of Ruhengeri, and the lowest values of Ca, Mg and K on weathered granite derived soil at Rubona, accompanied by lower banana yield. An increase in positive global nutrient imbalance values from Kibungo to Ruhengeri suggest a greater soil fertility level and better plant nutrition at Ruhengeri which resulted in higher yields compared with other sites. However, it was also reported that as a banana plantation produces more, nutrient removal also increases (Lopez, 1999). The fact that yields were correlated positively with soil pH at Kibungo, but negatively at Rubona and Ruhengeri, implies that low soil pH seems to limit banana yield at Kibungo rather than Rubona and Ruhengeri. Nonetheless, this suggests a large tolerance to acidity of bananas since high yield can be achieved over the pH range of 4.7–8.0 (Turner et al., 1989).

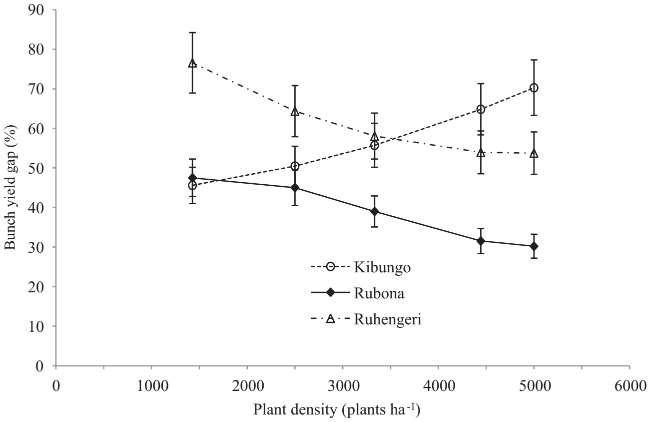


Fig. 4. Predicted banana yield gap explained by plant density at the Kibungo, Rubona and Ruhengeri sites. Yield gap is expressed as percentage of maximum yield attained.

4.2. Addressing nutrient deficiencies and yield gaps

This study was conducted for low input systems, and increases in yield resulted from a greater number of plants per unit area. However, observed bunch yields were still lower and comparable with those reported in the East African region (e.g. 5.7–19 t ha^{-1} yr^{-1}; Kalyebara et al., 2006, 9.7–20.0 t ha^{-1} yr^{-1}; Wairegi and van Asten, 2010). The maximum observed yield ranges from 30.9 to 42.2 t ha^{-1} yr^{-1}. These figures are considerably lower compared with the suggested potential yield of 70.0 t ha^{-1} yr^{-1} for the East African region (van Asten et al., 2005). These findings suggest that addressing yield constraints is paramount for achieving higher yields. In the East African highland region (e.g. the central and

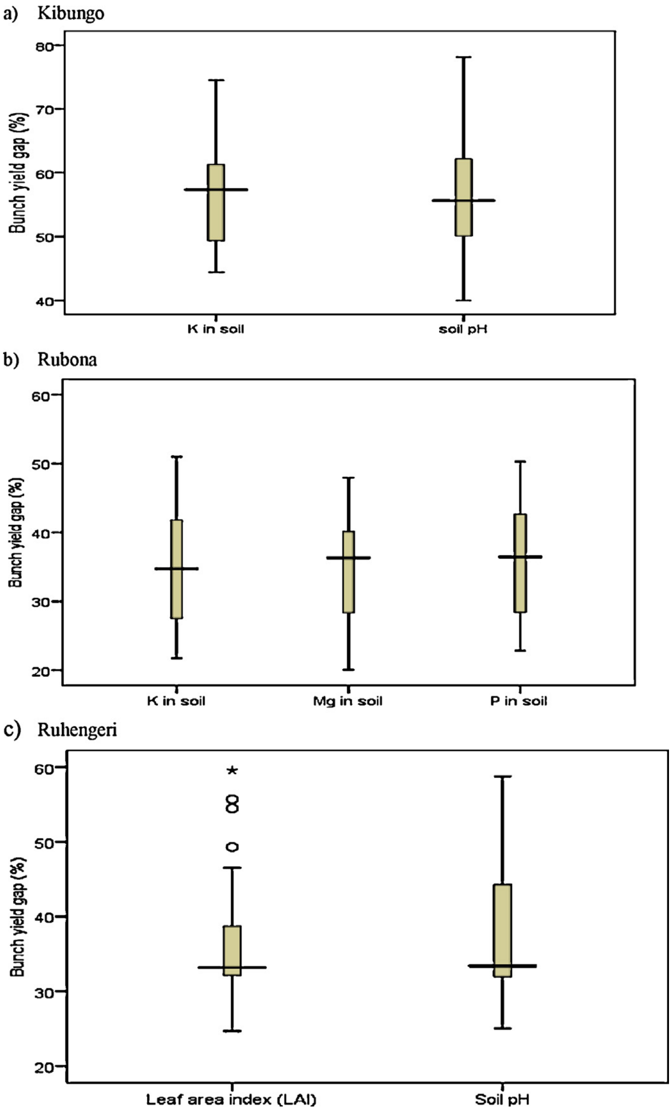


Fig. 5. The yield gap explained by soil nutrient and LAI, expressed as percentage of maximum yield attained at the (a) Kibungo, (b) Rubona and (c) Ruhengeri sites. The solid lines across boxes are medians. The boxes represent the inter-quartiles and bars represent the smallest and largest observations.

