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Plant Density Management and its Effect on the Productivity of Low Input East African Highland Banana (*Musa* spp.)-based Cropping Systems

by

Telesphore Ndabamenye

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Supervisor: Prof. R.O. Barnard
Co-supervisors: Prof. J.G. Annandale
Dr. Ir. P.J.A. Van Asten
Dr. G. Blomme

December, 2013

DECLARATION

I, Telesphore Ndabamenye, hereby certify that this research, unless specifically indicated to the contrary in the text, is the result of my own work and no part of this thesis has been previously submitted to any other University.

SIGNATURE: ______________________

TELESPHORE NDABAMENYE

DATE: ______________________________

DECEMBER, 2013

DEDICATION

This work is dedicated

to

The Almighty Lord

And my wife Bellancile Uzayisenga

PREFACE

This PhD thesis was prepared in the Department of Plant Production and Soil science at the University of Pretoria, South Africa. The research project was conducted under the framework of The Rwanda Agricultural Research Institute (ISAR) and the Consortium for Improved Agriculture-based Livelihoods in Central Africa (CIALCA) research project, led by Bioversity International. The key hypothesis of this thesis is that the optimal plant density of East African highland (EAH) bananas (*Musa* spp.) is location-specific and is influenced by a complex interaction between managerial, soil fertility levels and climatic factors. An understanding of this complex helps to determine the agronomic optimal density in contrasting agro-ecological zones with differences in rainfall and soil types. In addition, the first order magnitude of nutrient depletion was studied using nutrient balance calculations in order to account for the productivity of low input East African highland banana cropping systems. The work consisted of on-farm characterization of plant density management, which was complimented by on-station plant density experiments in three contrasting agro-ecological sites (i.e. that differed distinctly in terms of altitude, temperature, annual rainfall, soil type and agricultural value), in the East African highland region (Rwanda).

Chapter 1 provides the background on bananas as a food and cash crop in the East African highland region discusses the constraints to banana production in low input agricultural systems in the region and then plant density as management strategy and its impact on banana productivity. Chapter 1 also outlines the aim, and research questions with their subsequent hypotheses and the objectives of the study. Chapter 2 addresses the influence of ecological characteristics on farmer selection of on-farm plant density and its effects on bunch mass in field realties. Chapter 3 discusses the effects of plant density on growth and yield of East African highland bananas in relationship with contrasting ecological characteristics. It reports on differences from effects of site, cultivar and density on yield and growth parameters and discusses the probable causes of these differences with emphasis on resource capture and environmental characteristics. The optimal agronomic plant density with respect to the efficiency and sustainability of the system is also discussed. In Chapter 4, nutrient deficiencies and abiotic yield limiting factors are discussed. The question whether a particular plant density is sustainable, is therefore treated in Chapter 5, where partial nutrient balances are computed. This chapter discusses first order nutrient depletion and system evaluation with respect to sustainable production. It is expected that the outputs from this thesis will be useful for researchers, extension agents and policy makers in developing policies for sustainable production of EAH bananas in the region and general findings, conclusions and fruitful awareness for future research are reported in Chapter 6.

The thesis is prepared in accordance of guidelines provided by the *South African Journal of Plant and Soil* and presented in article format. Articles are published in peer review international journals. Two articles (Chapters 2 and 4) are published in *Field Crops Research*, another one (Chapter 3) is published in *Scientia Horticulturae*, and another one (Chapter 5) is published in *Nutrient Cycling in Agroecosystems*. This form of thesis presentation may cause redundancy among chapters, so I present my apologies for inconveniences that this may bring to the reader.

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ABSTRACT

East African highland bananas (*Musa* spp., AAA-EA genome group) are a major staple and income-generating fruit crop in the highlands of eastern and central Africa, grown across the countries of the Great Lakes region (i.e. Rwanda, Burundi, Uganda, eastern Democratic Republic of Congo and North-West Tanzania). Despite its importance, farmers and researchers are reporting that yields are declining, most notably in areas with low soil fertility. Although numerous studies have been conducted on yield constraints of bananas in the East African highland region, there is virtually no understanding of the impact of plant density management on the yields of these low-input banana systems. The productivity and profitability of various plant densities was studied in contrasting agro-ecological sites of Rwanda (Ruhengeri, Rusizi, Karongi, Butare, Ruhango, Kibungo and Bugesera), that differed distinctly in terms of altitude (1400-1960 m a.s.l), temperature (17-20°C), annual rainfall (950-1400 mm yr^{-1}) and soil types (Nitisols, Ferralsols, Acrisols and Andosols). Under those cropping systems, the plant density is one management factor that resource poor farmers have some control over.

An on-farm survey was conducted in all sites to determine the influence of climatic and edaphic factors on variations in on-farm plant density practices and bunch mass. In addition, three researcher-managed banana density experiments were conducted in contrasting agro-ecological sites (Kibungo low rainfall with medium soil fertility, Rubona high rainfall with low soil fertility and Ruhengeri high rainfall with high soil fertility) to (i) investigate the influence of plant density on the vegetative growth and yield parameters of AAA-EA bananas for typical highland agro-ecological zones, (ii) to assess the effect of plant density on nutrient deficiencies and imbalances, and (iii) to assess the magnitude and variability of nutrient depletion in the smallholder banana systems that are characterized by low external input use. Three different local EA highland banana varieties (i.e. “Ingaju”-cooking type, “Injagi”-cooking type, “Intuntu”-beer type) were each planted at five different plant densities (plants ha^{-1}) of 1428, 2500, 3333, 4444 and 5000. Agronomic data (growth and yield traits) were collected over two cropping cycles (plant and ratoon crops). Soil, plant and climate data were also collected. Approaches such as compositional nutrient diagnosis (CND), boundary line functions and yield gap analysis were used to quantify the contribution of each identified yield limiting factor to yield gap. A first order magnitude of nutrient depletion was determined using partial nutrient balance calculations.

Plant density positively correlated with water supply (i.e. difference between rainfall and evapotranspirative demand of bananas), with highest plant densities (>1500 mats ha^{-1}) found in high rainfall areas (>1200 mm yr^{-1}) with water surplus (218-508 mm yr^{-1}) and lowest plant densities (1000-1400 mats ha^{-1}) found in lower rainfall areas (1000-1200 mm yr^{-1}) with water deficit (from -223 to -119 mm yr^{-1}). Bunch masses were significantly higher at the lowest plant densities (18.1-20.8 kg fresh mass plant^{-1}) when compared to the highest plant densities (14.7-15.5 kg). Lower soil and banana leaf nutrient contents were observed on weathered soils (Acrisols) and were associated with smaller bunch mass in comparison to fertile soils (Andosols, Nitisols). Farmers tended to reduce mat densities (i) if they wanted to intercrop, and (ii) to increase bunch mass to adapt to market preferences for large bunches. The plant densities generally recommended by extension bodies (3 × 3 or 2 × 3 m; i.e. 1111 and 1666 mats ha^{-1}, respectively) are seldom practiced by farmers, nor do they seem to be very appropriate from an agronomic or economic perspective.

Per hectare bunch and above ground biomass yields increased with increasing plant density, but maximum yield strongly depended on agro-ecological site. Bunch yields of beer bananas continued to increase with density, but maximum yields for the cooking cultivars were observed at 4444 plants ha^{-1} at Kibungo and Rubona, whereas yields continued to increase linearly beyond this level at Ruhengeri. Relationships between bunch yield, the total above ground dry matter yields and soil chemical properties suggest that nutrient deficiencies were larger at Kibungo (i.e. notably K) and Rubona (i.e. K, P, Ca, Mg) when compared with Ruhengeri. With increasing densities, leaf area index (LAI) continues to increase up to a value of 4 with 95% of photosynthetic active radiation (PAR) intercepted by the crop canopy. This suggests that further density and LAI increases would probably have little additional positive effect on total per hectare production.

Compositional nutrient diagnosis (CND) indices showed that K, Mg and P were the most deficient elements in areas with low inherent soil fertility (Kibungo and Rubona) compared with relatively fertile areas (Ruhengeri). The boundary line functions and yield gap analysis also confirmed that K was the most limiting factor, contributing to an expected yield gap of 55.3% at Kibungo, while P and Mg 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 average yield gap decreased significantly from 47.5% to 30.2% at Rubona, and 76.6 to 53.7% at Ruhengeri. Nutrient uptake increased with plant density. Partial N and K balances (kg ha^{-1} yr^{-1}) were estimated to be strongly negative at Rubona and Ruhengeri, while Ca and Mg were positive at Kibungo and Ruhengeri, but negative at Rubona. The results of this study indicate that, generally, soil fertility is a more limiting factor than water, but both CND norms and boundary line analysis showed that expected yield gaps seem to be high for plant density due to low inherent soil fertility. Partial nutrient balances provide a first order magnitude of nutrient depletion. Nutrient mining is significant, particularly for K. The current

extraction rates will not allow farmers to sustain their yields, and options should be developed to improve the productivity of EAH banana cropping systems. The limited availability of manure and inorganic fertilizers is a real threat to the food and income security role that banana production plays in smallholder systems.

In summary, the results from this study suggest the optimal density for bananas depends on water availability, soil fertility and cultivar. The agronomic optimal plant density is lower (< 4444 plants ha^{-1}) in low rainfall (< 1000 mm yr^{-1}) and less fertile areas, but seems to be higher (> 5000 plants ha^{-1}) in areas with high fertility, which receive high rainfall (> 1300 mm yr^{-1}). Improved plant density management can serve as an important entry point for resource poor farmers to maximize yield potential of EAH bananas in the various production zones. Blanket density recommendations do not make sense. While farmers can significantly improve their banana production, increased densities will put significant additional stress on limited nutrient resources, and region-specific integrated soil fertility recommendations should be developed and adopted to ensure sustained improvements of banana production and smallholder livelihoods.

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LIST OF SYMBOLS AND ABBREVIATIONS

AAA-EA: Triploid *M. acuminata* belonging to East African highland banana (subgroup Lujugira-Mutika)

Ca: Calcium

CEC: Cation exchange capacity

CIALCA: Consortium for Improved Agriculture-based Livelihoods in Central Africa

DGDC: Directorate General for Development Cooperation (of Belgium)

DRC: Democratic Republic of Congo

EAH: East African highland bananas

FAO: Food Agriculture Organization of the United Nations

GDD: Growing degree days

INIBAP: International Network for the Improvement of Banana and Plantain

ISAR: Institut des Sciences Agronomiques du Rwanda (National Agricultural Research Institute)

K: Potassium

LAI: Leas area index

m a.s.l: m above sea level

Mg: Magnesium

N: Nitrogen

NARO: National Agricultural Research Organisation, Uganda

P: Phosphorus

PAR: Photosynthetically active radiation

PCA: Principal component analysis

S: Sulphur

SOM: Soil organic matter

UNESCO: United Nations Educational, Scientific and Cultural Organization

Ruhengeri: Current nomination is Musanze

Butare: Current nomination is Huye

Kibungo: Current nomination is Ngoma

CHAPTER 1

GENERAL INTRODUCTION

1.1 EAST AFRICAN HIGHLAND BANANAS (*MUSA* SPP.)

Bananas are among the most important food and cash crops worldwide (Samson, 1992). They provide food and income to over 70 million people (INIBAP, 1994). In Africa, their annual production has been estimated at 15.9 million metric tons (FAO, 2010). East African highland (EAH) bananas are a distinct subgroup in the genus group of *Musa* spp. (Karamura, 1998). They include four divisions: group, subgroup, clone set and clone (or variety). EAH bananas are grouped depending on clone, and their primary use for cooking or beer (Sebasigari, 1987). Morphological characters such as bunch shape, pulp taste, and flower properties are also used to distinguish clone sets (Karamura, 1998). Five clone sets have been described in highland bananas, namely Beer, Musakala, Nakabululu, Nakitembe and Nfuuka and the majority are AAA (*acuminata*) triploids (Karamura, 1998).

In the East African highland region, bananas remain the major cash and staple food crop (Gowen, 1995; Frison & Sharrock, 1999) for more than 30 million people (Karamura *et al*., 1998). They are grown across the countries of Rwanda, Uganda, Burundi, the Kagera region of Tanzania, western and central Kenya and eastern Democratic Republic of Congo (Frison & Sharrock, 1999). The crop is mainly produced by small scale farmers for their subsistence needs and income when surplus is traded. The destination of a large proportion of the bananas sold by the producers is village and urban trading centres, consequently creating employment for both rural and urban traders, transporters and vendors. Total banana production (in million metric tons per year) is estimated at 2.75 in Rwanda, 9.55 in Uganda and 0.14 in Burundi (FAO, 2010). In 2007, Uganda was the second largest producer of banana in the world, and the most important in Africa (FAO, 2009). In East Africa, Uganda is the largest producer, Rwanda is the second and Burundi the third (FAO, 2009). The banana per capita production was estimated at 472 kg in Uganda, 383 in Rwanda and 236 kg in Burundi (Frison & Sharrock, 1998). In the East African region, bananas contribute 16 to 31% of total calorie intake (Abele *et al.*, 2007), indicating their important role in food security.

1.2 SOIL FERTILITY PROBLEMS IN THE EAST AFRICAN HIGHLAND REGION

Poor crop yields in East African cropping systems are primarily attributed to poor and declining soil fertility (Smaling *et al.*, 1997; Bekunda *et al.*, 2004). Most soils in the East African highland region are characterized by low inherent soil fertility (Stoorvogel & Smaling, 1990), which is accompanied by continuous degradation, resulting in low nutrient content (Sanchez & Logan, 1989). Farming is dominantly practiced on highly weathered soils, such as Ferralsols and Acrisols, with low nutrient contents such as N, P, K, Ca, Mg and S (Sanchez & Logan, 1989; Zake, 1992). Large quantities of nutrients continue to be exported from these systems, while use of external nutrient inputs is very limited (Baijukya & De Steenhuijsen Piters, 1998), which results in soil nutrient mining (Bekunda *et al.*, 2004). Crop production strongly depends on soil fertility replenishment with additional inputs (Bekunda *et al.*, 2004). Although an overall negative nutrient balance trend was reported in African land use systems (Cobo *et al.*, 2010), the highest annual nutrient depletion rates of 41 kg ha^{-1} N, 4 kg ha^{-1} P and 31 kg ha^{-1} K were recorded in sub-Saharan Africa (Bekunda *et al.*, 2004). Although soil fertility depletion occurs throughout Africa, it is more acute in Rwanda where annual losses are estimated at 54 kg N, 20 kg P and 56 kg K ha^{-1} year^{-1}, due to over exploitation of natural resources and increased cultivation of marginal areas (Godefroy *et al.*, 1991).Continuous high nutrient depletion was experienced in East African countries (Stoorvogel *et al.*, 1993) due to high population density and continuous cultivation (Table 1.1).

Table 1.1 Calculated nutrient balances of N, P, and K (kg ha^{-1} year^{-1}) of the arable land of some Eastern Africa countries (Bekunda et al, 2004).

Country	N		P		K	
	1982-84	2000	1982-84	2000	1982-84	2000
Kenya	-41	-47	-6	-7	-29	-36
Tanzania	-27	-32	-4	-5	-18	-21
Rwanda	-54	-60	-9	-11	-47	-61
Uganda	-33	-	-13	-	-35	-

Strategies for soil fertility management are mainly based on inadequate recycling of crop residues; biomass transfer and nonexistent fallows (Bekunda *et al.*, 2004). Recycling of crop residues can contribute to soil fertility replenishment through their decomposition and release of nutrients. However, the contribution of crop residue recycling to soil nutrient availability depends on residue nutrient contents and management. Researchers evaluate soil fertility status using indicators such as crop yield, soil chemical parameters, plant nutrient concentrations and imbalances, and nutrient balances at plot and farm level (Bekunda *et al.*, 2004). Using a single indicator to assess the soil fertility status and its dynamics is not very reliable, since indicator values often result from complex interactions between abiotic and biotic factors (e.g. soil weathering, erosion, plant pests and disease pressure, climatic conditions and farm management) with large temporal and spatial variability.

1.3 CONSTRAINTS AND OPPORTUNITIES OF EAST AFRICAN HIGHLAND BANANA CROPPING SYSTEMS

East African highland bananas are rain-fed and mostly grown in high rainfall (> 800 mm yr^{-1}) areas at high altitudes (> 800 m) (Karamura, 1998). Banana production systems in the region are also characterised by frequent intercropping, nutrient mining, low external input use and soil degradation that results in low banana yields (Murekezi *et al.,* 2004). Poor banana yields are generally attributed to abiotic factors such as low soil fertility (Wairegi *et al.*, 2010; Okumu *et al.*, 2011) and inadequate soil water and/or low rainfall (Okech *et al.*, 2004; van Asten *et al.*, 2011). Pest and disease pressure also reduces banana yields (Gold *et al.*, 1999; Tushemereirwe, 2006). However, the importance of each factor may differ geographically from one site to another, depending on prevailing biophysical conditions (Wairegi *et al.*, 2010). Although soil fertility is a major constraint to banana yield, it is very important to consider interrelations between abiotic and biotic factors when addressing soil fertility replenishment. For instance, the use of inorganic fertilizers has only increased banana bunch yields significantly when nematode and weevil pressure was low (Smithson *et al.*, 2001). In addition, fertilizers did not significantly increase yield with severe drought (Okech *et al.*, 2004).

Smallholder farmers continue to grow bananas on highly weathered soils (Acrisols and Ferralsols) with inherent low soil fertility (UNESCO, 1977; Nyombi *et al*., 2010) and limited capacity to supply nutrients (Zake *et al*., 1994). Banana is a crop with high nutrient demand (Jones, 1998), making nutrient deficiencies often the primary limiting factor (Zake *et al*, 2000; Nyombi *et al*., 2010). The use of fertilizers should result in yield improvement, but the problem of high cost limits its use by smallholder farmers (Camara & Heinman, 2006; van Asten *et al*., 2010). High banana plant densities, accompanied with high yields, are found near homesteads where crop and kitchen residues are applied more often than is the case for distant fields (Rufino, 2003). Soil nutrient contents (especially P and K) are, as expected, often higher in plots near homesteads. This results in a field soil fertility gradient that leads to lower banana yields with distance from homesteads (Rufino, 2003; Okumu *et al*., 2011).

Concerned about soil fertility problems, farmers adopt different practices that integrate the use of crop residues from household refuse, cattle manure and compost in some cases (Bekunda & Woomer, 1996). However, these strategies are not enough to sustain soil fertility which is declining rapidly under banana cropping systems. Nutrient cycling in banana systems is highly dynamic due to the large amount of nutrients in the banana biomass (van Asten *et al*., 2004; Yamaguchi & Araki, 2004). Therefore, banana productivity might be correlated with the amount of nutrients released during mineralization and those taken up by the banana plants, or inversely correlated with those lost from the system through erosion and leaching. In banana cropping systems, soil nutrients removed with harvested plant parts, primarily bunches, are not replenished, so that contributes to soil fertility decline (Smaling, 1993). Produced bunches are sold in urban centres, resulting in nutrient depletion from rural banana fields (van Asten *et al*., 2004). Banana systems are characterized by high biomass production, with pseudostems, corms and leaves being important nutrient sinks (Stover & Simmonds, 1987). Lekasi *et al.* (2001) reported about 1.0% N and 7.7% K in banana stalks and 2.8% N and 4.9% K in leaf dry matter. Nnutrient exports from banana fields are higher than imported (Table 1.2). For instance in Uganda, in the Lake Victoria region, Bekunda *et al.* (1999) reported 82% of the farmers sell banana fruits, which results in net resource outflows (Table 1.2).

TABLE 1.2. Nutrient balances (kg ha-1 year-1) in banana farming systems.

Country	Site	Biomass	N	P	K
Uganda/Lake Victoria Crescent[(1)]	Kiboga	-101	-33.8	-5.8	-42.0
	Butambala	-550	-93.6	-15.2	-113.0
	Luwero	+580	-45.3	-8.1	-5.1
	Bulemere	+1030	+18.0	+0.8	+8.0
	Kabale	+60	-52.6	-9.0	-63.0
	Mityana	+280	-25.7	-4.8	-31.0
	Makenke	+45	-132.0	-22.7	-159.0
	Mean value	*+192*	*-52.6*	*-9.3*	*-58.0*
Tanzania/Bukoba district[(2)]	In home gardens		-27 to 17	-1 to 7	-5 to 12
	In crop pure stands		-15 to -2	-2 to -1	- 14 to -1

Source: (1)Bazira *et al.* (1997), (2)Baijukya *et al.* (1998).

In Rwanda, bananas are cultivated by smallholders in low input farming systems (i.e. no access to inputs) with farm sizes mostly ranging between 0.5-2.0 ha (Karamura *et al.*, 1999). Bananas are often grown on Acrisols and Ferralsols that have low soil N, P and K contents (Bosch *et al.*, 1996; Gaidashova *et al.*, 2009). Banana plantations are however, also found on Nitisols and young rich volcanic soils (Andosols) with relatively high inherent soil fertility. Rainfall distribution (800-2000 mm) is bi-modal and increases from < 900 mm yr^{-1} in the lower (1300 m above sea level) eastern plains, to rainfall exceeding 1300 mm yr^{-1} in the high altitudes (>1400 m above sea level) of the Congo-Nile ridge in the west of the country (Verdoodt & Van Ranst, 2003).

1.4 PLANT DENSITY MANAGEMENT AS YIELD MAINTAINING FACTOR

Addressing declining and often inherently low soil fertility could result in improved banana yields when coupled with appropriate crop management. Plant density and banana residue management can affect soil fertility constraints and crop yields. Farmers believe that among the yield improving factors, plant density management offers some prospect. Farmers use bunch size per plant as their indicator of yield. They often decrease banana mat densities (i.e. a single mother plant with interconnected suckers), in an effort to increase bunch size. The spacing of banana plants is still a subject of extreme complexity and debate between extension bodies and scientists. The optimal density can be defined as that at which gross margin per hectare per annum is maximized over the entire plantation life (Robinson, 1995) (commercial plantations). Choosing the correct planting density is vitally important for maximizing the yield potential of the plantation. There are a wide range of commercial practices regarding banana plant densities and spatial arrangements around the world. At wider spacing, bananas tend to produce poor yields, but of bunches having a high average grade. In contrast, closer spacing produces higher yields of bunches of poorer grade in terms of fruit length, fruit girth and bunch mass (Robinson *et al*., 1989; Robinson, 1995). There is a big diversity of banana use in East Africa, so that the use of different plant densities on-farm can reflect different market preferences for product quality of cooking and beer genotypes (Ferris *et al.*, 2002). A yield by density curve (Daniells *et al.* 1985) shows a steep initial linear response, suggesting increasing density leads to higher yields per ha, but this then levels off when higher competition between plants leads to lower yields per plant but with similar yield per ha (plateau). If the plant density increases still further, then a reduction in yield per ha (extreme case) is observed. The rule of thumb is that you want to be "on the plateau" of the curve. Farmers may currently still be on the "steep response" part of the curve. Extension officers currently give a 3 × 3 m^2 density recommendation across all agro-ecological regions. This may appear to be sub-optimal, since it results in leaf area indices (LAI) between 1 and 2 m^2 m^{-2} (Nyombi *et al.*, 2009) and LAI should be at 4-5 m^2 m^{-2} for optimal radiation interception when water and nutrient are not limiting (Robinson, 1995). One may therefore ask where banana farmers of the East African highland region are on the curve, in order to help them reach the "plateau"?

1.5 RATIONALE OF THE STUDY

Despite the effort devoted to characterizing banana farming systems and formulating recommendations that address improved crop management, an in-depth investigation of plant density as the major tool to manipulate production is lacking. There is little information on existing banana plant densities and their effects on yields in relation to environmental conditions. Yield figures are generally estimated by means of allometric relationships (Mukasa *et al.*, 2005; Wairegi *et al.*, 2009). However, within and across different agro-ecological zones, banana cropping systems are characterized by a great heterogeneity in terms of (i) mono or intercropping, (ii) wider or closer intra-mat spacing, iii) crop management practices, (iv) soil types, and (v) prevailing climatic condition (i.e. temperature, rainfall quantity and distribution). Thus, differences in field conditions due to human management, determine optimal plant densities, as well as production.

Banana is a perennial crop which develops at its own rhythm, the stools are successively regenerated by suckers and the fruit can be produced all year round (Dorel *et al.*, 2008). In the East African highland region, farmers usually apply a phased planting strategy or inherit fields already planted to bananas. In practice, farmers do not usually clear a whole field and replant it at a fixed spacing, but rather uproot some old mats and plant new ones in between the older ones. As the plantation becomes older, more suckers migrate from the original planting hole so that desuckering is needed to maintain an optimum plant density. In contrast, densities rapidly increase in a few years to several thousand mats per hectare. However, within the East African smallholder farming context, growers are encouraged by extension bodies to follow blanket recommended plant densities (3 × 3 or 2 × 3 m; i.e. 1111 and 1666 mats ha^{-1}, respectively), irrespective of differences in cultivars and prevailing ecological site characteristics. This study attempts to investigate whether large variations in on-farm plant densities exist, and if so what factors drive their variability.

Manipulation of plant density affects harvesting period and bunch quality (Kesavan *et al.*, 2002). Within banana plantations, both growth and yield attributes are affected by the intra and inter mat competition for resources, namely water, nutrients and solar radiation (Turner, 1984; Daniells *et al.*, 1987; Robinson & Nel, 1989; Morse & Robinson, 1996). Quantitative analysis of the complex interactions and the effects of plant density on resource capture in time and space requires understanding of the importance of each of these above and below ground factors in terms of their contribution to the performance of the banana crop. This is not well studied and documented in low input East African highland banana cropping systems. There is little information on banana densities used in East African highland banana systems and an in-depth analysis on managerial and climatic conditions is lacking.

For the East African highland banana systems, nutrient recycling was mostly studied for farmer fields, where there is a large variability in terms of nutrient stocks (Bekunda & Woomer, 1996; Baijukya *et al*., 2005). Nutrient imbalances were also investigated (Wortman *et al*., 1994; Wairegi *et al*., 2010). Banana fields are managed differently depending on plant density and prevailing climatic conditions, but smallholder farmers still lack information on efficient management of nutrient inputs and outputs, which could result in positive or negative nutrient balances; hence they cannot easily achieve potential yields for their conditions. The influence of planting density in space and time, on nutrient content in banana plant and nutrient dynamics in low input banana cropping systems is not well documented; and this requires a quantitative analysis of nutrient balances and factors that are responsible for yield gaps of those cropping systems.

The key hypothesis of this thesis is that optimal plant density is location-specific and is influenced by a complex interaction between managerial factors, soil fertility levels and climate. An understanding of these interactions helps to determine the optimal density in contrasting agro-ecological sites with differences in rainfall, soil types, temperature and management.

Three main research questions and their subsequent specific hypotheses are addressed:

1. What factors affect variations in observed on-farm banana plant densities?

The question requires:

a) Determining on-farm existing banana plant densities and their variation in different agro-ecological sites, and

b) Determining the influence of ecological characteristics on plant density and bunch mass

From the two research questions, we hypothesized that that (i) high rainfall regimes and more fertile sites should favour high densities and heavier bunches and (ii) high densities and heavier bunches are expected in banana monocropping compared with intercropping systems due to closer spacing and less competition.

2. How does resource availability (water, nutrients, solar radiation) influence the choice of optimal plant density of a cultivar under different environments?

The question requires:

a) Studying the influence of plant density on the vegetative growth and yield parameters of AAA-EA bananas with the aim to develop plant density recommendations for typical highland agro-ecological zones,

b) Exploring germplasm × environment interaction, by studying plant performance of three cultivars in contrasting agro-ecological sites, and

c) Investigating resource availability and effects on growth and yield attributes.

From the above three research questions, it is hypothesized that the agronomic response of cultivars (i.e. plant height, girth, number of leaves, crop cycle, etc, and yield attributes) to plant density depends on genotype, prevailing site conditions, climatic characteristics and resource capture (nutrients, solar radiation, water). Therefore, by assuming that water and radiation are not limiting, the degree of soil fertility as major constraint to banana production would govern the agronomic optimal plant density where the optimal plant density would be higher in fertile compared to poor soils.

3. How does plant density affect short and long-term efficiency and sustainability of low input banana-based cropping systems?

This question requires:

a) Investigating nutrient deficiencies by determining the range of nutrient uptake by use of a Compositional Nutrient Diagnosis and evaluating the effect of site quality on banana growth and yield by determining the most limiting nutrients as driven by ecology,
b) Quantifying nutrient flows and balances in different banana plant density systems, and
c) Contributing to the understanding of the magnitude of nutrient depletion and evaluating the system with respect to sustainable production.

From the above three research questions, it is hypothesized that the cumulative effect of biomass production and fruit removal could be unsustainable as it would most likely result in nutrient depletion of the system due to nutrient mining.

1.6 OBJECTIVES OF THE STUDY

The aim of the study was to assess the potential contribution and / or effects of plant density management for improvement of banana yields in low input East African highland banana-based cropping systems.

Specific objectives were:

i. To assess banana planting densities in contrasting agro-ecological sites and explain differences in relation to agro-ecological characteristics (i.e. soil fertility and water), and determine the effect of planting density and cropping system (mono and intercrop on bunch mass.

ii. To investigate the influence of plant density on the vegetative growth and yield parameters of AAA-EA bananas with the aim to develop plant density recommendations for typical highland agro-ecological zones by studying plant performance of banana cultivars in contrasting agro-ecological sites.

iii. To assess the effect of plant density on nutrient deficiencies and imbalances in distinct agro-ecological sites and identify the most yield-limiting factors in relation to site characteristics (soil nutrients and water), and advise on fertilizer recommendations based on the most deficient elements.

iv. To assess the magnitude and variability of nutrient depletion in smallholder banana systems that are characterized by low external input use, but large variability in agro-ecological conditions (soil properties and water), but with similar crop density management.

CHAPTER 2

ECOLOGICAL CHARACTERISTICS INFLUENCE FARMER SELECTION OF ON-FARM PLANT DENSITY AND BUNCH MASS OF LOW INPUT EAST AFRICAN HIGHLAND BANANA (*MUSA* SPP.) CROPPING SYSTEMS

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ABSTRACT

East African highland bananas (*Musa* spp., AAA-EA group) are a primary food and cash crop for smallholders in Rwanda and much of the East African highlands. Their production generally declines over time due to poor farm management and declining soil fertility. Farmers believe that among the bunch mass maintaining factors, plant density management offers some prospect. They often decrease banana mat (i.e. a single mother plant with interconnected suckers) density in an effort to increase bunch size, but the effectiveness and profitability of this practice has not been studied. In addition, not much research has been executed on the influence of climatic and edaphic factors on variations in on-farm plant density. An on-farm survey was conducted in contrasting agro-ecological sites of Rwanda (Ruhengeri, Rusizi, Karongi, Butare, Ruhango, Kibungo and Bugesera) to determine existing densities and their relationship to bunch mass. A plant density assessment method was used that measures the average distance of five mats to their respective nearest four mats to calculate average mat spacing. Plant density positively correlated with surplus/deficit water supply (i.e. difference between rainfall and water demand by bananas) (r^2 = 0.62), with highest plant densities (>1500 mats ha^{-1}) found in high rainfall areas (>1200 mm yr^{-1}) with water surplus (218-508 mm yr^{-1}) and lowest plant densities (1000-1400 mats ha^{-1}) found in lower rainfall areas (1000-1200 mm yr^{-1}) with water deficit (from -223 to -119 mm yr^{-1}). Heaviest bunches (18.1-20.8 kg fresh mass plant^{-1}) were found at lowest plant densities and medium sized bunches (14.7-15.5 kg) at highest plant densities. Lower soil and banana leaf nutrient contents (especially N, K, Ca and Mg) were observed on weathered soils (Acrisols) and were associated with smaller bunch mass in comparison to fertile soils (Andosols, Nitisols). Farmers tended to reduce mat densities (i) if they wanted to intercrop bearing in mind site characteristics, and (ii) to increase bunch mass to adapt to market preferences. The plant densities generally recommended by extension bodies (3 × 3 or 2 × 3 m; i.e. 1111 and 1666 mats ha^{-1}, respectively) are seldom practiced by farmers, nor do they seem to be very appropriate, as higher densities seem productive in areas with high rainfall and relatively good soil fertility. Results from this study have a regional application as East African highland bananas are mainly grown across the countries of Rwanda, Uganda, Burundi, the Akagera region of Tanzania, and the eastern Democratic Republic of Congo, with similarities in banana cropping systems.

Keywords: Agro-ecological sites, water balance, intercrop

2.1 INTRODUCTION

East African highland (EAH) bananas (*Musa* spp.) are an important food and income-generating fruit crop in Rwanda (Okech *et al*., 2005). Their total production (in million tonnes per year) is estimated at 2.75 (FAO, 2010) and about 80% of households produce bananas and per capita consumption is one of the highest (258 kg annually) in the Great Lakes region (Frison & Sharrock, 1998). However, the actual yields reported in national statistics range between 6.0 and 15.0 t ha^{-1} year^{-1} (FAO, 2008), which is considerably lower than the attainable yields of 37.0 t ha^{-1} year^{-1} and potential yields exceeding 100 t ha^{-1} year^{-1} (Wairegi *et al*., 2010). Similarly, an average yield as low as 4.0 t ha^{-1} has been recorded in Tanzania (Gallez *et al*., 2004) and 5.9 t ha^{-1} in Uganda (Kagoda *et al*., 2005). Poor banana yields are attributed to low soil fertility (Wairegi Wairegi *et al*., 2010), pests and diseases (Gold *et al*., 1999; Tushemereirwe, 2006) and inadequate soil water (Okech *et al*., 2004).

In Rwanda, bananas are cultivated by smallholders in low input farming systems (i.e. no access to inputs) with farm sizes mostly ranging between 0.5-2.0 ha (Karamura *et al*., 1998). These systems are highly diverse in terms of soil type and climate (Anon., 2001). Bananas are grown on Acrisols, Ferralsols and Nitisols (UNESCO, 1977). The Acrisols and Ferralsols are characterized by low inherent soil fertility (Sanchez *et al*., 1989) with low soil N, P and K contents (Lassoudière 1989; Rubaihayo *et al*., 1994; Gaidashova *et al*., 2009). Banana plantations are also found on young, rich volcanic ash soils (Andosols) with high inherent soil fertility. Banana plantations are rain-fed and mostly established on lower slopes, valleys and in between-hill depressions where soil water is higher during dry periods (Rockström, 2000).

Rainfall distribution (800-2000 mm) is bi-modal and its pattern follows a south-north orientation, with highest rainfall (> 1600 mm yr^{-1}) in the north-western highlands and lowest rainfall (< 900 mm yr^{-1}) in the eastern lowlands (Verdoodt & Van Ranst, 2003). Temperatures vary little throughout the year and are strongly linked to altitude. The high altitude regions have the lowest average temperature of around 16-17°C. The central plateau has average temperatures of 18-21°C and the highest average temperatures of 20-24°C are found in the eastern plateau and the western lowlands (Verdoodt & Van Ranst, 2003).

Due to both soil and climatic variations within Rwanda, farmers seem to adapt their banana planting densities to prevailing abiotic conditions. However, extension bodies recommend plant densities of 1111 (3 × 3 m) or 1666 (3 × 2 m) plants ha^{-1} (NARO, 2001; Tushemereirwe *et al.*, 2003) irrespective of the agro-ecological zone characteristics (i.e. soil fertility and rainfall). Banana farming systems have evolved over hundreds of years and recommendations made by extension officers are based on a very limited knowledge base in relation to agro-ecological zone characteristics. To maintain soil fertility, farmers often adopt a system where plant nutrients flow from distant fields and grazing areas to the banana fields close to the homestead, through cattle and biomass transfer (Bekunda & Woomer, 1996). Consequently, well managed banana fields remain relatively productive without replanting for more than 100 years (Gold *et al.*, 1999). The soil fertility gradient that is subsequently created results in farmers adapting plant densities as a function of distance from the homestead. Plots near homesteads tend to have higher soil fertility levels resulting from the recycling of household refuse (Swennen, 1990). Due to the land fragmentation that led to small farms of about 0.25-0.5 ha (Karamura *et al.*, 1998), farmers tend to adopt banana intercropping with annual crops depending on the region.

Several methods for estimating bunch mass have been developed for EAH bananas, generally by using allometric relationships (Ssali *et al*., 2003; Yamaguchi & Araki, 2004; Mukasa *et al*., 2005; Wairegi *et al*., 2009). Despite, banana fields are heterogeneous within and across different agro-ecological sites. There is great heterogeneity in terms of (i) mono or intercropping, (ii) wider or closer intra-mat spacing, (iii) different soil types and rainfall distribution, iv) non-standardized management practices and (v) within field, mat plant losses that complicate mat identification. Such field heterogeneity results in variations in plant densities as well as in bunch mass. This study investigates whether large variations in on-farm densities exist and if these are driven by ecology and farmers' objectives. We expect that (i) high rainfall regimes and more fertile sites should favour high densities and heavier bunches and (ii) high densities and heavier bunches are expected in banana monocropping over intercropping systems due to closer spacing. The objectives were (1) to identify existing banana planting densities in contrasting agro-ecological sites and explain differences in relation to agro-ecological characteristics (i.e. soil fertility and water), (2) to determine the effect of planting density on bunch mass and (3) to determine the effect of cropping system (mono and intercrop) on plant density and bunch mass.

2.2 MATERIALS AND METHODS

2.2.1 Surveyed areas and methodology

During August 2008 (i.e. a month which represents the peak harvest period for bananas in the East African highland region; Birabwa *et al*., 2010), a survey was conducted in seven Rwandan agro-ecological sites (Ruhengeri, Rusizi, Karongi, Butare, Ruhango, Kibungo and Bugesera) that differed distinctly in terms of altitude, temperature, annual rainfall, soil type and agricultural value (Table 2.1). All sites were simultaneously surveyed. The banana fields were mostly planted with cultivars that belong to AAA genomic group, representing 70% of banana genotypes in the surveyed sites (Nsabimana & Van Staden, 2005). They were between 10 and 65 years old. Throughout, farmers used to replace dead plants by planting new ones.

The methodology used was adapted from Perrier & Delvaux (1991). In each site, one district was selected and two villages in each district were surveyed. In each village, banana fields were randomly selected from large farms (> 50 mats) (Table 2.2), based on the importance of bananas in the farming system and the biophysical representativity of the location in the region. Banana fields both near to and distant from homesteads were surveyed. Distant fields (about 1 km from each other) were considered to capture as much spatial variability in plant density within farms as possible as functions of (1) variability in soil fertility with distance from homesteads and (2) intercropping practices. In this study, data on individual plants were not collected. Only the number of mats per plot was accounted for. However, most banana farmers do desuckering which maintains banana mat density at three plants (mother, follower as first ratoon and a sucker as second ratoon). They select vigorous daughter or grand-daughter suckers for planting at the end of the wet season (i.e. December-January). So, we can assume that once a bunch is harvested, two individual plants remain at mat level.

TABLE 2.1 Ecological characteristics of surveyed sites.

Main land zones	Agro-ecological zones	Surveyed site	Altitude (m a.s.l)			Annual temperature (C°)			Total annual rainfall (mm)			Soil type/ soil parent material	Agricultural value
			Mean	Min	Max	Mean	Min	Max	Mean	Min	Max		
Highlands	Birunga	Ruhengeri	1960	1460	2500	17.0	14.0	20.0	1317	1110	1678	Andosol / volcanic ash	Excellent
Midlands	Impala	Rusizi	1700	1400	1900	19.4	19.0	22.0	1400	1300	2000	Ferralsol/basaltic rocks	Good
	Kivu Lake borders	Karongi	1600	1460	1900	19.5	18.0	21.0	1200	1150	1300	Acrisol and Cambisol/ schist, shallow	Good-excellent
	Central plateau	Butare	1749	1400	2110	19.5	17.0	22.0	1200	1133	1993	Acrisol / granitic rocks	Moderate-good
		Ruhango	1600	1400	1700	19.2	18.0	20.5	1100	1050	1200	Acrisol/coarse, gravely, granitic rocks	Moderate
Lowlands	Eastern plateau	Kibungo	1575	1370	2200	20.0	18.0	21.0	950	891	1255	Nitisol / shale	Moderate-good
		Bugesera	1400	1300	1500	20.5	20.0	21.0	1101	901	1310	Acrisol/ shale and granitic rocks, strongly weathered	Poor-moderate

Soil type classification is from IUSS-WRB (FAO, 2006). Data adapted from Verdoodt & Van Ranst (2003). m a.s.l-meters above sea level.

TABLE 2.2 Number of banana fields sampled and number of observations in surveyed sites.

Main land zones	Surveyed site	Number of banana fields sampled	Number of observations for plant density and bunch mass data	Number of observations for soil and plant analyses
Highlands	Ruhengeri	12	44	17
Midlands	Rusizi	30	110	-
	Karongi	15	95	-
	Butare	6	41	17
	Ruhango	28	43	-
Lowlands	Kibungo	12	44	17
	Bugesera	30	103	-
Total		133	480	51

2.2.2 Field measurements

2.2.2.1 Plant density

Plant density is expressed as the number of mats per hectare (ha). A mat consists of a mother plant and its suckers of younger generation(s) connected through below ground corm attachments. Suckers originating from the same mother plant will each become a separate mat after the harvest of the mother plant because these suckers will no longer be connected by living corm tissue. To determine the average spacing between mats, the distance between the mother plant of one mat and the mother plants of the four closest mats was measured. This procedure was repeated for five single mats randomly selected in each field. As banana fields were not homogeneous and not planted in rows (Figure 2.1), it was assumed that the surface occupied by each mat was equal to the square of the average mat spacing. The number of plants per hectare (mats ha^{-1}) was calculated as 10000 divided by the square of the average mat spacing (in meters) of the five sampled mother plants.

FIGURE 2.1 Differences in plant spacing in Rwandan banana cropping systems. Left and right photos illustrate low and high plant densities.

2.2.2.2 Estimation of bunch mass

During the survey visits, all matured bunches in each field were harvested and the following parameters recorded: number of hands per bunch, total number of fingers and number of fingers of the lower row of the second lowest hand. Bunch masses of plants between flowering and harvest (i.e. with immature bunches) were estimated using the allometric relationships for East African highland bananas (AAA genomic group) developed by Wairegi *et al*. (2009), based on measuring the girth (circumference) of the pseudostem at the base and at 1.0 m height, number of hands, and number of fingers of the lower row of the second lowest hand in a bunch. The relation used follows:

$\ln(\text{Bm}) = -8.908 + 0.561\ln(\text{Hands}) + 0.482\ \ln(\text{Fingers}) + 0.925\ \ln(\text{Vol}_{stem})$, whereby

Bm = Bunch mass estimate (kg)

Hands = Number of hands on the bunch

Fingers = Number of fingers in the lowest row of the second lowest hand

Vol_{stem} = Pseudostem volume (cm^3) = $\frac{100}{12\pi}\ [G^2{}_{base} + G^2{}_{1m} + (G^2{}_{base} \times G^2{}_{1m})]$

G_{base} = Girth of pseudostem (cm) at the base

G_{1m} = Girth of pseudostem (cm) at 1.0 m height

As bunches are harvested all year round, but their masses are seasonally variable, the survey was undertaken during the harvest peak period which corresponds to harvesting month of the year (i.e. in August 2008). This implies that bunch mass was only assessed in a time span of one month at each site (i.e. we conducted single on-farm visits).