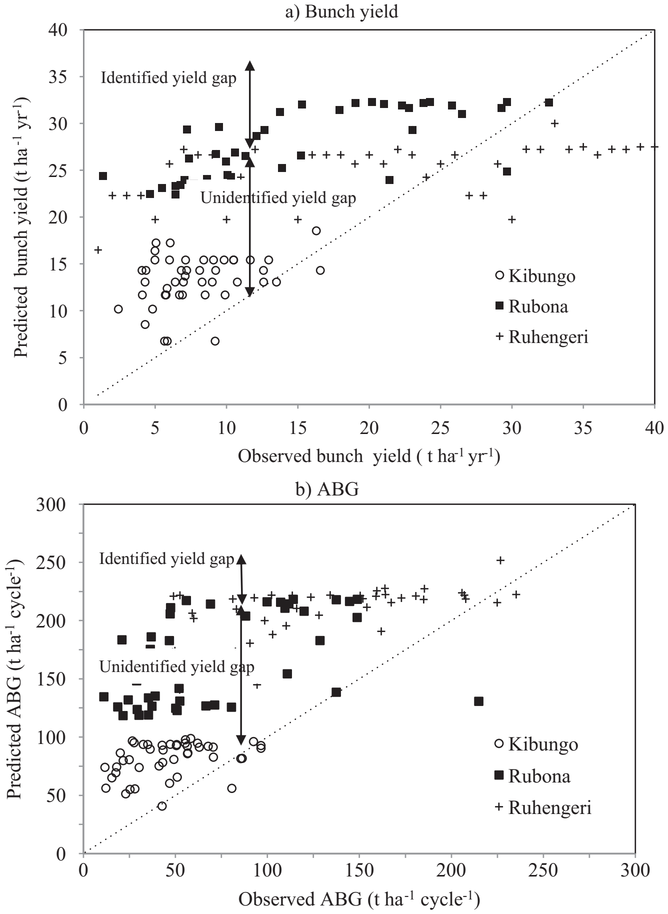


Fig. 6. Observed and predicted (a) bunch yield and (b) above ground dry matter yield at the Kibungo, Rubona and Ruhengeri sites. The dotted diagonal line depicts the relationship $y = x$. The predicted yield was the minimum prediction based on biophysical factors.

southwest parts of Uganda), studies have shown that the most limiting nutrients can be addressed by N, P, K fertilizer use and this resulted in a significant increase in banana yield (Smithson et al., 2004; Wairegi and van Asten, 2010). Similarly, our results confirm that addressing nutrient deficiency can improve banana yield and that fertilizer recommendations should be site-specific. Therefore, to increase banana yields, K fertilizer should be recommended at Kibungo and K, P, Mg fertilizers at Rubona. The use of single or multiple-nutrient fertilizers was proven to improve the profitability and increase the adoption of fertilizer use in East African highland banana cropping systems (Wairegi and van Asten, 2010).

The results on boundary line functions and yield gap analysis also showed that K was the most limiting element that contributed to a predicted yield gap of 55.3% at Kibungo while K, Ca and Mg were limiting at Rubona, with an average expected yield gap of 35%. The observed average yield gaps in this study seem to be higher than those reported in the East African highland region (e.g. in central, south and southwest Uganda) (Wairegi et al., 2010). Soil constraints (i.e. soil pH, K, Mg and Ca) were found to account for 67% of yield limitations to banana (cv. Cavendish) production in smallholder farms in central Kenya (Okumu et al., 2011). A higher predicted yield gap caused by soil nutrients (especially K) in combination with an increase in plant density might result in declining banana productivity in most cultivated areas with bananas (e.g. Kibungo which is among the cooking banana producers in the region; Okech et al., 2004). Furthermore, under high density banana plantations, the dynamics of the one element may differ greatly from one soil to another, so that soil properties are prominent factors that explain yield gap under different environments.

Significant positive correlations between LAI and soil nutrient concentration (K, P, and Mg) at Rubona imply higher plant growth if soil is replenished with those elements. The correlations between LAI and bunch yield and above ground biomass (ABG) at Rubona and Ruhengeri suggest that the greater the active leaf area, the larger the bunches and the higher the total dry matter production. Although this study did not investigate the effect of banana residues as mulch on banana yield, the combination of fertilizer and mulch has increased banana yield significantly in the East African highland region (Wairegi and van Asten, 2010).