2.2.3 Plant and soil nutrient status

Three of the seven sites (Ruhengeri, Butare and Kibungo) were selected for soil and leaf sampling, and thereafter for assessing intercropping systems. These sites were considered representative of high, mid and lowlands respectively. On selected farms, 10 x 10 cm leaf samples of the internal lamina in the middle section of a leaf were taken from the third youngest fully expanded leaf on flowering plants (Martin-Prével, 1987). Samples were taken from five different plants, randomly selected, and a composite sample made for each location, covering differences in soil fertility levels from close to the homesteads to the border of outer fields. To account for spatial variability in soil nutrients, a composite topsoil sample (0-30 cm depth) was collected from sampling points close to the plants used for foliage samples. Foliage samples were oven dried at 72°C for 48 hours, 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. Soil samples were oven dried at 105°C for 48 hours, ground and sieved (< 2.0 mm). Soil pH was measured in 1:2.5 (sediment:water suspension) as described by Okalebo *et al*. (2003). Soil organic carbon content was determined using the Walkley-Black procedure (Nelson & Sommers, 1982). Total N was determined by Kjeldahl digestion and measured with spectrophotometry (Okalebo *et al*., 2003). Exchangeable cations (Ca, Mg and K) were extracted using a 1.0 M ammonium acetate solution, while for available P, Mehlich-3 solution (Mehlich, 1984) was used. Phosphorus was measured colourimetrically using the molybdenum blue method. Potassium was measured using a flame photometer, while the other cations were determined using an atomic absorption spectrophotometer.

2.2.4 Rainfall and evapotranspiration data

Due to off-farm data on banana plant water use, data on rainfall and evapotranspiration (mm yr^{-1}) of the surveyed sites were simulated using the LocClim estimator (FAO, 2006). The 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. For a mean annual rainfall < 5000 mm yr^{-1}, LocClim was found to provide reliable rainfall estimates (Mokany *et al*., 2006) and has been used successfully to estimate rainfall for EAH banana systems (Wairegi *et al*., 2010). Water demand (mm yr^{-1}) by bananas was calculated by multiplying the reference evapotranspiration by the crop factor (which is 0.9 for bananas in Rwanda). The surplus/deficit water supply for surveyed sites was roughly calculated as the difference between rainfall and water demand by bananas.

2.2.5 Data exploration and statistical analyses

To compare differences between means for plant density and bunch mass, data were subjected to analysis of variance using SPSS 16.0 (Statistical Package for Social Sciences) for Windows. When differences were significant ($p < 0.05$), means were compared between agro-ecological sites using Duncan's multiple range test. A chi-squared test (SPSS 16.0 for Windows) was used to reveal any significant difference between plant densities within each agro-ecological site. In multivariate analysis, principal component analysis (PCA) was carried out in JMP statistical discovery software version 10.0 (SAS Institute Inc., NC, USA) to explore possible patterns between variables (e.g. soil and foliar nutrient contents) and bunch mass. In the PCA, the original variables were transformed into a few new variables, designated as principal components. Lastly, factors influencing plant density were examined. Correlations were calculated to illustrate the relationship between (1) the overall average field plant density (mats ha^{-1}) and bunch mass (kg plant^{-1}), (2) the altitude and plant density and (3) plant density and surplus/deficit water supply. Further, all densities were mapped in different agro-ecological zones of Rwanda following the rainfall distribution (rainfall data were from 1951 to 2005).

2.3 RESULTS

2.3.1 Plant density and bunch mass

Highest plant densities were found in Ruhengeri and Rusizi followed by Bugesera, Ruhango, Butare, Karongi, and lastly Kibungo (Table 2.3). Kibungo and Karongi, with the lowest densities (1006 and 1416 mats ha^{-1}), produced significantly heavier bunches (20.8 and 17.6 kg fresh mass) compared to Ruhengeri and Rusizi (15.5 and 14.7 kg fresh mass), Bugesera (10.8), Ruhango (13.4), Butare (11.9), and Karongi (18.1 kg fresh mass). At all sites, an increase in mat density resulted in a decrease in bunch mass. Variations in data were showed by weak negative correlations between plant density and bunch mass at all sites (r^2= 0.001-0.223). Figure 2 shows that in the range of 1000-3000 mats ha^{-1}, it is possible to get a bunch mass of 20.0-30.0 kg but the bunch mass becomes smaller (<15.0 kg) when plant density becomes higher (> 3000 mats ha^{-1}).

TABLE 2.3 Plant density and bunch mass of surveyed sites.

Site	Plant density (mats ha^{-1})			Bunch mass (kg fresh mass plant^{-1})		
	Mean	Min	Max	Mean	Min	Max
Ruhengeri	2326 ± 99 a	581	3752	15.5 ± 0.8 c	5.7	32.0
Rusizi	2130 ± 72 a	397	6274	14.7 ± 0.4cd	5.0	27.6
Bugesera	1513 ± 53 b	298	4581	10.8 ± 0.5 f	2.4	36.5
Ruhango	1509 ± 62 b	106	5696	13.4 ± 0.6 de	2.7	25.3
Butare	1491 ± 150 b	278	3906	11.9 ± 0.5 ef	7.3	22.3
Karongi	1416 ± 62 b	596	3651	18.1 ± 0.9 b	7.5	34.1
Kibungo	1006 ± 33 c	322	1432	20.8 ± 0.8 a	9.5	37.4

Data with different letters within a column are significantly different at $p = 0.05$. A value followed by ± a value refers to the standard error of the parameter.

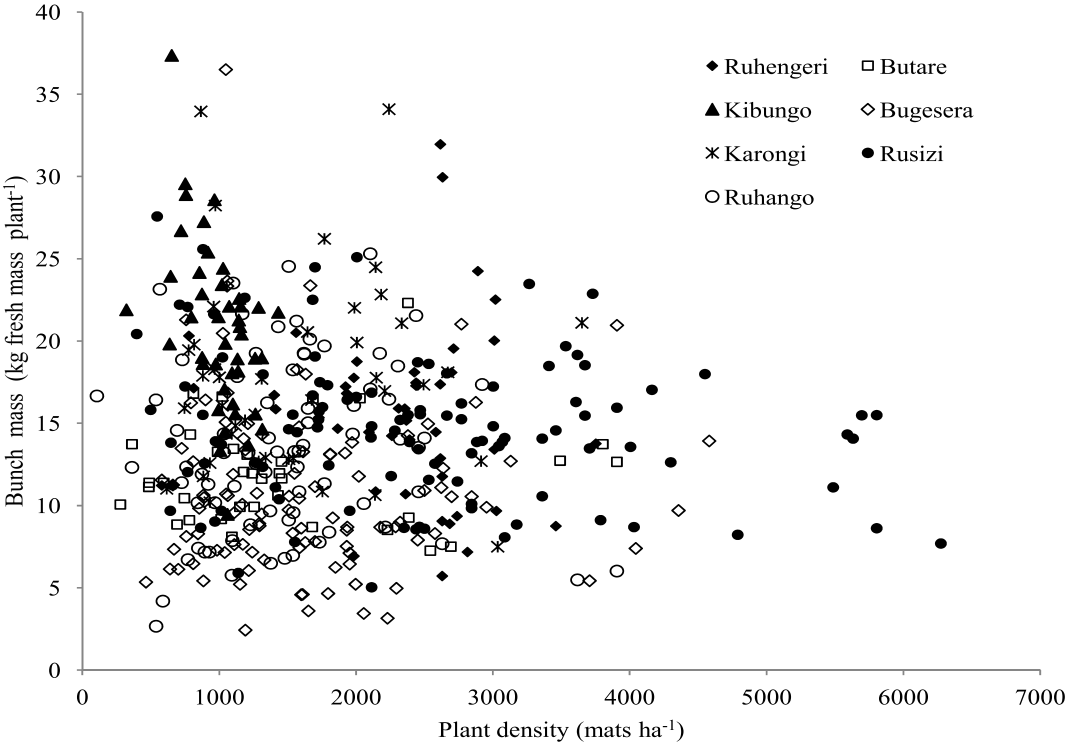

FIGURE 2.2 Relationships between plant density (mats ha^{-1}) and bunch mass (kg fresh mass plant^{-1}) in seven surveyed sites.

2.3.2 Plant density, soil and plant nutrient contents and bunch mass relationships

Within sites, differences between plant densities (mats ha^{-1}) near to and at some distance from homesteads were not significantly different (results not shown). Soil fertility parameters, foliar nutrient concentrations and bunch mass (kg fresh mass) were also not significantly different. Ruhengeri and Kibungo soils had higher organic matter (OM), N, P, K, Ca and Mg contents than Butare. Weak correlations were found between bunch mass and soil K ($r^2 = 0.31$, $p < 0.023$), N ($r^2 = 0.43$, $p < 0.001$), Ca ($r^2 = 0.51$, $p < 0.001$), and Mg ($r^2 = 0.57$, $p < 0.001$) contents. For leaf nutrient content, regions differed significantly for N ($p < 0.002$), P ($p < 0.036$), Ca ($p < 0.001$), and Mg ($p < 0.001$). Ruhengeri had higher leaf K, Ca, and N contents but less Mg than Kibungo (Table 2.4). It was observed that N, P, K and Ca tended to decline from Ruhengeri to Kibungo, but an increase in Mg was observed. At all sites, actual soil nutrient concentrations were above critical values except for Ca in Butare and Ruhengeri and Mg in Butare (Table 2.4). Results on dry matter leaf nutrient concentrations showed that leaf K was suboptimal at all sites. Leaf Ca content was above the optimum values in Butare and Ruhengeri whilst leaf Mg content was below the optimum values in these both sites (Table 2.4).

TABLE 2.4 Soil and plant nutrient analyses at the Ruhengeri, Butare and Kibungo sites.

Sites					Soil nutrient					
	Soil pH	OM	Total N	P	Ca	Mg	K	K/Mg	K/(Ca+Mg)	Zn
		(%)	(%)	(ppm)	------------cmol$_c$ 100g^{-1}----------					(ppm)
Ruhengeri	7.1 a	6.21 a	0.30 a	78.86 a	4.74 a	2.18 b	1.41 a	0.65 a	0.20 a	14.97 a
Butare	6.1 b	3.45 b	0.21 b	13.31 b	1.7 b	1.0 c	0.55 b	0.52 b	0.19 a	2.80 b
Kibungo	7.2 a	6.65 a	0.33 a	29.50 b	5.44 a	3.46 a	1.77 a	0.50 b	0.19 a	5.37 b
Critical values(1)	*> 5.2*	*> 3.00*	*> 0.12*	*> 5.00*	*> 5.0*	*> 2.0*	*> 0.34*	-	-	*> 20.0*
					Leaf nutrient					
			Total N	P	Ca	Mg	K	K/Mg	K/(Ca+Mg)	K/N
			(%)	(%)	(%)	(%)	(%)			
Ruhengeri			2.66 a	0.19 ab	1.43 a	0.22 c	3.04 a	1.46 a	1.96 a	1.16 a
Butare			2.48 ab	0.20 a	1.31 a	0.25 b	2.35 b	9.78 b	1.74 a	0.95 b
Kibungo			2.28 b	0.16 b	0.86 b	0.34 a	2.76 ab	7.96 b	2.48 a	1.22 a
Optimum (2)			*2.7-3.6*	*0.18-0.27*	*0.25-1.20*	*0.27-0.60*	*3.5-5.4*	-	-	-

OM = organic matter. Means followed by different letters within the same column are significantly different at 5% significance level, (1) Bananuka and Rubaihayo (1994a), (2) Martin-Prével (1987).

The principal components of all soil and dry matter leaf nutrient concentrations showed that bunch mass correlated with K in leaf dry matter in Ruhengeri and Butare (Figure 2.3). In Butare, bunch mass was also associated with soil K and P. In Kibungo, bunch mass was associated with soil pH but none of leaf nutrient concentrations correlated with bunch mass. For both soil and plant data respectively, the two principal components accounted for 77.6% and 76.4% of the total variation in Ruhengeri, 66.7% and 70.1% in Butare and 67.5% and 81.5 in Kibungo (Figure 2.3). Table 2.5 shows variance in soil and plant analyses in survey sites. In Ruhengeri, the PCA showed that soil pH explained 52.8% of total variance, OM (24.8), and N (12.2). In Butare, soil pH explained 44.6% of the total variance, OM (22.1), N (14.5) and P (8.6). In Kibungo, soil pH explained 44.2% of the total variance, followed by OM (25.4) and N (10.8). The nitrogen content in foliage explained 53.0% of the total variance in Ruhengeri, 52.8 in Butare and 59.7 in Kibungo. The Phosphorus in foliage explained 23.2% in Ruhengeri, 17.3 in Butare and 21.9 in Kibungo. Potassium in foliage was retained only in Ruhengeri (12.0%) and Butare (13.6) whilst Ca in foliage was retained in Butare and explained 11.5% of total variance.

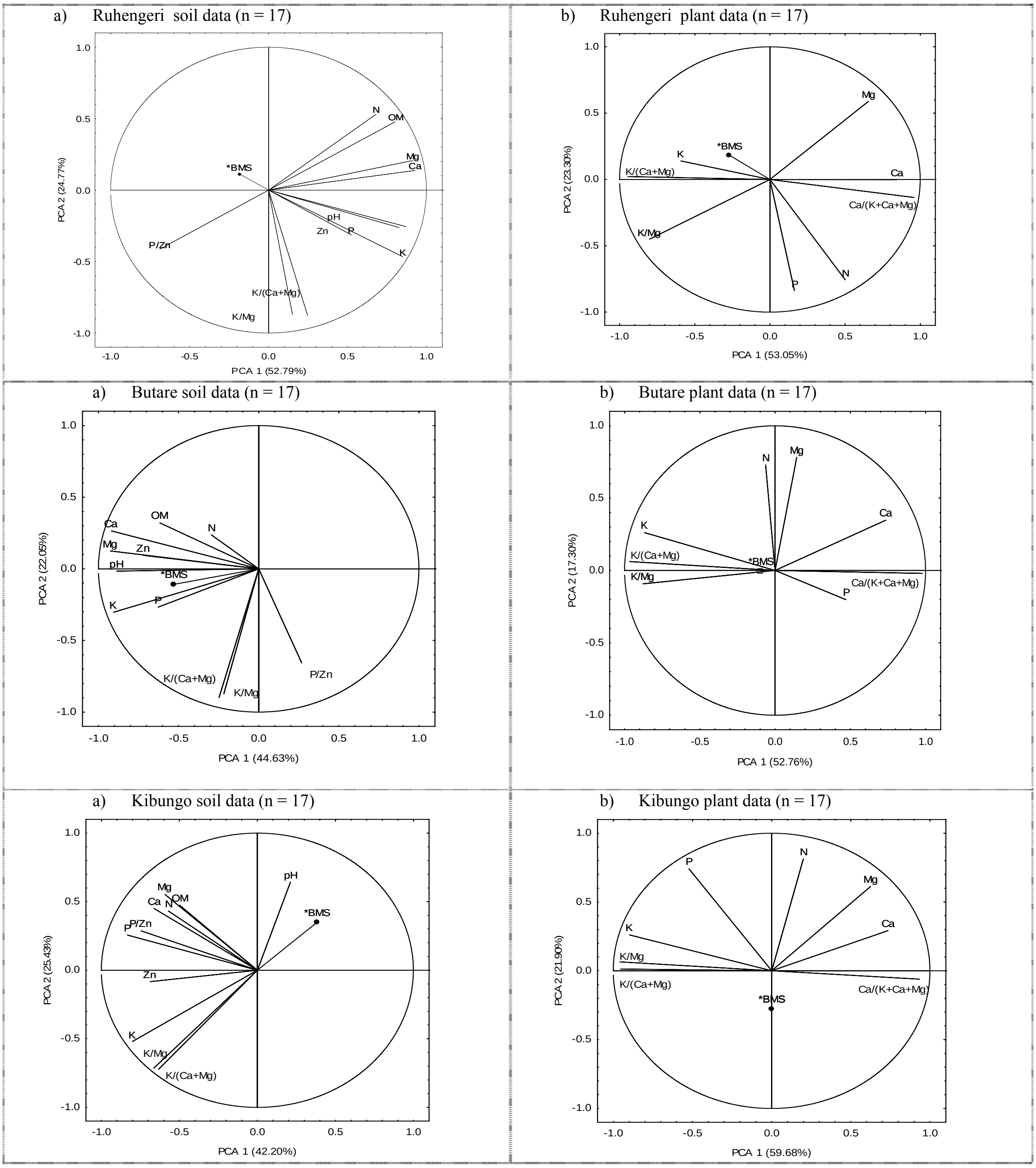

FIGURE 2.3 PCA score plots of PCA 1 and PCA 2 of soil and plant analyses and bunch mass in Ruhengeri, Butare and Kibungo sites. *BMS refers to bunch mass (kg fresh mass plant^{-1}) and OM refers to soil organic matter. PCA 1 and PCA 2 refer to principal component 1 and 2 respectively.

TABLE 2.5 Variance in soil and plant nutrient analyses at the Ruhengeri, Butare and Kibungo sites.

Type of data	Site	Retained parameter	Eigenvalue	Total variance (%)	Cumulative variance (%)
Soil data	Ruhengeri	Soil pH	6	52.8	52.8
		OM	3	24.8	77.6
		N	1	12.2	89.7
	Butare	pH	5	44.6	44.6
		OM	2	22.1	66.7
		N	2	14.5	81.2
		P	1	8.6	89.8
	Kibungo	Soil pH	5	42.2	42.2
		OM	3	25.4	67.6
		N	1	10.8	78.4
Plant data	Ruhengeri	N	4	53.0	53.0
		P	2	23.3	76.3
		K	1	12.0	88.4
	Butare	N	4	52.8	52.8
		P	1	17.3	70.1
		K	1	13.6	83.6
		Ca	1	11.5	95.1
	Kibungo	N	5	59.7	59.7
		P	2	21.9	81.6

OM refers to soil organic matter.

2.3.3 Distribution of plant density and influence rainfall and altitude

The plant density was positively correlated with water balance (i.e. difference between rainfall and water demand by bananas) (r^2 = 0.62), with highest plant densities (> 1500 mats ha^{-1}) found in high rainfall areas (> 1200 mm yr^{-1}) with positive water balance (218-508 mm yr^{-1}) and lowest plant densities (1000-1400 mats ha^{-1}) found in lower rainfall areas (1000-1200 mm yr^{-1}) with negative water balance (from -223 to -119 mm yr^{-1}) (Figures 2.4 and 2.5). Mapping existing densities showed that the highest plant densities were in regions with greater rainfall (Figure 2.6). The highest plant densities were observed in the Birunga (Ruhengeri site) and Impala (Rusizi site) agro-climatic zones. It was observed that high rainfall (> 1300 mm) was associated with high plant densities (> 1800 mats ha^{-1}) while lower rainfall (between 900 and 1200 mm) was associated with lower plant densities (ranging from 1000 to 1500 mats ha^{-1}). The influence of variation in altitude on plant density was evaluated. Results showed a weak correlation (r^2 = 0.14) between altitude and plant density (Figure not shown), although bananas were cultivated up to altitudes of 2000 m above sea level.

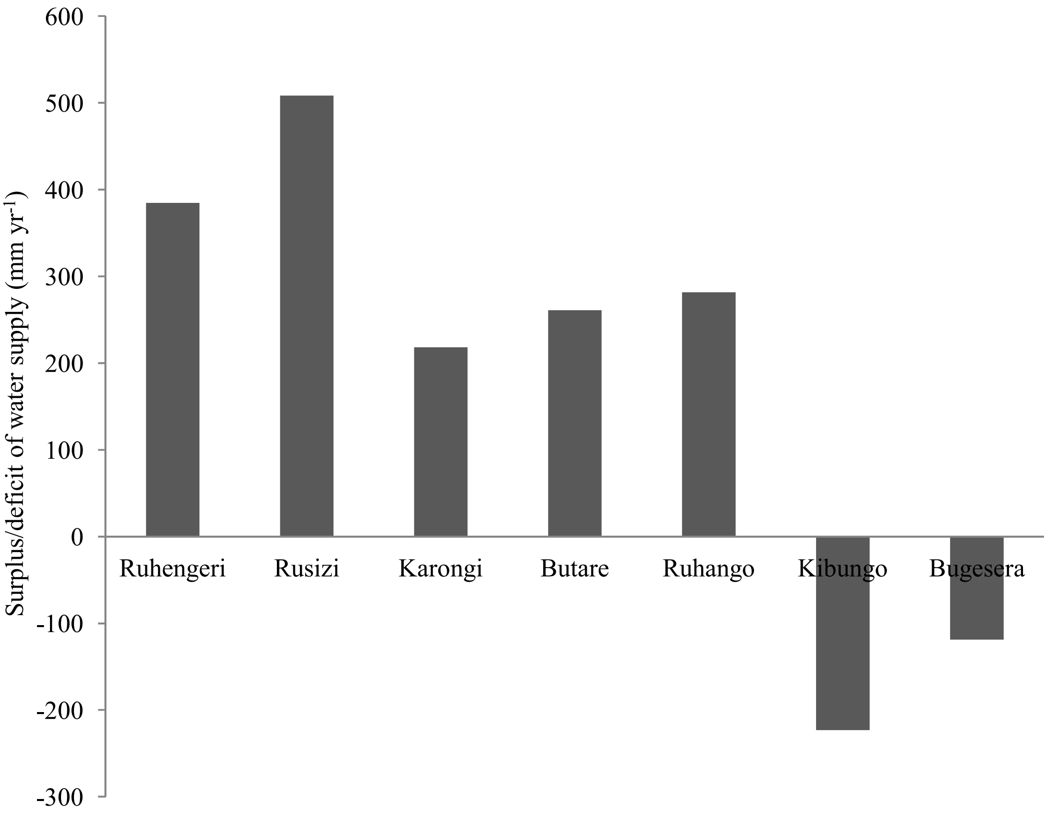

FIGURE 2.4 Surplus/deficit of water supply (mm yr^{-1}) in seven surveyed sites. Surplus/deficit (i.e. difference between rainfall and water demand by bananas) refers to positive/negative balance respectively.

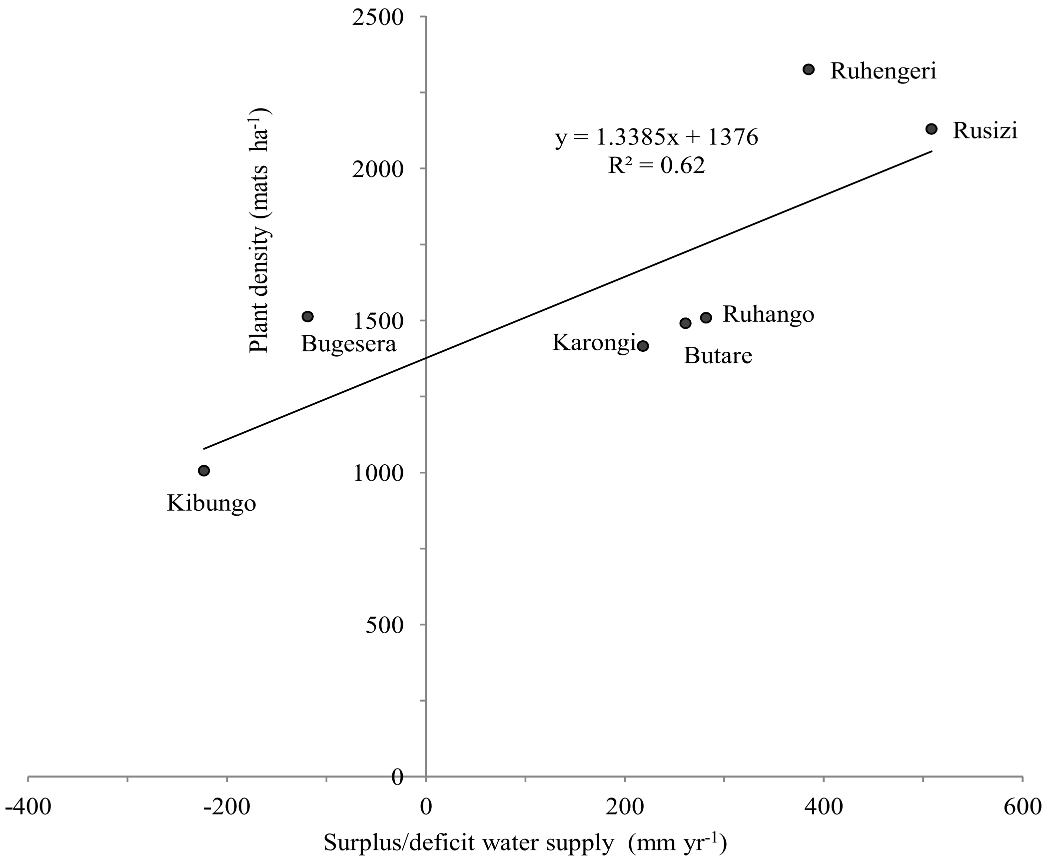

FIGURE 2.5 Relationship between surplus/deficit of water supply (mm yr^{-1}) and plant density (mats ha^{-1}) in seven surveyed sites.

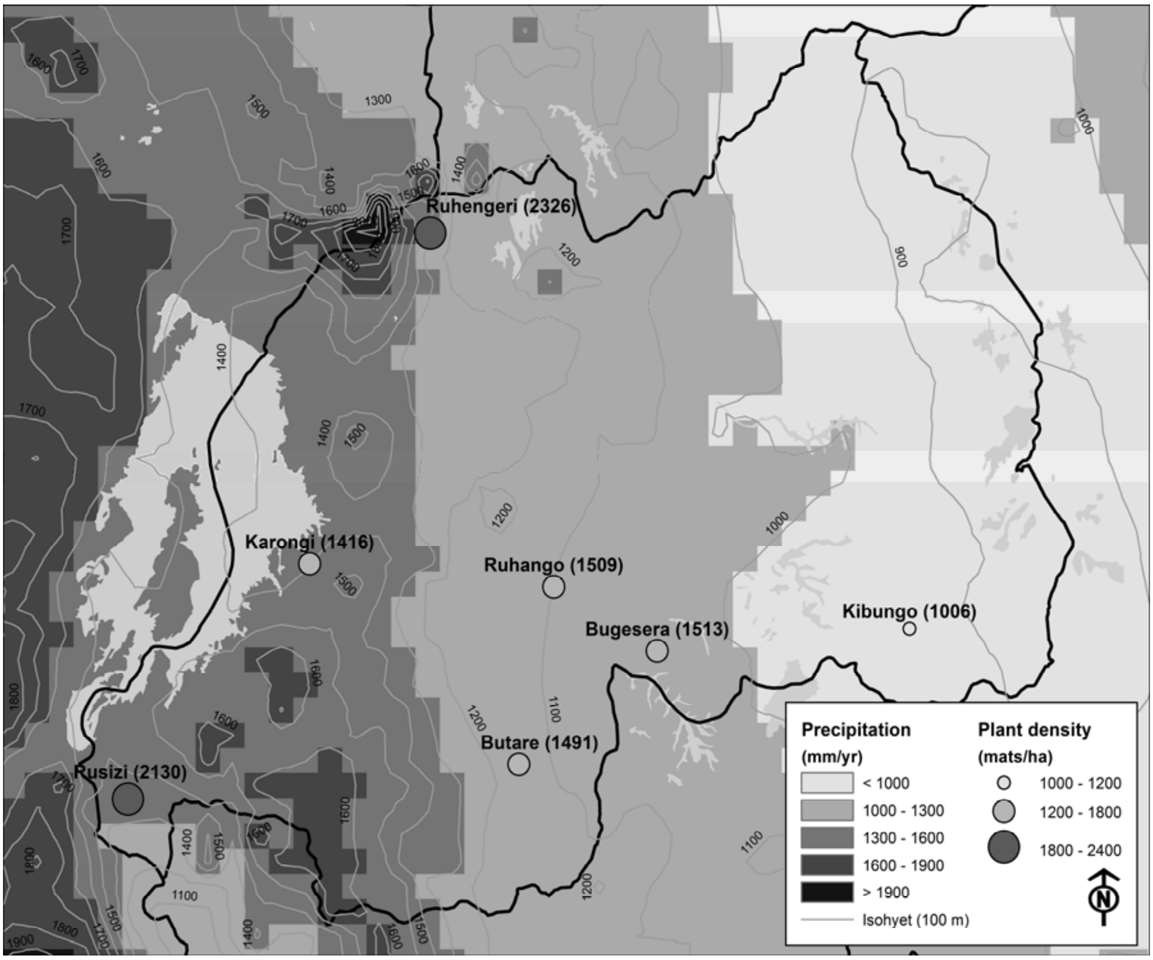

FIGURE 2.6 Map of Rwanda showing banana plant density (mats ha^{-1}) and rainfall distribution (mm year^{-1}) in seven surveyed sites. Data adapted from Verdoodt & Van Ranst (2003).

2.3.4 Influence of intercropping on plant densities and bunch mass

Table 2.6 shows density differences between intercropping systems within the Kibungo site, whilst intercropping systems did not differ significantly in Ruhengeri and Butare. In Ruhengeri, plant densities did not differ significantly for banana-cocoyam (*Colocasia esculenta*), banana-cocoyam-beans (*Phaseolus vulgaris*), monocrop (bananas alone) and banana-cucumber *(Cucumis sativus)*-cocoyam-beans intercropping systems. However, the highest banana plant densities were recorded in monocrop (bananas alone) with an average plant density of 2598 mats ha^{-1}, followed by fields intercropped with cucumber-cocoyam-beans with an average mat density of 2391 mats ha^{-1} (Table 2.6).

In Butare, plant densities in banana-sweet potato (*Ipomoea batatas)*-cocoyam-sorghum (*Sorghum bicolor*)-beans differed significantly from those in intercrops with cassava (*Manihot esculenta*)-cocoyam-beans-sorghum and monocrop. Banana plant densities for banana-coffee (*Coffea arabica*) intercropping systems did not differ significantly from those for banana-cocoyam-beans in Kibungo, but differed significantly from banana-beans and monocrop (bananas alone) cropping systems. High bunch mass (20.2 kg) was observed in monocrops in Ruhengeri, where banana-cocoyam and banana-cucumber-cocoyam-bean intercrops differed significantly from banana monocrops. High bunch mass (22.9 kg) was also observed in monocrops in Kibungo but occurred in banana-cocoyam-bean intercrops (19.4 kg). Medium bunch mass (17.5 kg) was recorded in banana-bean cropping systems. Lower bunch masses (11.7-12.1 kg) were recorded in Butare.

TABLE 2.6 Intercropping, plant densities and bunch mass at the Ruhengeri, Butare and Kibungo sites.

Cropping system		Plant density (mats ha^{-1})			Bunch mass (kg fresh mass plant^{-1})		
	N	Mean	Min	Max	Mean	Min	Max
Ruhengeri							
Banana-cocoyam	18	2317 ± 138 a	779	3026	14.6 ± 1.5 b	5.7	32
Banana-cocoyam-beans	11	2157 ± 233 a	581	3010	16.4 ± 0.7ab	11.2	19.5
Monocrop (bananas alone)	5	2598 ± 357 a	1729	3752	20.2 ± 3.0 a	13.8	30
Banana- cucumber-cocoyam-beans	10	2391 ± 192 a	1403	3460	13.8 ± 1.5 b	6.9	20
Butare				Butare			
Monocrop (bananas alone)	4	1396 ± 358 b	745	2385	11.7 ± 1.7 a	9.3	16.6
Banana-sweet potatoes-cocoyam - sorghum-beans	15	1835 ± 208 a	989	3906	12.1 ± 1.0 a	7.3	22.3
Banana-cassava-cocoyam-beans-sorghum	17	1183 ± 241 b	278	3803	11.8 ± 0.5 a	8.1	16.8
Kibungo							
Banana-beans	5	1188 ± 105 a	875	1432	17.5 ± 1.5 ab	13.3	21.7
Banana-coffee	4	998 ± 83 ab	757	1134	18.6 ± 4.0 ab	9.5	28.9
Monocrop (bananas alone)	21	906 ± 49 b	322	1287	22.9 ± 1.2 a	14.4	37.4
Banana-cocoyam-beans	14	1094 ± 34 ab	856	1265	19.4 ± 0.8 ab	13.7	21.1

Data with different letters within a column are significantly different (Univariate analysis, one-way ANOVA, Duncan test at $p = 0.05$). n = Number of observations. Cocoyam = *Colocasia esculenta*, Cucumber = *Cucumis sativus*, Beans = *Phaseolus vulgaris*, Sweet potato = *Ipomoea batatas*, Sorghum = *Sorghum bicolor*, Cassava = *Manihot esculenta,* Coffee = *Coffea arabica*. A value followed by ± a value refers to the standard error of the parameter.

2.4 DISCUSSION

2.4.1 Variations in plant density and their impact on bunch mass

The variation in plant density followed agro-ecological classes, with soil fertility status and water being the predominant determining factors. Average banana plant densities varied from 1006 to 2326 mats ha^{-1} in Rwandan agro-ecological regions where average rainfall varied between 950 and 1400 mm yr^{-1} and altitude between 1400 and 1960 m a.s.l. The highest plant densities were observed in the Birunga (Ruhengeri) agro-climatic zone, with young volcanic soils, and the Impala (Rusizi) agro-climatic zone with fine basalt-derived clay soils of the highest agricultural potential. Lower plant densities in the central plateau corresponded to poor soils mainly developed on granitic material. In the East region (Bugesera and Kibungo), generally deep and highly weathered tropical soils dominate, and only the soils of the foot slopes have moderate to good agricultural value. High densities in high rainfall areas were also found in the Great Lake Kivu region (CIALCA, 2008). The highest densities (1800-3300 mats ha^{-1}) were observed near the Albertine Rift, where soils are relatively young and with high rainfall (> 1400 mm year^{-1}). Low plant densities (1000-1700 mats ha^{-1}) were observed in Burundi, which has strongly weathered soils and low rainfall (< 1100 mm year^{-1}). Weak correlations between altitude and plant density were also reported in data from the South Kivu-DRC region (CIALCA, 2008), where a poor correlation ($r^2 = 0.06$) prevailed between altitude and plant density, with bananas cultivated up to altitudes of 2000 m a.s.l.

Average fresh bunch masses were between 10.8 and 20.8 kg plant^{-1}. As the highest plant densities were observed in Ruhengeri and Rusizi high rainfall areas and the lowest in Kibungo low rainfall area, this implies that plant density decreases with decreasing rainfall and it is accompanied by greater water demand by bananas (in accordance with high water negative balance). Heaviest bunches were found in less densely planted fields in Kibungo and lower bunch mass was estimated in both Bugesera and Butare. The similar ranges of bunch mass were reported in the previous studies in the East African highland region (Wairegi *et al*., 2009; Birabwa *et al*., 2010; Wairegi & van Asten, 2010). Medium bunch masses were recorded in more dense fields in Ruhengeri and Rusizi high rainfall areas and they are comparable to those found in the Great Lake Kivu region (CIALCA, unpublished data).

Plant density estimations confirm that bunch mass was up to 34 % higher in low density areas (e.g. Kibungo; 1006 mats ha^{-1}) than high density areas (e.g. Ruhengeri; 2326 mats ha^{-1}). However, the reliability of the density estimation method in terms of the effects of plant distribution patterns within the field should be further studied. The determination of the least number of measurements to establish a reliable estimate of plant density requires further in-depth investigation. Although increase in plant density is expected to reduce bunch mass, our findings suggest that in wet and fertile areas, by having plant density up to 2326 mats ha^{-1}, farmers can still get medium sized bunch mass of 14.7-15.5 kg. This suggests that ecological characteristics are an important factor to consider when exploring plant density and bunch mass relationship. It is generally accepted that pest and disease pressure decline with rising altitude and this contributes to higher production. Productivity of bananas grown in the East and Central African highlands is impacted negatively by low rainfall and inadequate use of soil inputs (Gold *et al*., 1999; McIntyre *et al*., 2000; Ssali *et al*., 2003). The lower bunch mass in Butare might be largely attributed to low soil fertility and the occurrence of banana intercropping in that area. Gaidashova *et al*. (2009) also observed a high frequency of intercropping ($p < 0.05$) in banana plantations in the midlands of Butare and lowlands of Kibungo. This is in accordance with the observed highly significant negative correlation ($r =$

-0.72) between average field spacing and bunch mass per unit area (i.e. bunch mass in kg m^{-2}) (data not shown).

2.4.2 Soil fertility, plant density and bunch mass relationships

It has generally been reported in different studies that soil nutrient levels (especially P and K) were higher in plots near homesteads compared to distant plots, due to the recycling of household refuse (Swennen, 1990; Rufino, 2003). Results from this study did not support this. Considering soil nutrient content, plots near homesteads did not significantly differ from ones further away at all sites (data not shown). In a study on the relationship between soil properties and banana plant growth and vigour, Gaidashova *et al*. (2009) found that plots with poor and good vigour differed significantly in pH and soil nutrient content in Butare-Gitarama (i.e. Ruhango site) and Gashonga and Bugarama (i.e. Rusizi site), while plots with similar vigour were uniform in soil characteristics in Kibungo and Ruhengeri eco-regions. This might suggest that the statements from Swennen (1990) (who observed tremendous differences between the home gardens and the fields in West and Central Africa) and Rufino (2003) depend on the way the household refuse is distributed within the farm and on the inherent soil fertility of these systems. Although use of mulch and/or crop residue in banana small-holder farms was previously cited by a large number of farmers (from 82 to 92% of respondents) (CIALCA, 2008), it is not known whether these were applied near to or far from homesteads. Results from this study confirmed that homestead plots were similarly managed to distant plots. It was also observed earlier that bunch mass did not differ significantly ($P > 0.05$) for both near and distant plots. The weak correlations between bunch mass and soil fertility parameters (K, N, Ca and Mg) were also found in studies of Bananuka and Rubaihayo (1994), Smithson *et al*. (2001) and Rufino (2003). These significant correlations are good indicators for high banana productivity (bunch per plant). However, the interactions between these elements need to be better understood.

Based on the above correlations, bunch mass also seemed to be related to the degree of inherent soil fertility. Lower bunch masses were recorded in Bugesera and Butare, which have low fertility levels, whilst medium sized and heavier bunches were found in Ruhengeri, Rusizi and Kibungo with relatively good soil fertility status. Gaidashova *et al*. (2009) reported the lowest values of Ca, Mg and K on weathered soil on granites in Butare, higher Ca, Mg and soil organic carbon in a Nitisol in Kibungo, and higher pH, Ca, Mg and P contents on the young volcanic soils of Ruhengeri. Wairegi *et al*. (2010) also suggested that banana production is constrained by low inherent soil fertility. Results from Table 2.4 suggest that soils with K deficiency as high as 1.41-1.77 cmol_c 100g^{-1} (i.e. Ruhengeri and Kibungo) are associated with very large amounts of exchangeable Ca and Mg (Turner *et al*., 1989) and therefore, from the ratios K/ (Ca + Mg) and K/Mg, it appears that Ruhengeri soils are rich in K compared to Rubona and Kibungo although the ratio K/(Ca + Mg) did not differ significantly ($P > 0.05$).

As crop residues were not frequently applied and inorganic fertilizers not used at all, observed nutrient reserves might be attributed to release from soil parent material over the years. The presence of nutrient reserves may depend also on organic matter content, which is linked to farm management practices and field age. Results from this survey did not answer the question whether soil nutrient contents were influenced by plant density, as there were no significant correlations between density and soil chemical parameters. However, due to the fact that inorganic fertilizer is not used, it was suggested that more dense plots would be more depleted but depending on field age, hence the low bunch mass. In contrary, high density areas have medium sized bunch mass compared with others. High Ca content in high Ruhengeri soils was probably attributed to the presence of volcanic ash having high reserves of Ca (Delvaux, 1989). Leaf nutrient content followed the same trend as soil nutrient content. A decrease in leaf N, P, K and Ca contents from Ruhengeri to Ruhango might suggest a decrease in soil nutrient content as well. Thus, the lower leaf Mg content in Ruhengeri can probably be attributed either to the relatively low Mg content in the volcanic soils or antagonism between K and Mg (Lassoudière, 1989; Jeyabaskaran, 2000; McIntyre *et al*., 2000). Our findings agree with results of leaf analyses from samples collected in the Great Lake Kivu region where soil nutrient status was related to soil type (CIALCA, 2008). Phosphorus and Mg deficiencies were observed on highly weathered soils and potassium deficiencies generally dominate on soils that have a slower weathering rate or where it is inherently lacking (i.e. quartzite and granite).

2.4.3 Influence of cropping systems on plant density and bunch mass

Intercropping did not always significantly reduce bunch mass in less fertile and high rainfall areas (i.e. Butare) and low rainfall areas (i.e. Kibungo), but did so in high rainfall areas (i.e. Ruhengeri). Where bunch mass is smaller due to low soil fertility (i.e. Butare), farmers can compensate for this with intercrops, thereby reducing banana bunch mass but lowering the risk of failure of the entire crop. The occurrence of different intercrops was suggested to influence plant density and these differed within agro-ecological zones. This occurrence is partially attributed to crop land suitability with respect to climatic conditions. The study showed that cassava (*Manihot esculenta*) was intercropped on poor soils and cocoyam (*Colocasia esculenta*) on fertile soils. The less number of intercrops in Kibungo is due to the fact that this was traditionally considered as a banana growing area where management practices such as mulching, with limited intercropping, were widely adopted by banana growers (Gaidashova *et al*., 2009). One can conclude that farmers adapted densities if they wanted to intercrop, bearing in mind site characteristics. Furthermore, most intercrops other than cocoyams were found distant from the homesteads, while monocrops were nearby (results not shown). As smaller spacing could lead to smaller bunches, farmers would plant further apart to have bigger bunches if they owned larger fields. These results suggest that, irrespective of cultivar type, the maximal production per plant (kg bunch mass plant^{-1}) was the main objective of the farmers (Vanhoudt, 2009). In the present study, the choice of plant density varied with region and largely depended on whether the field was intercropped.

2.5. CONCLUSIONS

This study explored variations in on-farm plant densities in East African highland banana cropping systems. It showed that variation in plant density followed agro-ecological classes and overall regional plant density varied greatly. Water and inherent soil fertility were found to be the drivers of variation in density across regions. The plant density was positively correlated with surplus/deficit water supply, with highest plant densities found in high rainfall areas with a positive water balance, and lowest plant densities found in lower rainfall areas with a negative water balance. Heaviest bunches were found at lowest plant densities and medium sized bunches at highest plant densities. Surprisingly, results showed no correlation between density and soil chemical parameters; hence soil fertility differences found between positions near to and distant from homesteads did not result in changes to farmers' density management. Across regions, trends in bunch mass also followed soil fertility status. The study showed that estimated bunch masses were in the expected range under low input conditions. The choice of plant density varied with region and depended on whether the field was intercropped or whether the manager desired large bunch size to meet market preferences. Despite, more large scale investigation would be required to account for the profitability of monocropping compared with intercropping systems (i.e. land equivalent ratio, cost and benefit analysis). Results from this study have a regional application as East African highland bananas are mainly grown across the countries of Rwanda, Uganda, Burundi, the Akagera region of Tanzania, and the eastern Democratic Republic of Congo, with similarities in banana cropping systems.