4.3. Influence of climate on banana production

Significant correlations between yield and soil water content suggest that water might be restrictive in low rainfall areas (e.g. Kibungo). Results on soil water content (measured overtime at 40 and 60 cm soil depth) partially imply that high rainfall favours high bunch yield, suggesting that rainfall could increasingly limit banana yield as one moves from wetter to drier areas. van Asten et al.

(2011) also concluded that, as East African highland banana production is completely rainfed, drought seems to be the second most limiting factor after soil fertility. Similar constraints were reported for most banana-growing regions in Uganda, where annual rainfall varies between 1000 and 1300 mm yr^{-1} (van Asten et al., 2003). Purseglove (1985) also reported 1300 mm yr^{-1} as an optimal value, that bananas need for optimal production. Furthermore, the results on soil water balance and correlations between bunch yield and soil water content imply that evaporation is much greater, accompanied by lower yields, at lower rainfall areas (e.g. Kibungo), than at high rainfall areas (e.g. Ruhengeri), and high yield is associated with high water content, accompanied by high yield in wet areas (Ruhengeri).

A significant effect of rainfall on banana yield seemed to be masked by the effect of plant density. The results showed that the rooting system was shallow at Kibungo ($\leq$40 cm soil depth) compared with Rubona ($\leq$80 cm soil depth) and Ruhengeri ($\leq$60 cm soil depth) (data not shown). Apart from the effect of plant density that resulted in smaller bunches, but with higher yields per unit area, the above supports the observations of lower banana production at Kibungo compared with other sites. Similar observations were reported by Landon (1991) for banana soils in Uganda.

4.4. Implications of findings and research outlook

Smallholder farmers in the East African highland region are still adopting different managerial practices with little knowledge of nutrient interactions which could results in nutrient imbalances that may limit their achievement of high yield. Although nutrient concentration was expected to be influenced by plant density and cultivar type, the CND norms did differ significantly within density treatments at experimental sites that resulted in an overall comparative effect between sites. Nevertheless, the most limiting soil nutrients of the attainable yield were identified using boundary line analysis. Identification of the most deficient element is an effective tool to help farmers prioritize investments for purchasing fertilizer (Wairegi and van Asten, 2010). This can increase efficient fertilizer use rate in the East African highland region, especially in banana cropping systems where adopted plant densities in different regions may cause nutrient imbalance either over the short and/or long term.

In this study, plant density did not show any significant effect on chemical soil properties but identified boundary lines showed that yield limiting factors differed within and between sites. This boundary line approach was also used to determine crop response to soil variables (Shatar and McBratney, 2004) and yield gap in relation to soil properties and crop management (Casanova et al., 1999; Fermont et al., 2009). Recently, the same approach which identifies and ranks yield constraints was also applied to East African highland bananas (Wairegi et al., 2010). Previous studies reported on scenarios that improve banana yield by determining the most limiting factors (Smithson et al., 2004; Wairegi and van Asten, 2010, 2011), but not much attention was given to plant density as one of the prominent banana yield factors.

This study explored, for the first time, the influence of plant density on nutrient mass fractions and nutrient imbalance indices in bananas under small-scale, low-input systems. This study showed that plant density management can increase yield gap but this depends on inherent soil fertility levels. Incidence of pests and diseases, which are known to cause significant banana yield losses (Gold et al., 1999; Tushemereirwe, 2006) was not investigated. However, their effect on soil fertility dynamics (either through slower or higher nutrient mining) requires further in-depth research. Nevertheless, the findings of this local study have wider regional application due to similarities in agro-ecological characteristics e.g. highly weathered tropical soils such as Acriols and Ferralsols (FAO, 1987), and rainfall which has a bimodal pattern and averages 900–1100 mm yr^{-1} (van Asten et al., 2010) and farm management practices e.g. single 3 m × 3 m blanket recommended plant spacing with different farmers adaptations (Tushemereirwe et al., 2001), low rates of inorganic fertilizer use (Wairegi and van Asten, 2010), and scarcity of crop residue for mulch (Nankinga et al., 2005).

5. Conclusions

This study explored variability in soil and plant nutrients and to some extent water availability under low input systems. To a certain extent, an increase in plant density resulted in negative nutrient indices denoting the overall magnitude of deficiency in inherently poor soils compared to relatively fertile soils. Larger negative nutrient imbalances were accompanied with lower yield. Both the CND and boundary line approaches were successful in determining yield gap and related limiting factors. The boundary line analysis showed that yield gap differed significantly between sites and the global nutrient imbalance (N, P, K, Ca, and Mg) was much higher in high rainfall areas with relatively fertile soils (Ruhengeri) compared with low rainfall areas with low inherent soil fertility (Kibungo). Exploring the long-term dynamics of these nutrients is of importance. This study also showed that yield gaps for plant density are high, implying that plant density management might be looked at as an entry point to optimize yield of East African highland bananas.

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