CHAPTER 3

ECOLOGICAL CHARACTERISTICS AND CULTIVAR INFLUENCE OPTIMAL PLANT DENSITY OF EAST AFRICAN HIGHLAND BANANAS (*MUSA* SPP. AAA-EA) IN LOW INPUT CROPPING SYSTEMS

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ABSTRACT

Numerous studies have been conducted on the effects of plant density on growth and yield of dessert bananas in the humid tropics, but effects of plant densities in relations with ecological characteristics in low input East African highland banana (*Musa* spp., AAA-EA genome) cropping systems have not been reported. On-station field experiments were conducted in three contrasting agro-ecological sites of Rwanda (Kibungo low rainfall with medium soil fertility, Rubona high rainfall with low soil fertility and Ruhengeri high rainfall with high soil fertility) to explore germplasm × environment interactions. Five different plant densities (plants ha^{-1}): 1428, 2500, 3333, 4444 and 5000 and two cooking ("Ingaju", "Injagi") and one beer ("Intuntu") cultivars were investigated. The effect of plant density on plant performance (growth and yield) over two cropping cycles in low input systems was determined. The effects of site × cultivar and site × density interactions on yield traits were significant ($P < 0.05$). Annual yield increased with increasing plant density but strongly depended on agro-ecological site (from 6.1 to 9.2 t ha^{-1} yr^{-1} at Kibungo, 9.5 to 21.5 t ha^{-1} yr^{-1} at Rubona and 7.0 to 25.0 t ha^{-1} yr^{-1} at Ruhengeri). Yields of beer cultivars increased with density, but those of cooking cultivars decreased. Maximum yields were attained at 4444 plants ha^{-1} at Kibungo and Rubona whilst yields increased linearly beyond this level at Ruhengeri. Crop cycle duration was prolonged with increasing plant density. Relationships between bunch yield, the total above ground dry matter yields and soil chemical properties suggest that nutrient deficiencies were larger at Kibungo (e.g. K) and Rubona (e.g. K, P, Ca, Mg) compared with Ruhengeri, where yield correlated significantly with leaf area index (LAI). LAI increases up to 4, where 95% of solar radiation was intercepted by the crop canopy, indicating that increasing the LAI above 4 would have little effect on production. Evaporation was much greater at lower rainfall areas (e.g. Kibungo) and accompanied by negative annual water deficit (-135 mm yr^{-1}) than at high rainfall areas (e.g. Ruhengeri) with positive water surplus (382 mm yr^{-1}). Growing degree days from planting to bunch harvest were higher at Kibungo (3675 °Cdays) but much less at the Ruhengeri cooler site (1729 °Cdays), implying temperature is not restrictive at Ruhengeri. This study showed that the optimal density for bananas depends on water availability, soil fertility and cultivar, which serves as an entry point to maximize yield potential for the East African smallholder farmers rather than using a uniform blanket recommended density. We suggest that agronomic optimal plant density should be lower (< 4444 plants ha^{-1}) in low rainfall (< 1000 mm yr^{-1}) and less fertile areas but seem to be higher (> 5000 plants ha^{-1}) in areas with high fertility which receive high rainfall (> 1300 mm yr^{-1}).

Keywords: Agro-ecological site, leaf area index, optimal plant density, Rwanda.

3.1 INTRODUCTION

East African highland bananas (*Musa* spp., AAA-EA genome group) are a major staple and income-generating fruit crop in the highlands of eastern and central Africa (Gowen, 1995), grown across the countries of the Great Lakes region (i.e. Rwanda, Burundi, Uganda, eastern Democratic Republic of Congo and North-west Tanzania) (Frison & Sharrock, 1998). Total banana production (in million tonnes per year) is estimated at 2.75 in Rwanda, 9.55 in Uganda and 0.14 in Burundi (FAO, 2010). In Rwanda, about 80% of households produce bananas and per capita consumption is one of the highest (258 kg annually) in the Great Lakes region (Frison & Sharrock, 1998). Despite its importance, actual average banana yields are poor (< 30 t ha^{-1} year^{-1}) (Wairegi *et al*., 2010), well below the best yields measured (up to 70 t ha^{-1} year^{-1}) in on-station or on-farm trials (Smithson *et al*., 2001; Tushemereirwe *et al*., 2001; van Asten *et al*., 2005).

In the East African smallholder farming system context, there have been several reports of yield decline due to declining soil fertility (van Asten *et al*., 2005; Wairegi *et al*., 2010; Okumu *et al*., 2011). This is attributed to low or inadequate use of external nutrient inputs (Bekunda & Woomer, 1996) and decreasing opportunities for farmers to use manure or leave land fallow due to high human density population (Fermont *et al*., 2008). Other important factors explaining low on-farm yields are pests and diseases (Gold *et al*., 1999) and the occurrence of droughts (van Asten *et al*., 2011). Virtually no attention has been given to the impact of plant density management on banana bunch size and per hectare yields in these low input systems. This is surprising, given the low plant densities that are generally reported in highland banana systems (< 1000 mats ha^{-1}; Wairegi *et al*., 2010) compared with the plant densities commonly used in commercial dessert banana systems (1000-6000 mats ha^{-1}; Robinson & Nel, 1986, Raveendra *et al.*, 2004, Dens *et al.*, 2008).

Numerous studies have been conducted on density recommendations for commercial dessert banana cultivars ("Williams" and "Graind Naine") in subtropical and humid tropical lowlands (Daniells *et al.*, 1987; Robinson & Nel, 1988, 1989; Lichtemberg *et al.*, 1998; Kesavan *et al.*, 2002). In high density banana plantations, strong intra and inter mat competition for light, nutrients and water occurs (Daniells *et al.*, 1987; Robinson & Nel, 1989; Morse & Robinson, 1996), resulting in taller but thinner plants with delayed floral initiation and longer crop cycle duration. Yield characteristics like fruit length, fruit girth and bunch mass decrease with an increase in population density (Robinson, 1996).

Managing canopy characteristics to optimize leaf area index (LAI) and interception of photosynthetically active radiation (PAR) requires site-specific fine-tuning of plant densities (Robinson, 1996). Productivity increases linearly with plant density until a certain maximum at each specific location (Daniells *et al.*, 1987), then level off and even decrease with further plant density increase. While numerous studies have reported on the linear part of this curve, little is known about the densities, conditions, and yield characteristics when reaching the plateau of such curves. East African smallholder farmers are generally recommended a single plant density (1111 plants ha^{-1}), irrespective of differences in cultivars and prevailing ecological site characteristics (e.g. NARO, 2001, Tushemereirwe *et al.*, 2003). Highland bananas are dominantly cultivated by smallholders with little or no use of external inputs (Murekezi *et al.*, 2004). Yields therefore strongly depend on the local agro-ecological conditions (Gaidashova *et al.*, 2010; Wairegi *et al.*, 2010) and banana cultivars used (Nsabimana *et al.*, 2008; Bagamba *et al.*, 2010), which both varying widely within the region.

The objectives of this study were to investigate the influence of plant density on the vegetative growth and yield parameters of AAA-EA bananas with the aim to develop plant density recommendations for typical highland agro-ecological zones. We explored germplasm × environment interaction, by studying plant performance of three cultivars in three contrasting agro-ecological sites. We hypothesized that soil water and nutrient availability limit yield and therefore determine optimal plant density in low soil fertility sites (e.g. Rubona) and low rainfall sites (e.g. Kibungo), whereas above-ground solar radiation competition is the yield limiting factor in high rainfall fertile sites (e.g. Ruhengeri).

3.2 MATERIALS AND METHODS

3.2.1 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 3.1 and Figure 3.1). Kibungo, which is located in the eastern part of the lowlands of Rwanda (1572 m a.s.l, E30°35’311’’, S02°12’825’’), is characterized by weathered soils (i.e. Nitisols, Ferralsols; FAO, 1987) derived from schistose materials. Rainfall is bimodal with average annual rainfall of 931 mm (from 2007 to 2009). Rubona, which is located in the mid-altitude agro-ecological zone of Rwanda (1727 m a.s.l, E029°46’475’’, S02°29’327’’), is characterized by poor soils (i.e. Acrisols; FAO, 1987) derived from granitic parent material. Average annual rainfall is 1039 mm. Ruhengeri, which is located in the north west of Rwanda (1875 m a.s.l, E029°39’348’’, S01°29’204’’), is characterized by young volcanic ash soils (i.e. Andosols, Nitisols; FAO, 1987). Average annual rainfall from 2007 to 2009 is 1366 mm. The Rubona and Kibungo trial sites were under natural fallow for over six years, whereas the Ruhengeri site was cultivated with maize and potatoes (*Solanum* spp.) prior to trial establishment. The Rubona site presents low soil fertility compared with Kibungo and Ruhengeri. All soils have an optimum pH for banana nutrition ranging from 5.5 to 6.2. Average soil organic matter (SOM) and total N values were higher at Kibungo compared to Rubona and Ruhengeri.

TABLE 3.1 Biophysical characteristics of the Kibungo, Rubona and Ruhengeri experimental sites.

Variables	Site		
	Kibungo	Rubona	Ruhengeri
Altitude (m) above sea level	1572	1727	1875
Latitude	S02°12’825’’	S02°29’327’’	S01°29’204’’
Longitude	E30°35’311’’	E029°46’475’’	E029°39’348’’
Rainfall distribution (bimodal)			
First rains	March-May	March-May	March-May
Second rains	October-December	October-December	October-December
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	Sandy clay	Sandy clay loam
	(71.3% clay)	(64.4% sand)	(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 ($\mathrm{cmol_c\ kg^{-1}}$)	3.30 (3.10-3.69)	2.42 (2.02-3.15)	3.04 (2.90-3.19)
Exchangeable Mg ($\mathrm{cmol_c\ kg^{-1}}$)	1.16 (1.02-1.35)	0.67 (0.48-1.00)	0.55 (0.54-0.57)
Exchangeable K ($\mathrm{cmol_c\ kg^{-1}}$)	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 & Van Ranst (2003). **Soil type classification by FAO (1987).

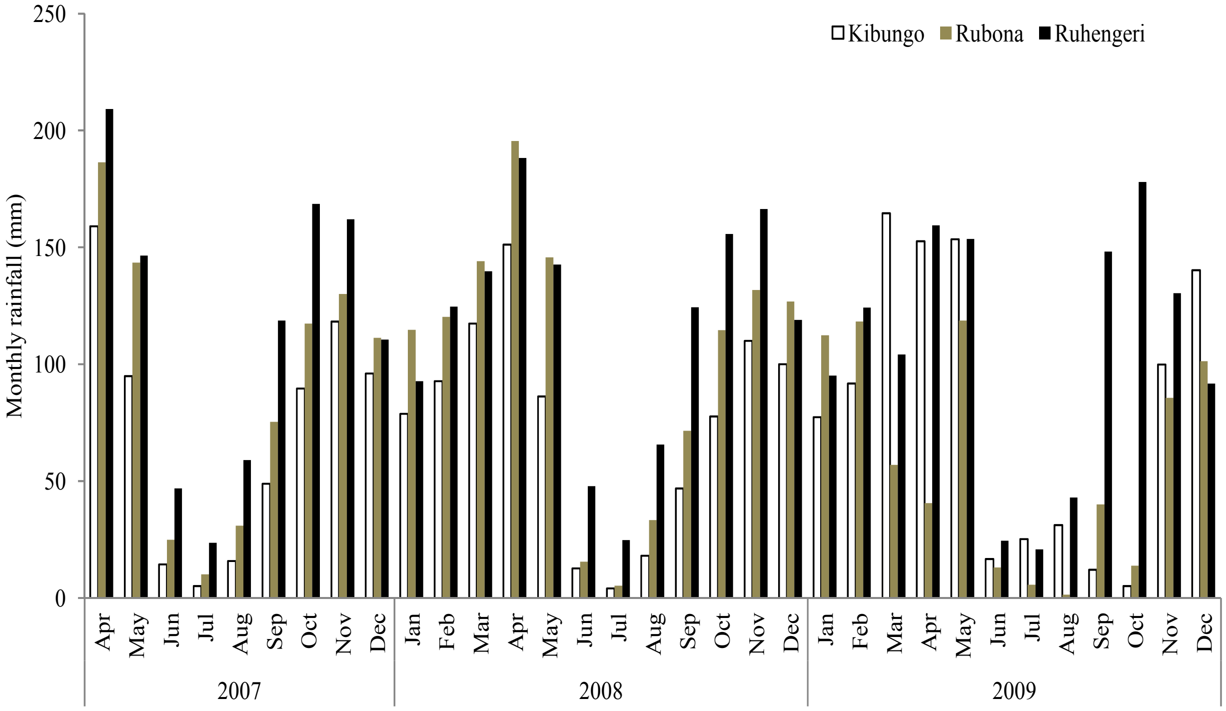

FIGURE 3.1 Monthly rainfall (mm) during the experimentation period at the Kibungo, Rubona and Ruhengeri sites.

3.2.2 Plant material, treatment structure and cultural practices

Three East African highland banana cultivars, including two cooking cultivars ("Ingaju" and "Injagi") and one beer cultivar ("Intuntu"), were used in this study. Plants were established from young (< 1.0 m height), healthy sword suckers. All suckers originated from farmers' fields near the Kibungo site. Corms were pared to remove any lesioned tissue and were subsequently subjected to hot water treatment at 50-55°C for 20-25 minutes (Sarah *et al*., 1996; Speijer *et al*., 2000; Elsen *et al*., 2004; Hauser, 2007) to reduce nematode infestation in the plant and improve sucker establishment and survival. Trials were established in April 2007 at Kibungo and Rubona, and in November 2007 at Ruhengeri. The experimental design was a randomized complete block 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 x 2.0 m. There were three replicates per site. Plots were 14 m × 12 m and planting pits were 45 × 45 × 45 cm in size. A basal dressing of 6 kg dry cattle manure was applied in each planting hole. Thereafter, neither external mulch, nor inorganic inputs were applied. A minimum sample of 15 plants surrounded by a border row was considered as the net plot for data collection for both growth and yield parameters (Nokoe & Ortiz, 1998). Throughout the trial period, desuckering was done to maintain a maximum of three plants per mat; i.e. one mother, one follower as first ratoon and one sucker as second ratoon. Weeded grass, old banana leaves and split pseudostems of harvested plants were left as self mulch in all treatments.

3.2.3 Measurements of vegetative growth characteristics

During the early stages of growth (i.e. up to nine months after planting), plant growth traits were measured at one month intervals. Thereafter, measurements were taken at two month intervals and terminated at the flowering stage. Pseudostem height and circumference at ground level and at 1 m were measured. Pseudostem volume was calculated using allometric relationships from Wairegi *et al*. (2009). At each interval-measurement, the number of functional (considered as > 50% green) and dead leaves were recorded, as well as the length and the width of the third middle leaf from the top. The total plant leaf area was then calculated following the methodology of Nyombi *et al*. (2009). Leaf area index (LAI) was computed for each density as the total leaf area per plant divided by the ground area available to each plant. LAI measurements were made from six months after planting to early flowering.

3.2.4 Measurement of yield parameters

At each harvest, the following data were recorded: date, bunch mass, number of hands per bunch, and number of fingers of the lower row of the second lowest hand. Total fresh mass of bunches, pseudostems, and leaves were measured using a field balance (± 0.5 kg). Fresh subsamples of fingers, pseudostems and leaves were oven-dried at 70°C for 72 h for dry matter determination. Total above ground dry matter yields (bunches + leaves + pseudostems) were expressed as t ha^{-1} cycle^{-1}. The harvest index on a dry mass basis was computed as the bunch dry matter divided by total above ground dry matter and multiplied by 100 to express it as percentage. The total fresh yield in t ha^{-1} was calculated from the mean bunch mass and plant density. The yield per ha per year (t ha^{-1} yr^{-1}) was then computed as [(yield per ha)/cycle duration in months] × 12 (Robinson & Nel, 1989; Kesavan *et al.*, 2002). Cycle duration was from planting to harvest for plant crop, and between two successive harvests from the same mat for the ratoon crop. Due to wind damage at Rubona and the incidence of Bacterial Wilt Disease (caused by *Xanthomonas vasicola* pv. *Musacearum,* formerly *Xanthomonas campestris* pv. *musacearum*) at Ruhengeri, bunch mass and yields from the ratoon crop in both sites were estimated at pre-harvest stages using allometric relationships developed by Wairegi *et al.* (2009), a reliable non-destructive method to estimate bunch mass in the field.

3.2.5 Soil and plant analyses

Prior to experimental set up, composite soil samples from each plot were collected. Before flowering of the plant crop, soil subsamples were collected at 0-30 cm depth and composited for each plant density treatment. Soil samples were oven dried at 105°C for 48 hours, ground and sieved (< 2.0 mm). Soil pH was measured in 1:2.5 (sediment:water suspension) as described by Okalebo *et al*. (2003). Soil organic carbon content was determined using the Walkley-Black procedure (Nelson & Sommers, 1982). Total N was determined by Kjeldahl digestion and measured with spectrophotometry (Okalebo *et al*., 2003). Exchangeable cations (Ca, Mg and K) were extracted using a 1.0 M ammonium acetate solution, while for available P, Mehlich-3 solution (Mehlich, 1984) was used. Phosphorus was measured colourimetrically using the molybdenum blue method. Potassium was measured using a flame photometer, while the other cations were determined using an atomic absorption spectrophotometer. Texture analysis was performed using the hydrometer method (Gee & Bauder, 1986). To analyse 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 a flowering plant (Lahav, 1995) and composited for each density treatment. Foliage samples were oven dried at 72°C for 48-96 hours, ground, sieved to < 2 mm particle size, and digested in a sulphuric acid and selenium mixture (Okalebo *et al*., 2003). N and P were determined colourimetrically, while K, Ca and Mg were determined using the atomic absorption spectrophotometer.

3.2.6 Climatic data

During later growth stages (i.e. > 12 months after planting), solar radiation interception was measured to determine any differences in canopy coverage between planting densities. PAR interception around mid-day was recorded using an AccuPAR 2000 (Decagon Devices, Inc., Pullman, Washington, USA). Throughout the measurement period, the dead lower leaves were pruned prior to these measurements to avoid their effect on the fraction of PAR intercepted. To measure PAR below the canopy, a grid of 6 m × 2 m was laid out in each plant density treatment. Eight individual readings were taken across these grids to cater for the large variability in radiation intercepted over short distances. The above canopy readings were collected outside the plots in non-shaded areas to compute the fraction of PAR intercepted following the methodology of Nyombi *et al*. (2009).

Throughout the experimentation period (April 2007- December 2009), rainfall and temperature were recorded hourly with automatic micro weather stations. At each site, cumulative growing degree days (i.e. the cumulative amount of heat; Fortescue *et al*., 2011) from planting to bunch harvest were computed as follows:

Cumulative degree days = Σ (mean temperature - base temperature) × days. The base temperature for banana growth is 14 °C (Robinson, 1996; Nyombi *et al*., 2009).

Data on monthly evapotranspiration (mm) at the experimental sites were simulated using the LocClim estimator (FAO, 2006). The 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. For a mean annual rainfall < 5000 mm yr^{-1}, LocClim was found to provide reliable rainfall and evapotranspiration estimates (Mokany *et al*., 2006) and has been used successfully to estimate rainfall and evapotranspiration for East African highland banana systems (Wairegi *et al*., 2010; Ndabamenye *et al*., 2012). 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 surplus/deficit water supply for experimental sites was roughly calculated as the difference between rainfall and water demand by bananas.

3.2.7 Statistical analyses

All data were tested for normality using the statistical analysis system (SAS) for Windows, 9.2 (SAS Institute Inc. 1990). Variables that did not show normal distributions were square root-transformed, and then re-checked for normality. Growth data (i.e. from planting to flowering) were subjected to General Linear Model predictions using repeated measures (Littell *et al*., 1991). Tests of fixed effects were chosen as they help in deciding which model should be used to represent the trends over growth phases. 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. As the interactions site x cultivar and site × density effects were significant ($p < 0.05$), the cultivar responses were analyzed separately using the linear regression model. Stepwise regression analysis automatically selected all significant parameters (Miles & Shevlin, 2001) and in every case, the best regression model was selected on the basis of the largest F-values to indicate the actual response for the cultivar. For each cultivar, significant regressions were used for plotting the means of plant response versus densities to identify the maximum response points.

3.3 RESULTS

3.3.1 Yield components

3.3.1.1 Bunch yields and bunch mass

In the plant crop, results for annual bunch yield (t ha^{-1} yr^{1}) showed that site × cultivar and site × density interaction effects were highly significant ($p < 0.05$) and yields consistently increased with an increase in plant density; significant differences in bunch yield were also observed between sites (Table 3.2). For instance at Ruhengeri, bunch yield (t ha^{-1} yr^{1}) at 5000 plants ha^{-1} was three times higher than the one at 1428 plants ha^{-1}. The interaction effect of site × cultivar on bunch yield differed significantly between cultivars and between sites. For instance, yields were consistently high for all cultivars at both the Rubona and Ruhengeri sites than those observed at the Kibungo site. At all sites, significant ($p < 0.05$) site × cultivar and site × density interaction effects on the number of fingers and bunch mass were noticed (Table 3.2). The overall trend was that an increase in plant density significantly decreased the number of fingers per hand at both the Kibungo and Rubona sites whilst the number of fingers was not significantly different at Ruhengeri. This reduction in number of fingers was accompanied by a high negative effect on bunch mass at Kibungo and Rubona (Table 3.2). In the ratoon crop, the site × cultivar and site × density interaction effects on bunch mass (kg plant^{-1}) and bunch yield (t ha^{-1}) were also significant (Table 3.3). Bunch masses at Kibungo were almost two times bigger than those for the plant crop and high yields (t ha^{-1}) were recorded for cooking cultivars (e.g. “Ingaju”) at Kibungo and for beer cultivars (e.g. “Intuntu”) at the Rubona and Ruhengeri sites. At all sites, bunch yield consistently increased from low to high plant densities (Table 3.3).

TABLE 3.2 Mean values for the effect of site × cultivar and site × plant density interactions on major yield traits of the plant crop.

Interaction		Number of fingers (bunch^{-1})	Bunch mass (kg plant^{-1})	Bunch yield (t ha^{-1} yr^{-1})	ABG (t ha^{-1} cycle^{-1})	HI (%)
Site × cultivar						
1	1	73.2 bcd	4.3 e	7.8 c	47.9 cd	10.6 bc
1	2	63.0 d	4.7 e	8.6 bc	52.1 cd	8.9 c
1	3	68.4 cd	4.0 e	7.5 c	40.3 d	10.2 bc
2	1	81.8 ab	5.6 de	11.6 b	64.9 bc	12.4 ab
2	2	77.0 bc	7.3 cd	15.3 a	71.5 b	12.7 ab
2	3	92.2 a	8.2 bc	17.9 a	75.8 b	14.2 a
3	1	49.2 e	10.2 ab	16.9 a	129.6 a	9.4 c
3	2	49.4 e	9.3 abc	15.1 a	130.8 a	8.2 c
3	3	49.5 e	10.6 a	17.1 a	115.7 a	9.1 c
SE		± 4.3	± 0.7	± 1.1	± 6.7	± 1.0
p		<.0001*	<.0001*	0.0153*	0.0393*	0.0114*
Site × density						
1	1428	79.4 abcd	5.3 cdef	8.7 fg	21.5 j	15.5 b
1	2500	67.2 d	4.3 def	6.1 g	30.8 ij	9.7 cd
1	3333	65.2 d	4.9 def	8.6 fg	50.4 ghi	10.1 cd
1	4444	64.7 d	4.2 ef	9.2 efg	57.4 gh	8.5 de
1	5000	64.5 d	3.0 f	7.0 g	73.8 fg	5.7 e
2	1428	94.6 a	9.3 ab	9.5 efg	32.0 ij	19.9 a
2	2500	89.1 ab	6.9 bcd	11.4 ef	48.6 hi	13.8 b
2	3333	72.8 cd	4.9 def	13.1bc de	52.8 ghi	12.7 bc
2	4444	86.8 abc	7.7 abc	21.5 ab	118.4 cd	9.4 cd
2	5000	74.9 bcd	6.3 cde	19.2 bc	101.9 de	9.8 cd
3	1428	48.8 e	9.8 a	7.0 g	53.3 ghi	8.8 de
3	2500	49.1 e	9.9 a	11.9 ef	86.4 ef	9.3 cd
3	3333	56.3 e	10.0 a	16.2 cd	127.3 c	9.6 cd
3	4444	49.0 e	10.1 a	21.8 ab	133.9 b	8.4 de
3	5000	49.0 e	10.4 a	25.0 a	143.9 a	8.3 de
SE		± 5.6	± 0.9	± 1.5	± 8.7	± 1.3
p		0.0422*	0.0293*	<.0001*	<.0001*	0.0032*

Site 1= Kibungo, Site 2 = Rubona and Site 3 = Ruhengeri. Cultivar 1= "Ingaju", Cultivar 2 = "Injagi" and Cultivar 3 = "Intuntu". An asterisk (*) means significant effect (Pr > *F*, $p < 0.05$) for site × cultivar and site × density interactions. Mean values with the same letter within the column are not significantly different at $p = 0.05$. ABG = Total above ground dry matter yields and HI = Harvest Index. SE = Standard error.

TABLE 3.3 Mean values for the effect of site × cultivar and site × plant density interactions on major yield and growth traits of the ratoon crop.

Interaction		Number of fingers (bunch^{-1})	Bunch mass (kg plant^{-1})	Bunch yield (t ha^{-1})	Pseudostem volume (cm^{3} plant^{-1})	Sucker emergence to flowering (days)
Site × cultivar						
1	1	85.8 a	10.3 abcd	30.1 abc	25675.6 a	567.1 bc
1	2	73.0 bc	9.8 bcd	27.2 bc	26467.0 a	552.6 c
1	3	83.5 ab	8.3 cd	23.6 c	21150.4 bc	593.5 b
2	1	64.3 cd	8.1 cd	22.9 c	17238.7 d	499.1 d
2	2	59.1 de	7.8 d	20.7 c	16865.4 d	495.1 d
2	3	71.3 c	9.0 cd	28.2 bc	18433.2 cd	475.0 d
3	1	45.1 f	10.8 abc	34.3 ab	23680.2 ab	654.4 a
3	2	49.7 ef	12.8 ab	34.4 ab	24361.5 ab	681.5 a
3	3	51.1 ef	13.7 a	41.0 a	26173.8 a	678.4 a
SE		±3.4-4.7	±0.9-1.3	±3.2-4.5	±1220.7-1726.3	±10.8-15.3
p		<.0001*	0.0204*	0.0332*	0.0438*	<.0001*
Site × density						
1	1428	94.7 a	12.8 ab	18.5 de	28205.5 a	530.0 cd
1	2500	83.4 ab	9.0 bcde	20.6 de	25934.7 ab	573.2 bc
1	3333	86.2 a	11.0 abc	35.3 abc	28639.0 a	588.7 b
1	4444	70.5 bc	6.8 def	25.5 cde	20287.6 c	584.2 b
1	5000	69.2 c	7.7 cdef	34.8 abc	19088.0 cd	579.4 b
2	1428	82.5 ab	13.2 a	19.3 de	23064.8 bc	475.0 e
2	2500	82.8 a	11.4 ab	28.5 cde	22685.8 bc	499.6 de
2	3333	44.1 de	5.1 f	16.9 e	15200.9 de	464.2 e
2	4444	57.8 cd	6.3 def	27.9 cde	15473.5 de	506.0 de
2	5000	57.3 cde	5.4 ef	27.1 cde	11137.1 e	503.9 de
3	1428	53.5 de	13.2 a	23.4 cde	25675.8 ab	645.7 a
3	2500	48.4 de	11.5 ab	31.3 bcd	22895.2 bc	679.1 a
3	3333	47.5 de	12.2 ab	44.5 ab	26426.3 ab	662.0 a
3	4444	41.4 e	10.4 abcd	36.9 abc	22126.3 bc	685.6 a
3	5000	52.3 de	14.8 a	46.7 a	26569.1 ab	684.7 a
SE		± 4.3-6.3	± 1.1-1.7	± 4.1-6.0	±1553.9- 2274.7	±13.7-20.1
p		0.0013*	0.0078*	0.01263	0.0032*	0.0215*

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

3.3.1.2 Total above ground dry matter yields and harvest index

For the plant crop, the site × cultivar and site × density effects on total above ground dry matter yields (ABG) (i.e. pseudostems + leaves + bunches; in t ha^{-1} $cycle^{-1}$) were statistically significant (Table 3.2). For all cultivars, ABG were considerably higher at Ruhengeri (115.7-130.8 t ha^{-1} $cycle^{-1}$) than Kibungo (40.3-52.1 t ha^{-1} $cycle^{-1}$) and Rubona (64.9-75.8 t ha^{-1} $cycle^{-1}$). ABG increased significantly with increasing plant density and there were significant differences between sites (Table 3.2). ABG were higher at Ruhengeri (from 53.3 to 143.9 t ha^{-1} $cycle^{-1}$), followed by Rubona (from 32.0 to 118.4 t ha^{-1} $cycle^{-1}$), and then Kibungo (from 21.5 to 73.8 t ha^{-1} $cycle^{-1}$). At all sites, an increase in ABG was accompanied by a decrease in harvest index but without any significant cultivar effect for each site. Low plant densities of 1428 plants ha^{-1} registered higher harvest index (i.e. 15.5% at Kibungo and 19.9% at Rubona) than the high densities of 4444-5000 plants ha^{-1} (i.e. 5.7% at Kibungo and 9.8% at Rubona).

3.3.2 Vegetative growth

3.3.2.1 Growth of the plant pseudo-system

In the plant crop, the site × density interaction effects on plant height were significant ($p < 0.05$) at Kibungo for the densities of 2500 and 3333 plants $ha^{-1}$and Rubona for the densities of 1428 and 4444 plants ha^{-1} but no significant effect ($p > 0.05$) was found at Ruhengeri (Table 3.4). The effects of site × cultivar interaction on plant height were not significant at Kibungo and Rubona, but significant effects were observed at Ruhengeri. In the ratoon crop, increasing density showed a gradual decrease in plant height for all cultivars and a significant effect of site × density interaction was observed at low densities of 1428-3333 plants ha^{-1}

compared with higher densities of 4444-5000 plants ha^{-1}at Kibungo (Table A.5). The plant crop exhibited a linear increase in plant height as plant density increased at Ruhengeri whilst height leveled out at high plant density at Kibungo and Rubona (Figure 3.2). At all sites, the effect of site × cultivar and site × plant density interactions on the girth at the base of the plant crop was significant (Table 3.4) with the greatest increase in girth for cooking cultivars ("Injagi") followed by beer cultivars ("Intuntu").

TABLE 3.4 Estimated effects of cultivar and plant density on the height and girth at the base of the plant crop from planting to flowering at the Kibungo, Rubona and Ruhengeri sites.

Interaction		Plant height (cm)		Girth at the base (cm)	
Site × cultivar		Estimate	Pr > |t|	Estimate	Pr > |t|
1	1	8.374	0.171NS	26.427	<.0001*
1	2	7.151	0.233NS	18.990	<.0001*
1	3	0.000	-	23.453	<.0001*
2	1	-0.054	0.996NS	25.086	<.0001*
2	2	-20.640	0.089NS	20.339	<.0001*
2	3	0.000	-	24.789	<.0001*
3	1	138.420	<.0001*	24.556	<.0001*
3	2	66.896	0.0003*	10.377	0.0012*
3	3	92.634	<.0001*	16.235	<.0001*
Site × density					
1	1428	-14.050	0.068NS	-0.360	<.0001*
1	2500	-23.740	0.003*	-0.331	<.0001*
1	3333	-20.420	0.009*	-0.264	<.0001*
1	4444	-4.761	0.499NS	-0.275	<.0001*
1	5000	0.000	-	-0.246	<.0001*
2	1428	-33.540	0.002*	-0.348	<.0001*
2	2500	13.802	0.208NS	-0.316	<.0001*
2	3333	-2.033	0.852NS	-0.252	<.0001*
2	4444	-26.430	0.012*	-0.263	<.0001*
2	5000	0.000	-	-0.234	<.0001*
3	1428	-1.027	0.933NS	-0.162	<.0001*
3	2500	-23.219	0.066NS	-0.172	<.0001*
3	3333	0.011	0.999NS	-0.154	<.0001*
3	4444	-30.347	0.058NS	-0.155	<.0001*
3	5000	0.000	-	-0.145	<.0001*

Site 1 = Kibungo, Site 2 = Rubona, Site 3 = Ruhengeri, Cultivar 1= “Ingaju”, Cultivar 2 = “Injagi” and Cultivar 3 = “Intuntu”. An asterisk (*) means significant effect (Pr > |t|, $p < 0.05$) for cultivar or plant density, and NS = not significant ($p > 0.05$). Empty brackets mean that no value was selected by the model.

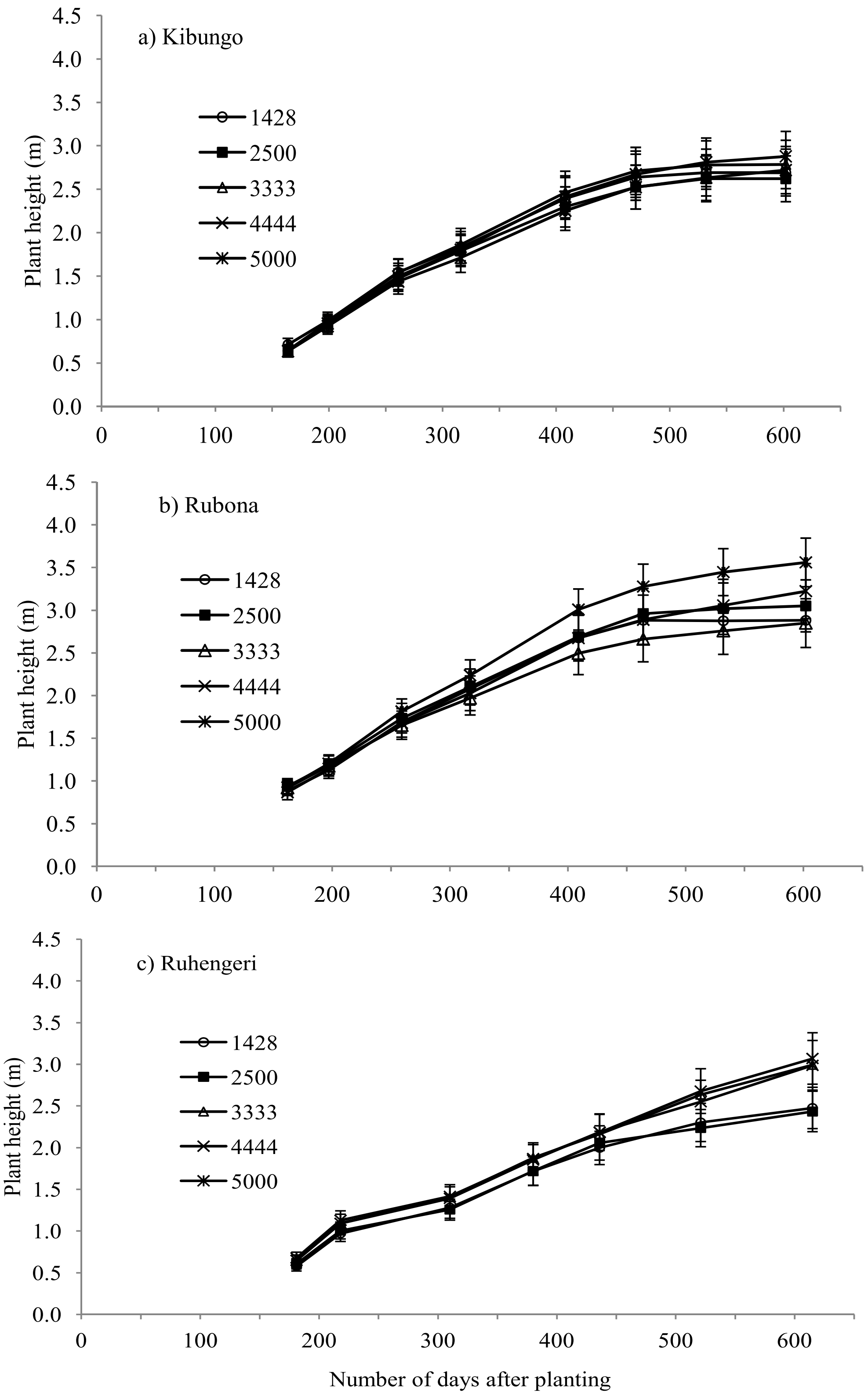

FIGURE 3.2 Effect of plant density (plants ha^{-1}) on the height (m) of the plant crop at the Kibungo, Rubona and Ruhengeri sites. All cultivars are considered together.

In the plant and ratoon crops, the site × cultivar and site × density interaction effects on pseudostem volume were significant at all sites and high plant densities of 4444 and 5000 plants ha^{-1} reduced pseudostem volume significantly at Kibungo compared with those found at low densities of 1428 plants ha^{-1} (Table 3.5). The linear regressions between different growth and yield parameters for the plant and ratoon crops showed that at Kibungo and Rubona, the more the pseudostems become taller, the more the volume increased and the bunch mass also increased. There was a good correlation between plant volume and bunch mass with an increase in r^2 from Kibungo ($r^2 = 0.50$) to Rubona ($r^2 = 0.83$), indicating that the plant volume was more positively correlated to bunch mass at Rubona compared with Kibungo (Table A.4).

TABLE 3.5 Mean values for the effect of site × cultivar and site × plant density interactions on major growth traits of the plant crop.

Interaction		Pseudostem volume (cm^3 $plant^{-1}$)	Pseudostem height (m)	LAI (m^2 leaf m^{-2} soil)	Planting to flowering (days)	Flowering to harvest (days)	Crop cycle (months)
Site × cultivar							
1	1	18461.9 cd	2.7 bcde	4.1 ab	523.6 c	154.7 a	22.7 d
1	2	19747.5 abcd	2.7 bcd	3.8 b	544.6 bc	168.9 a	23.8 bc
1	3	18134.0 d	2.4 e	3.7 b	541.3 bc	163.3 a	23.5 cd
2	1	21772.0 abc	3.0 ab	4.1 ab	524.1 c	157.0 a	22.7 d
2	2	22160.6 ab	2.9 abc	3.8 b	546.7 bc	156.6 a	23.4 cd
2	3	22904.5 a	2.9 abc	4.2 ab	533.5 bc	163.3 a	23.2 cd
3	1	23039.6 a	3.2 a	4.8 a	562.4 ab	180.5 a	24.6 ab
3	2	18027.5 d	2.6 cde	3.8 ab	579.4 a	180.3 a	24.7 a
3	3	19075.0 bcd	2.5 de	3.9 ab	585.8 a	169.5 a	25.0 a
SE		± 1245.8	± 0.1	± 0.3	± 10.5	± 7.6	± 0.3
p		0.0437*	0.0477*	0.0412*	0.0464*	0.5574 NS	0.0104*
Site × density							
1	1428	21402.6 abcd	2.6 bcd	4.3 bcde	492.6 e	152.9 cd	21.5 f
1	2500	18488.9 de	2.5 cd	3.7 def	532.7 bcd	162.6 cd	23.1 d
1	3333	19713.8 bcde	2.7 bcd	3.8 def	541.2 bc	163.3 bcd	23.6 cd
1	4444	16795.0 e	2.5 cd	3.6 ef	561.0 ab	168.0 bcd	24.2 bcd
1	5000	17505.4 de	2.7 bcd	3.9 cdef	554.8 ab	164.6 cd	24.2 bcd
2	1428	24874.2 a	2.9 abcd	2.0 g	499.2 de	161.7 cd	22.0 e
2	2500	23533.1 abc	3.0 abc	3.5 ef	505.2 cde	157.5 cd	22.1 e
2	3333	19147.0 cde	2.7 bcd	3.9 cdef	555.7 ab	142.8 d	23.3 cd
2	4444	23971.6 ab	3.3 a	5.6 ab	558.3 ab	165.7bcd	24.1 bcd
2	5000	19869.3 bcde	2.9abcd	5.1 abc	555.6 ab	167.2bcd	24.1 bcd
3	1428	19029.4cde	2.6 bcd	3.3 ef	563.7 ab	191.5ab	24.1 bcd
3	2500	17402.4 de	2.4 d	2.8 fg	580.2 a	174.5 abc	24.7 bc
3	3333	23048.1 abc	3.0 ab	4.2 cde	582.7 a	166.5 bcd	24.9 b
3	4444	19909.2 bcde	2.9 abc	4.9 abcd	582.1 a	151.2 cd	24.4 bc
3	5000	20847.7 abcde	2.9 abcd	5.6 a	570.6 ab	200.3 a	25.7 a
SE		± 1608.3	± 0.2	± 0.4	± 13.6	± 7.6	± 0.40
p		0.0260*	0.0152*	0.0003*	0.0001*	0.0451*	0.0007*

Site 1= Kibungo, Site 2 = Rubona and Site 3 = Ruhengeri. Cultivar 1= "Ingaju", Cultivar 2 = "Injagi" and Cultivar 3 = "Intuntu". An asterisk (*) means significant effect (Pr > *F*, $p < 0.05$) for site × cultivar and site × density interactions. NS = Not significant ($p > 0.05$). Mean values with the same letter within the column are not significantly different at $p = 0.05$. LAI = Leaf area index. SE = Standard error

3.3.2.2 Crop cycle

At all sites, significant differences ($p < 0.05$) were noticed between densities with respect to days to flowering and flowering to harvest. High densities (4444 and 5000 plants ha^{-1}) significantly increased number of days to flowering, days from flowering to harvest and crop cycle (Table 3.5). Site × density interaction effects on days to flowering of the plant crop were greater at Kibungo, than at Rubona to Ruhengeri. However, site × density interaction effect varied among cultivars. At all sites, the number of days to flower for beer cultivars (e.g. "Intuntu") was increased whilst the reverse occurred for cooking cultivars (e.g. "Ingaju"). As density increases, the crop cycle of the plant crop was between 21.5-24.2 months at Kibungo, 17.9-18.8 at Rubona and 24.1-25.7 at Ruhengeri. At Kibungo, there was about two to three month's delay for the plant and ratoon crops when densities went from low to high. About one and half month's extension was recorded between density extremes at Ruhengeri for the plant crop but densities did not differ significantly at Rubona (Table 3.5).

3.3.3 Optimal agronomic plant density

Figure 3.3 shows that the optimal agronomic plant density varied by cultivar and by agro-ecological site. At Kibungo, yield attained a maximum, and level off and even decreased, at 3333 plants ha^{-1} for cooking cultivars ("Injagi") and at 4444 plants ha^{-1} for "Ingaju" but the maximum yields were not reached for beer cultivars ("Intuntu"). Higher yields were found at 4444 plants ha^{-1} at Rubona and at 5000 plants ha^{-1} at Ruhengeri but all cultivars did not show the optimal density. Results on regression analyses for cultivar response showed a quadratic and quartic cultivar response at Kibungo whilst cultivar response was still linear at the Rubona and Ruhengeri sites (Table A.5).

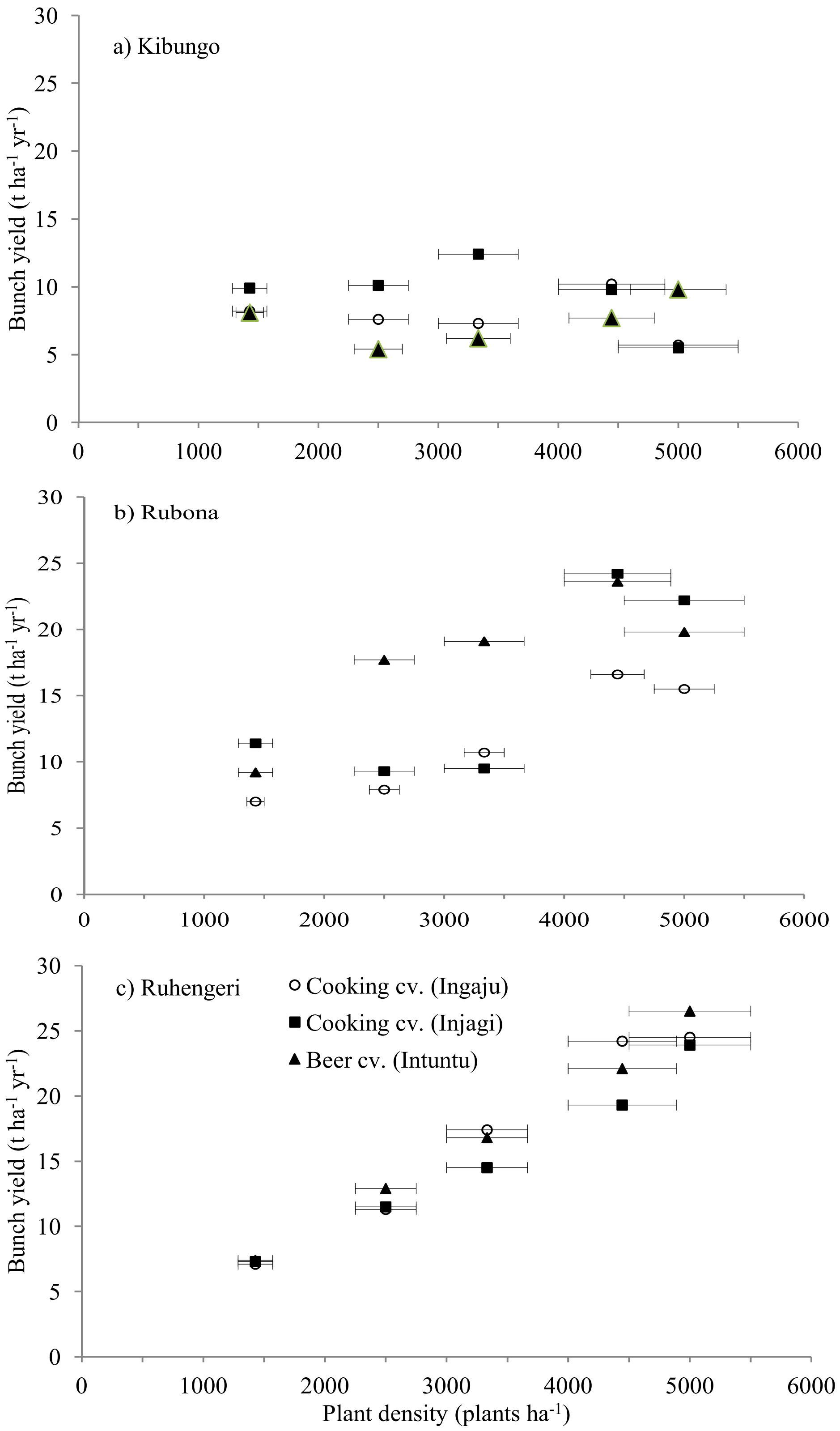

FIGURE 3.3 Optimal plant density (plants ha^{-1}) of banana cultivars at the Kibungo, Rubona and Ruhengeri sites.

3.3.4 Resource availability for banana performance

3.3.4.1 Water availability

Evaporation is much greater at lower rainfall areas (Kibungo) than at high rainfall areas (Ruhengeri) (Figure 3.4). The mean annual water balance (i.e. difference between rainfall and water demand by bananas) was negative (-135 mm yr^{-1}) at Kibungo whilst it was positive at Rubona (210 mm yr^{-1}) and Ruhengeri (382 mm yr^{-1}) (Figure 3.5).

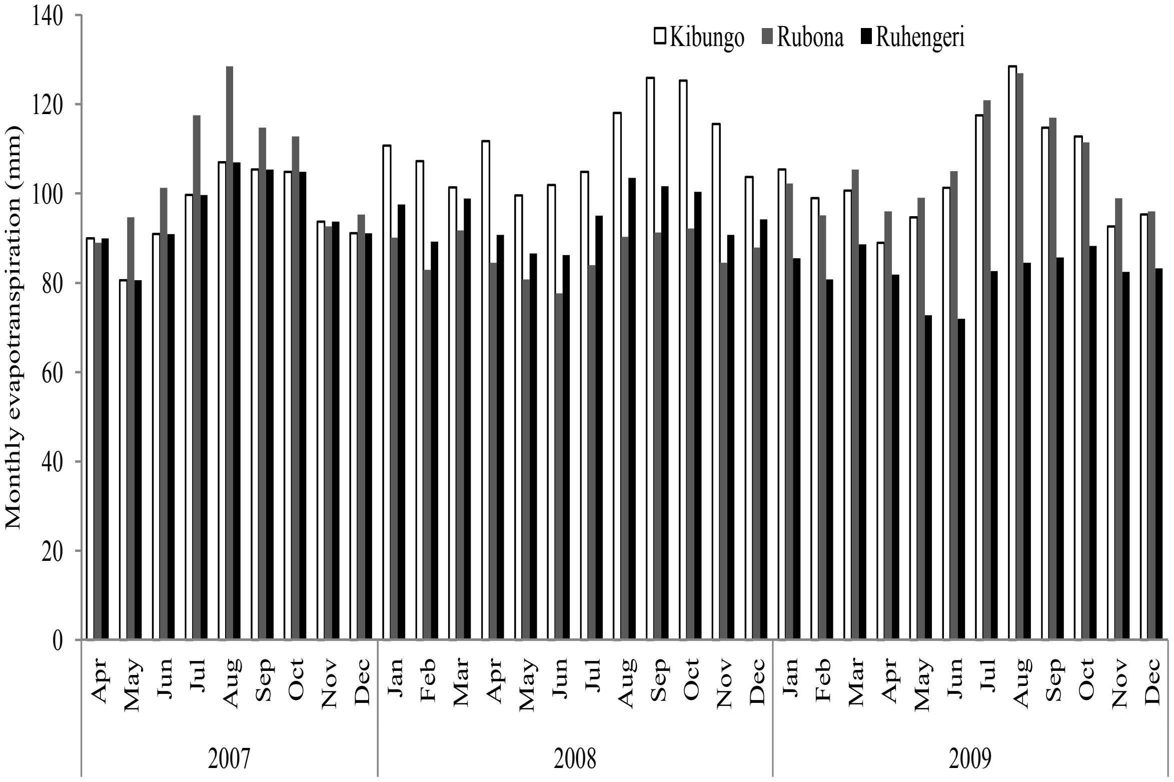

FIGURE 3.4 Estimated monthly evapotranspiration (mm) at the Kibungo, Rubona and Ruhengeri sites.

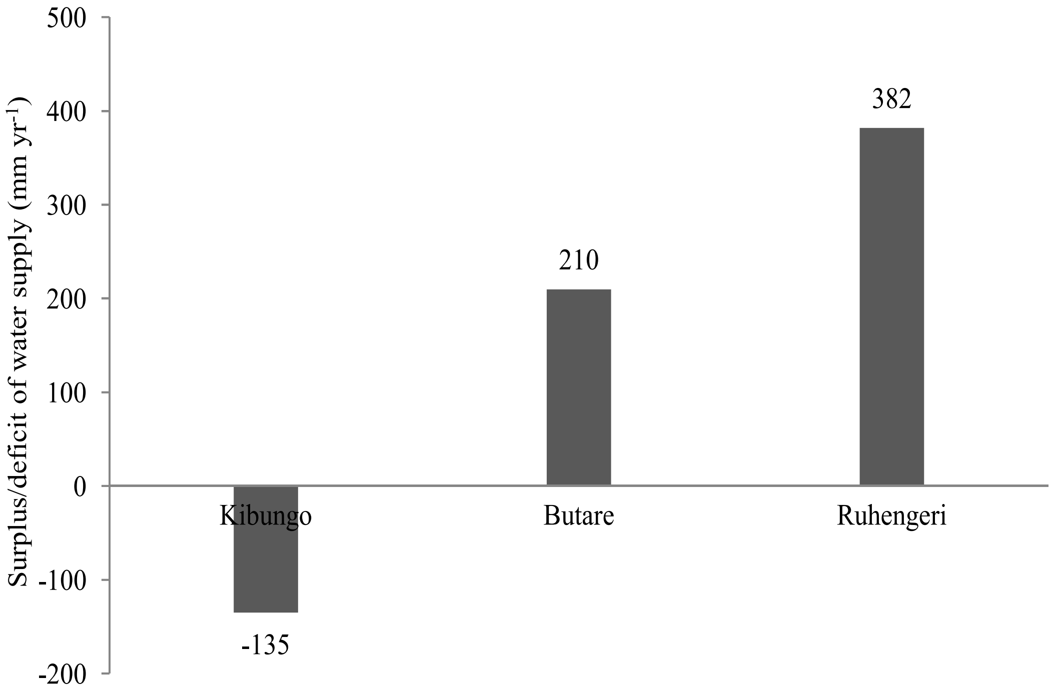

FIGURE 3.5 Surplus/deficit of water supply (mm yr^{-1}) at the Kibungo, Rubona and Ruhengeri sites. Surplus/deficit (i.e. difference between rainfall and water demand by bananas) refers to positive/negative balance respectively.

3.3.4.2 Soil and leaf nutrient contents

Significant correlations were found between soil and plant leaf nutrient concentrations and banana bunch mass, bunch yields and the ABG at Kibungo and Rubona, whilst no significant correlations were found at Ruhengeri (Table 3.6). These significant correlations were found for K in leaves, soil pH and K in soil at Kibungo; K, Ca and Mg in leaves, and P and K in soil at Rubona. At Rubona, the LAI also correlated significantly with K in leaves as well as with P and K in soil.

TABLE 3.6 Pearson correlation coefficients (n = 45, Pr > |r|) for soil and plant leaf nutrient contents, LAI and the bunch mass, bunch yield and total above ground dry matter yields at the Kibungo, Rubona and Ruhengeri sites.

Kibungo

	K-leaf	Ca-leaf	Mg-leaf	pH-soil	P-soil	K-soil	Ca-soil	Mg-soil
Ca-leaf	-0.51 *							
Mg-leaf	-0.63 *	0.66 *						
N-soil	0.17 NS	-0.10 NS	0.20 NS	0.41 *				
P-soil	0.44 NS	-0.15 NS	-0.15 NS	0.38 *				
K-soil	0.60 *	-0.07 NS	-0.29 NS	0.55 *	0.42 *			
Ca-soil	-0.06 NS	0.13 NS	0.15 NS	0.53 *	-0.01 NS	0.11 NS		
Mg-soil	0.07 NS	-0.02 NS	0.09 NS	0.68 *	0.16 NS	0.23 NS	0.78 *	
Bunch mass	**0.50 ***	-0.10 NS	-0.19 NS	**0.45 ***	0.27 NS	**0.59 ***	0.04 NS	0.13 NS
Bunch yield	**0.31 ***	-0.07 NS	-0.16 NS	**0.34 ***	0.09 NS	**0.53 ***	0.09 NS	0.14 NS
ABG	**0.32 ***	-0.07 NS	-0.28 NS	0.268 NS	0.21 NS	**0.37 ***	-0.12 NS	0.06 NS
LAI	0.20 NS	-0.26 NS	-0.11 NS	-0.08 NS	0.42 NS	0.04NS	0.03 NS	0.037NS

Rubona

	K-leaf	Ca-leaf	Mg-leaf	pH-soil	P-soil	K-soil	Ca-soil	Mg-soil
Ca-leaf	-0.74 **							
Mg-leaf	-0.54 *	0.67 **						
P-soil	0.58 *	-0.47 ns	-0.31 *	0.27 NS				
K-soil	0.75 **	-0.61 *	-0.47 *	0.11 NS	0.59 *			
Ca-soil	-0.03 NS	0.30 NS	0.34 *	0.55 *	0.26 NS	0.02 NS		
Mg-soil	0.47 *	-0.27 NS	-0.09 NS	0.47 *	0.71**	0.58 *	0.64 **	
Bunch mass	**0.66 ****	**-0.67****	**-0.52 ***	0.01 NS	0.30 NS	**0.63 ****	-0.32 *	0.16 NS
Bunch yield	**0.70 ****	**-0.47 ***	**-0.40 ***	-0.05 NS	**0.46 ***	**0.58 ***	-0.08 NS	**0.40 ***
ABG	**0.46 ***	-0.29 NS	-0.20 NS	-0.03 NS	0.36 NS	**0.41 ***	-0.06 NS	**0.35 ***
LAI	**0.50 ***	-0.23 NS	-0.19 NS	-0.03 NS	**0.52 ***	**0.41 ***	0.03 NS	**0.37 ***

Ruhengeri

	K-leaf	N-leaf	pH-soil	P-soil	K-soil	Ca-soil	Mg-soil
Ca-leaf	0.18 NS	0.09 NS					
Mg-leaf	0.40 *	-0.13 NS					
P-soil	0.03 NS	0.19 NS	**0.73 ****				
K-soil	-0.06 NS	-0.16 NS	0.36 *	0.34 *			
Ca-soil	-0.21 NS	-0.37 *	0.38 *	0.09 NS	**0.654****		
Mg-soil	-0.25 NS	-0.38 *	0.41 *	0.20 NS	**0.754****	**0.94 ****	
Bunch mass	0.12 NS	0.33 *	-0.28 NS	-0.09 NS	-0.06 NS	-0.35 *	-0.24 NS
Bunch yield	0.22 NS	0.18 NS	**-0.30 ***	-0.19 NS	-0.24 NS	-0.18 NS	-0.21 NS
ABG	0.17 NS	-0.04 NS	-0.13 NS	-0.17 NS	-0.18 NS	0.02 NS	-0.05 NS
LAI	0.08 NS	0.16 NS	-0.17 NS	-0.14 NS	-0.11 NS	-0.18 NS	-0.17 NS

*and ** mean that all *r* values are significant at $p = 0.05$ and 0.01 levels respectively and NS = Not significant. Bunch mass (kg fresh weight), Bunch yield (t ha^{-1} yr^{-1}), ABG is total above ground dry matter yields (t ha^{-1} $cycle^{-1}$).

3.3.4.3 Leaf area index (LAI)

The total number of leaves per plant was less at Ruhengeri than Kibungo, but this was not significantly ($p > 0.05$) influenced by density treatments. Total number of leaves for the plant crop, for all cultivars and densities, ranged from 36 to 42 at Kibungo, 36 to 39 at Rubona and 26 to 33 at Ruhengeri. At the Rubona and Ruhengeri sites, an increase in LAI was noticed as density increased but no significant increase was observed at Kibungo (Figure 3.6). LAI correlated significantly with bunch yield with $r = 0.75$ at Rubona and $r = 0.73$ at Ruhengeri. Similar correlations were consistently found for ABG with $r = 0.58$ and $r = 0.52$ for those locations respectively. An earlier increase in LAI was registered at Rubona, followed by Kibungo and lastly Ruhengeri (Figure 3.6). The overall relationships between LAI and the fraction of PAR intercepted showed that about 60-95% of PAR was intercepted at the LAI ranging from 3 to 4 with a higher fraction at Ruhengeri compared with other sites.

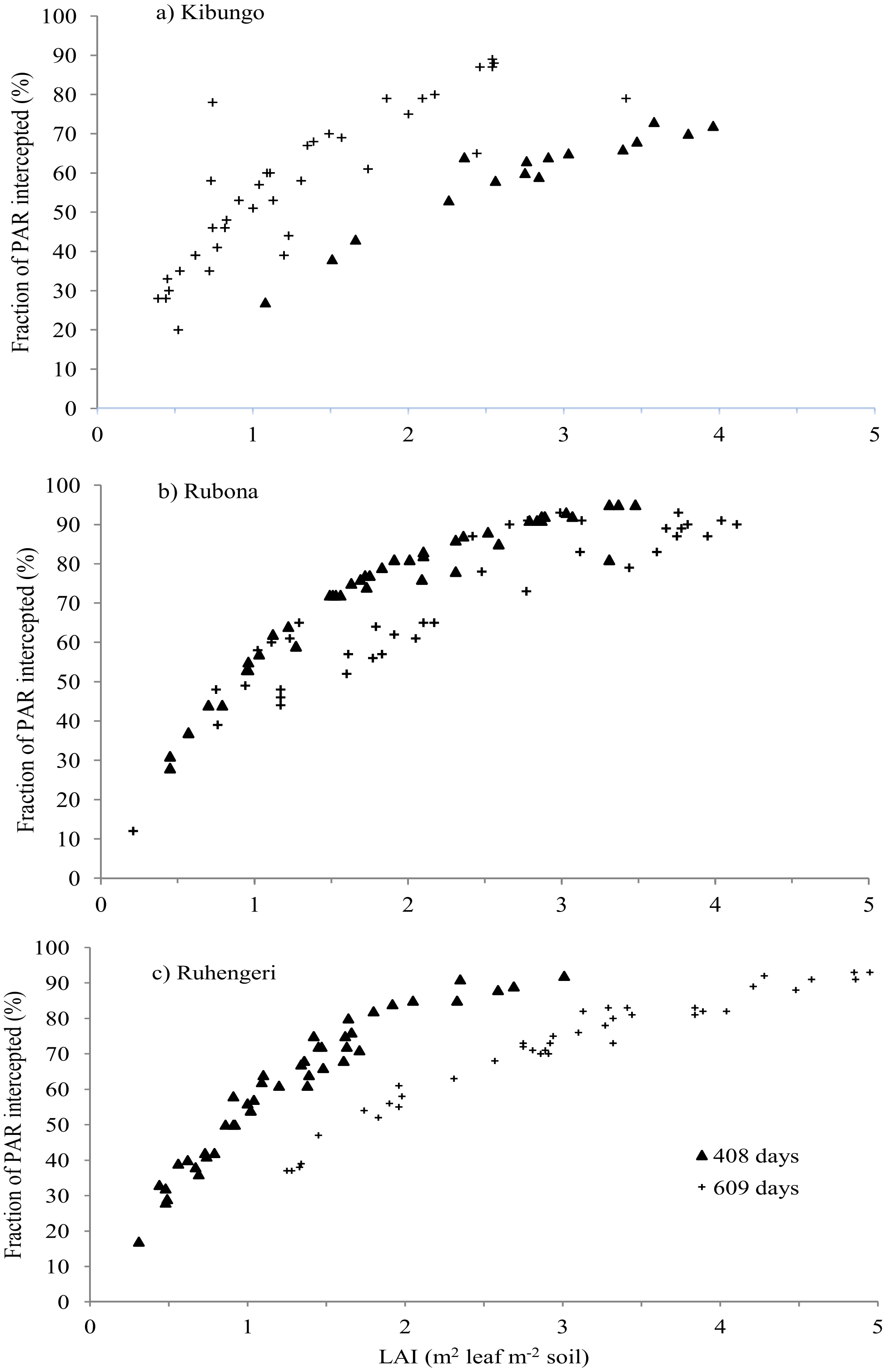

FIGURE 3.6 Overall relationships between leaf area index (LAI) and the fraction of the PAR intercepted (%) at different growing stages at the Kibungo, Rubona and Ruhengeri sites. All cultivars and densities are considered together. Days refer to days after planting.

3.3.4.4 Growing degree days

For the plant crop, growing degree days (GDD) from planting to bunch harvest were higher at Kibungo (3675 C°days), followed by Rubona (3486 C°days) but GDD were much less at the Ruhengeri cooler site (1729 C°days) (Table 3.7). This implies that temperature is the main driver of development at Ruhengeri but water deficits modify the effect of temperature at Kibungo.

TABLE 3.7 Mean values for the time from planting to harvest (days) and the cumulative degree days (°Cdays) at the Kibungo, Rubona and Ruhengeri sites.

Site	Planting to harvest (days)	Cumulative growing degree days (°Cdays)
Kibungo	699.8	3675
Rubona	551.6	2757
Ruhengeri	743.3	1729

3.4 DISCUSSION

3.4.1 Effects of plant density on yield components

Despite the differences in inherent soil fertility levels between sites, higher bunch yields at high densities are firstly due to a higher number of plants per unit area. Badgujar *et al*. (2004) reported an increase of 30.6% and 21.6% in yield per hectare of "Grand Naine" (AAA) banana in spacing of 1.2 × 2.0 m and 1.2 ×1.5 m respectively. An increase in yield with an increase in plant density was also recorded in the work of Kwa *et al*. (2005). It was interesting that an increase in density negatively affected bunch size but bunch yield per unit area still increased until it attained a maximum at 4444 plants ha^{-1} at Kibungo and Rubona. The trend was still linear up to 5000 plants ha^{-1} at Ruhengeri. This linear increase in bunch yield might be attributed, in addition, to the greater number of bunches per unit area and the bunch mass having a uniform average grade at different densities irrespective of cultivar type.

Our results showed that increasing plant density resulted in a reduction of the number of hands and fingers. Similar effects were reported for a plantain plantation in Cameroon by Kwa *et al*. (2005). Interestingly, this study revealed that the beer banana cultivars (e.g. “Intuntu”) can be subjected to a high planting density and still produce high yields whereas cooking banana cultivars (e.g.“Injagi”) reach their maximum yields at somewhat lower densities (Figure 3.3a). Nevertheless, farmers’ preferences for cooking or beer banana cultivar depends on socio-economic factors (Okech *et al*., 2005). Often, the market prefers bigger bunch sizes for cooking banana so that farmers may wish to cut their yield a bit if they can then offset the loss by more easily attracting buyers and get better prices per kg. This highlights the importance of using different plant densities on-farm to reflect different market preferences for both cooking and beer genotypes (Okech *et al*., 2005).

Crop cycle was extended and differed between sites as plant density increased so that annual yield (t ha^{-1} yr^{-1}) for plant crop was almost half of yield per unit area (t ha^{-1}). Similar trends in a decrease in annual productivity due to cycle extension were also reported by Kesavan *et al*. (2002) on the Cavendish cultivar “Williams” in subtropical Western Australia. Interestingly, the plant density system was much more efficient (i.e. high yield in t ha^{-1} yr^{-1}) at Ruhengeri high rainfall zone where crop duration was even longer compared to Kibungo and Rubona. Our findings suggest that an increase in density from 4444 plants ha^{-1} renders the plant density system inefficient in low and mid-altitude zones whilst the system is highly efficient even up to 5000 plants ha^{-1} in high altitude zones. Although the plant density of 5000 plants ha^{-1} was suggested to be the highest density to reach before yield declines, additional crop cycles would be desirable to verify a continued increase in yield from the first ratoon onwards. These findings anticipate that the degree of soil fertility and water availability (i.e. with 1305 mm of cumulative actual rainfall differences between low and high rainfall sites during the trial duration), are among the factors governing the optimal population density. We partially conclude that the optimal agronomic plant density in fertile and wet areas is higher (> 5000 plants ha^{-1}) than for less fertile and dry areas (< 4444 plants ha^{-1}). The harvest index results showed that high densities partially caused high biomass production at Kibungo and Rubona compared with the Ruhengeri site, indicating that low densities should be recommended at Kibungo and Rubona in order to increase bunch mass and yields. Lower harvest index at Ruhengeri compared with other sites is probably caused by high bunch yields over cropping cycle which resulted in high total above ground dry matter yields. Further studies on the sustainability of maintaining bunch yields but with higher biomass production are of importance. The quadratic response surface of cooking cultivars to density effect suggests that 4444 plants ha^{-1} is the optimal agronomic plant density at the Kibungo and Rubona site but no optimal density was reached at Ruhengeri.

3.4.2 Effect of plant density on plant growth characteristics

This study revealed that an increase in density led to taller plants, up to 4444-5000 plants ha^{-1}, where the height leveled out. An increase in plant height at high densities in banana plantations was also reported by Baruah & Shama (1996) and Kesavan *et al*. (2002). As density increases, the plants compete for solar radiation and become taller (Langdon *et al*., 2008). Kwa *et al*. (2005) studied the cultivation of plantain at high densities in Cameroon and also reported that because of the intra-plant competition for solar radiation, plants grew taller and had smaller girths as plant density increased. Negative effects were more often observed on ratoon rather than on plant crops, implying that the effect of plant density is more prominent with advanced crop cycles. Compared with lower densities, higher densities increased plant height in low, followed by mid and then high altitudes. This agrees with the findings of Robinson (1996) and proves that the influence of plant density on plant growth is site-specific and might be influenced by climatic conditions, especially solar radiation and soil water. As an increase in girth at the base was observed at high densities of 4444 plants ha^{-1}, it seems that the significant effect of site × density interaction was cultivar rather than density related. Significant effect of low densities (i.e. 1428 and 3333 plants ha^{-1}) to an increase in girth at the base for both crop cycles is supported by the findings of Lichtemberg *et al*. (1998). As reported by Badgujar *et al*. (2004) and Kwa *et al*. (2005), the total number of leaves per plant was not significantly influenced by plant density, although a decrease in total number of leaves from low to high altitudes was registered. The range of total number of leaves is supported by Turner *et al*. (2007), who reported the same range of number of leaves of 30 to 50 up to flower initiation. Since leaf area increases exponentially up to the 30th leaf and stays practically constant up to the 42nd leaf (Stover & Simmonds, 1987), maximum leaf area of the plant was obtained at flowering and positively increased the leaf area index (LAI), which drops after flowering. Low LAI (< 3), may be attributed to low leaf number (< 10) and low plant density (Nyombi *et al*., 2009). Earlier increase in LAI at Rubona is due to earlier sucker emergence (ratoon crop) accompanied by high growth rate of both plant and ratoon crops which resulted in maximum leaf area. As leaf area developed, solar radiation interception by leaves increased, but flowering terminated the leaf area development. However, early growth of individual plants was exponential due to minimal plant-to-plant competition. Within site, days from flowering to harvest were not strongly influenced by cultivar and plant density, suggesting that the fruiting time span of all bunches is similar irrespective of cultivar type and the level of planting density.

3.4.3 Crop performance and resource availability

Results on plant growth suggest that the taller pseudostems become, the more flowering is delayed and the longer the crop cycle is extended. The strong correlations between bunch mass and numbers of hands and fingers suggest that hands consisted of a very regular number of fingers and those hands are evenly distributed along the axis (peduncle). The delayed flower initiation in mid and high altitudes might partially be attributed to intra-mat competition (Robinson & Nel, 1989) for solar radiation to achieve high growth rates with more additional leaves. Similar effects of intra-mat competition were reported by Langdon *et al.* (2008) for “Goldfinger” (*Musa* spp.) banana, resulting in less sucker emergence under high densities accompanied by delay in follower selection. The extension in crop cycle under high densities was also attributed to intra and inter mat competition for solar radiation and others resources (Daniells *et al*., 1987; Morse & Robinson, 1996). Short crop cycle length observed in low altitudes is attributed to earlier flowering, as leaves benefit from maximum exposure to solar radiation resulting in more efficient photosynthesis (Badgujar *et al*., 2004). These earlier flowering plants under lower densities were expected to produce earlier than plants under higher densities (Lichtemberg *et al*., 1998; Kesavan *et al*., 2002). We conclude that lower densities should be recommended to allow faster plant growth and therefore bigger bunches at Kibungo (i.e. low and dry altitude zones).

Since the leaf area index of a plantation can be used to reflect the amount of solar radiation captured by the canopy, overall changes in LAI in three sites gave an idea of the LAI needed for maximum solar radiation interception. For instance, at Kibungo, an increase in LAI from 3.5 to 4.0, but with the same amount of intercepted radiation (70-71%) is explained by the fact that the maximum crop growth rate was attained and most of the radiation was intercepted. At Rubona, LAI increases up to 4, where 95% of solar radiation was intercepted by the crop canopy. Therefore, our results indicate that increasing the LAI above 4 would have little effect on production. Such ranges of optimal LAI and the fraction of intercepted solar radiation were also reported in the work of Nyombi *et al*. (2009) for AAA-EA bananas. Turner *et al*. (2007) also reported that the proportion of intercepted incoming radiation by the canopy was 97 % at an LAI of 4.5. We suggest that the relationship between LAI and solar radiation interception can be used as an important indicator of yield potential (Turner, 2003) through determining the “optimal LAI value”.

Significant positive correlations between soil and plant leaf nutrient contents and the bunch mass, the bunch yields and the total above ground dry matter yields imply the severity of K deficiency at Kibungo and Rubona banana soils and increase in Ca and Mg in leaves has a detrimental effect on bunch yields. Since soil K, Mg and P contents positively correlated with the LAI, suggesting their contributing to plant growth when supplied to soil. Lack of correlations between soil nutrient contents and yields implies that other factors rather than soil fertility may limit banana productivity at Ruhengeri. Good correlations between bunch yield and the LAI also suggest that as yield increases with increase in LAI, solar radiation might be a limiting factor as one moves from mid to high altitude zones.

Evaporation was much greater at lower rainfall areas (e.g. Kibungo) and accompanied by negative annual water deficit (-135 mm yr^{-1}) than at high rainfall areas (e.g. Ruhengeri) with positive water surplus (382 mm yr^{-1}). Growing degree days from planting to bunch harvest were higher at Kibungo (3675 °Cdays) but much less at the Ruhengeri cooler site (1729 °Cdays), implying that temperature is the main driver of development at Ruhengeri but water deficits modify the effect of temperature at Kibungo. In this study, we have used 14°C as base temperature (Nyombi et al., 2009). The data presented in this paper are for tropical latitudes, but the temperature regime at the high elevation is more subtropical. Fortescue *et al*. (2011) used 13°C for the tropics and 10°C for the subtropics.

3.4.4 Implications of the findings and further research

Firstly, this study showed that the optimal agronomic plant density of East African Highland bananas is influenced by ecological characteristics (e.g. water availability, soil fertility) and cultivar; which serves as an entry point to maximize yield potential for East African smallholder farmers rather than using the recommended blanket densities for the whole region. Nevertheless, the dynamics of identifying limiting soil nutrients needs further research. Different responses of beer and cooking banana to plant density effects also highlights the importance of using different plant densities on-farm to reflect different market preferences. Secondly, with respect to prevailing soil type and climatic conditions, farmers can still adopt alternative management practices with knowledge of nutrient interactions that may result in nutrient imbalances that limit the achievement of potential yields. Lastly, this is an opportunity to develop strategies for fertilizer recommendations based on the most limiting elements based on agro-ecological characteristics.

3.5 CONCLUSIONS

Site altitude and corresponding higher rainfall and soil fertility level had a positive effect on the number of fingers, bunch mass, annual bunch yield and total above ground dry matter yields. An increase in plant density led to small bunches, but resulted in a linear increase in bunch yield per hectare as fertility and soil water become non limiting factors from low (e.g. Kibungo) to high altitudes (e.g. Ruhengeri). Annual bunch yield of beer cultivars increased with an increase in plant density, whilst annual yields of cooking cultivars increased at lower densities. Harvest index values showed that an increase in plant density resulted in high biomass production over fruit yields, indicating that low densities should be recommended in order to increase bunch mass and yields, especially in dry and less fertile areas. Previously, it was observed that an increase in density leads to an increase in fruit yield, but the optimal agronomic density which shows the "plateau" was not reached. In this study, bunch yields attained a maximum at 4444 plants ha^{-1} at Kibungo and Rubona, while a linear increase in yield was found at Ruhengeri. However, additional crop cycles would be desirable to verify the continued increase in yield from the first ratoon onwards. Furthermore, an increase in density led to tall plants with thinner pseudostems up to a certain maximal density, where after the height levels out (e.g. Kibungo and Rubona). Crop cycle was shorter at low compared with high densities. At a leaf area index (LAI) of four, 95% of solar radiation was intercepted by the crop canopy, indicating that increasing the LAI above 4 would have little effect on production. Nutrient deficiencies were larger at Kibungo (K) and Rubona (K, P, Ca and Mg) compared with Ruhengeri. Significant correlations between yield and LAI suggested that solar radiation might be a limiting factor as one moves from Kibungo to Ruhengeri. The optimal agronomic plant density was influenced by water availability, soil fertility and cultivar and the conclusion is that optimal plant density is lower (< 4444 plants ha^{-1}) in dry and less fertile areas, and seems to be higher (> 5000 plants ha^{-1}) in wet and relatively fertile areas.

CHAPTER 4

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 (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.

Keywords: Boundary line analysis, compositional nutrient diagnosis (CND), yield gap analysis

4.1 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 t ha^{-1} yr^{-1} (FAO, 2008), which is considerably lower than attainable yields of 37.0 t ha^{-1} yr^{-1} and potential yields exceeding 100 t ha^{-1} yr^{-1} (Wairegi & 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 banana yields (Okumu *et al.*, 2011). For instance, compared with other factors, Wairegi &

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 & Heinman, 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 & 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.

4.2 MATERIAL AND METHODS

4.2.1 Experimental sites, plant material, treatment structure and cultural practices

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, as described in the previous sections 3.2.1 (i.e. experimental sites) and 3.2.2 (i.e. plant material, treatment structure and cultural practices).

4.2.2 Data collection

4.2.2.1 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.

4.2.2.2 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 hours, 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 hours, 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.

4.2.2.3 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 hours for dry matter determination. The bunch yield (t ha^{-1} 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 t ha^{-1} $cycle^{-1}$.

4.2.2.4 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), as described in the previous section 3.2.6 (i.e. climatic data). Correlations were calculated to illustrate the relationship between the overall average bunch yield (t ha^{-1} yr^{-1}) and ABG (t ha^{-1} 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 meters, 1 meter or 1.6 meters. 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.

4.2.3 Analytical approach

4.2.3.1 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 & Dafir, 1992; Raghupathi *et al*., 2002; Wairegi & van Asten, 2011). The CND approach is based on row-centered log ratios where each nutrient is adjusted to the geometric mean of all nutrients and to a filling value (Rd) (Parent & Dafir, 1992). To compute norms, the iteration procedure of Cate-Nelson (Nelson & 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 (t ha^{-1} 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.

4.2.3.2 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 & 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).

4.3 RESULTS

4.3.1 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 4.2). 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 4.1).

TABLE 4.1 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 experimental sites.

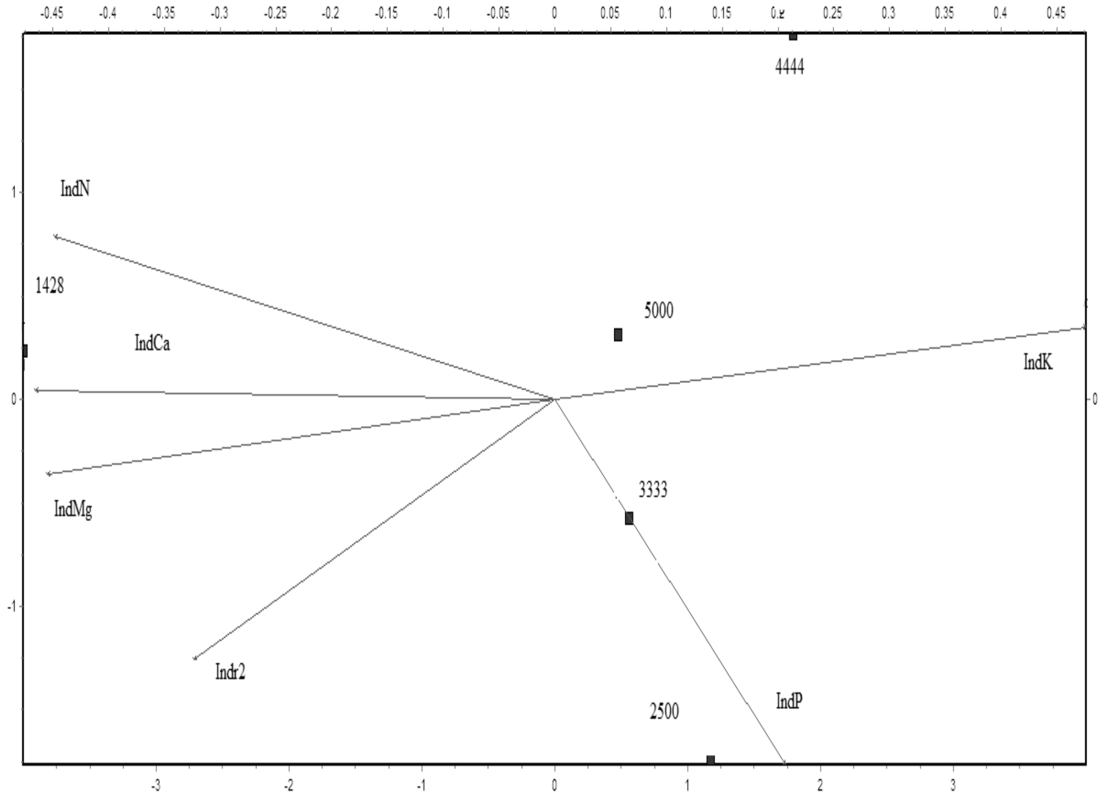
Interaction		Bunch yield (t ha^{-1} yr^{-1})	ABG (t ha^{-1} cycle^{-1})
Site × cultivar			
1	1	7.8 c	47.9 cd
1	2	8.6 bc	52.1 cd
1	3	7.5 c	40.3 d
2	1	11.6 b	64.9 bc
2	2	15.3 a	71.5 b
2	3	17.9 a	75.8 b
3	1	16.9 a	129.6 a
3	2	15.1 a	130.8 a
3	3	17.1 a	115.7 a
SE		± 1.1	± 6.7
p		0.0153*	0.0393*
Site × density			
1	1428	8.7 fg	21.5 j
1	2500	6.1 g	30.8 ij
1	3333	8.6 fg	50.4 ghi
1	4444	9.2 efg	57.4 gh
1	5000	7.0 g	73.8 fg
2	1428	9.5 efg	32.0 ij
2	2500	11.4 ef	48.6 hi
2	3333	13.1bc de	52.8 ghi
2	4444	21.5 ab	118.4 cd
2	5000	19.2 bc	101.9 de
3	1428	7.0 g	53.3 ghi
3	2500	11.9 ef	86.4 ef
3	3333	16.2 cd	127.3 c
3	4444	21.8 ab	133.9 b
3	5000	25.0 a	143.9 a
SE		± 1.5	± 8.7
p		<.0001*	<.0001*

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

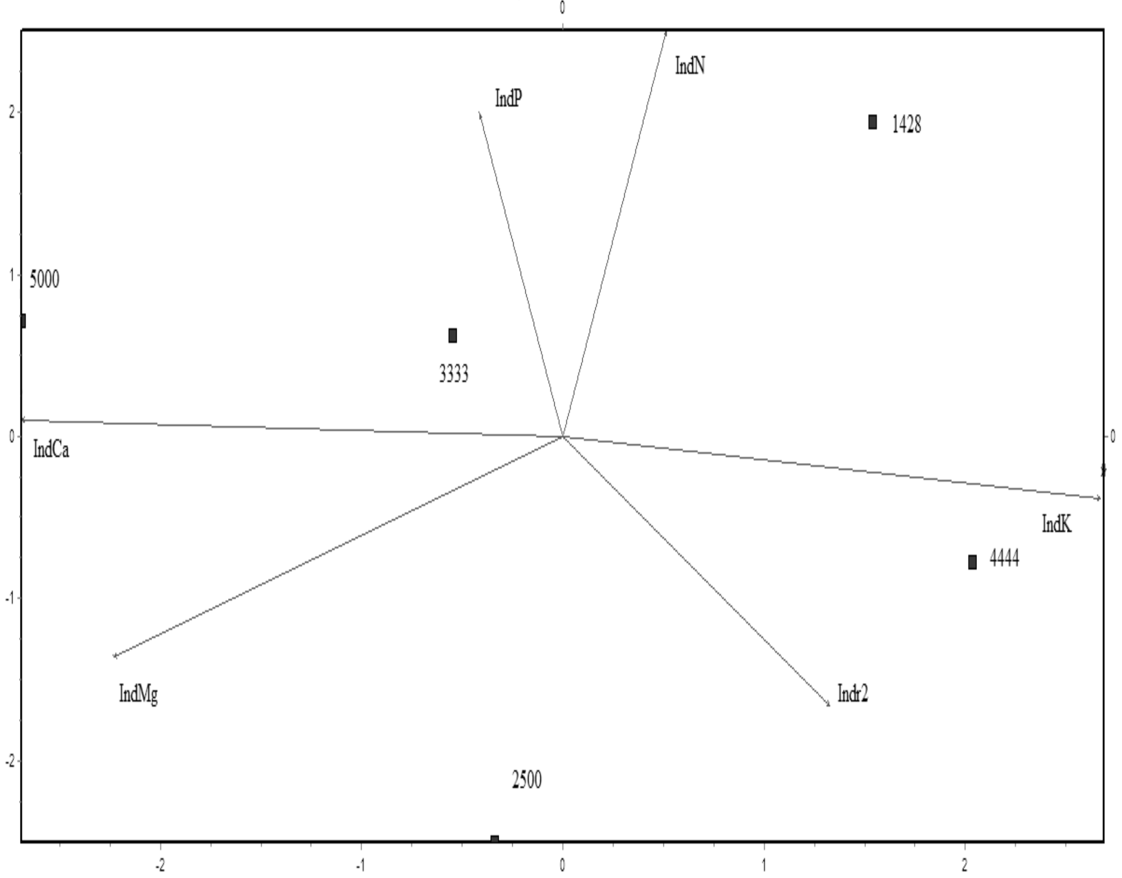
4.3.2 Leaf nutrient contents and compositional nutrient diagnosis (CND) indices

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 (Figure 4.1). 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 4.2). 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}).

a) Kibungo



b) Rubona



c) Ruhengeri

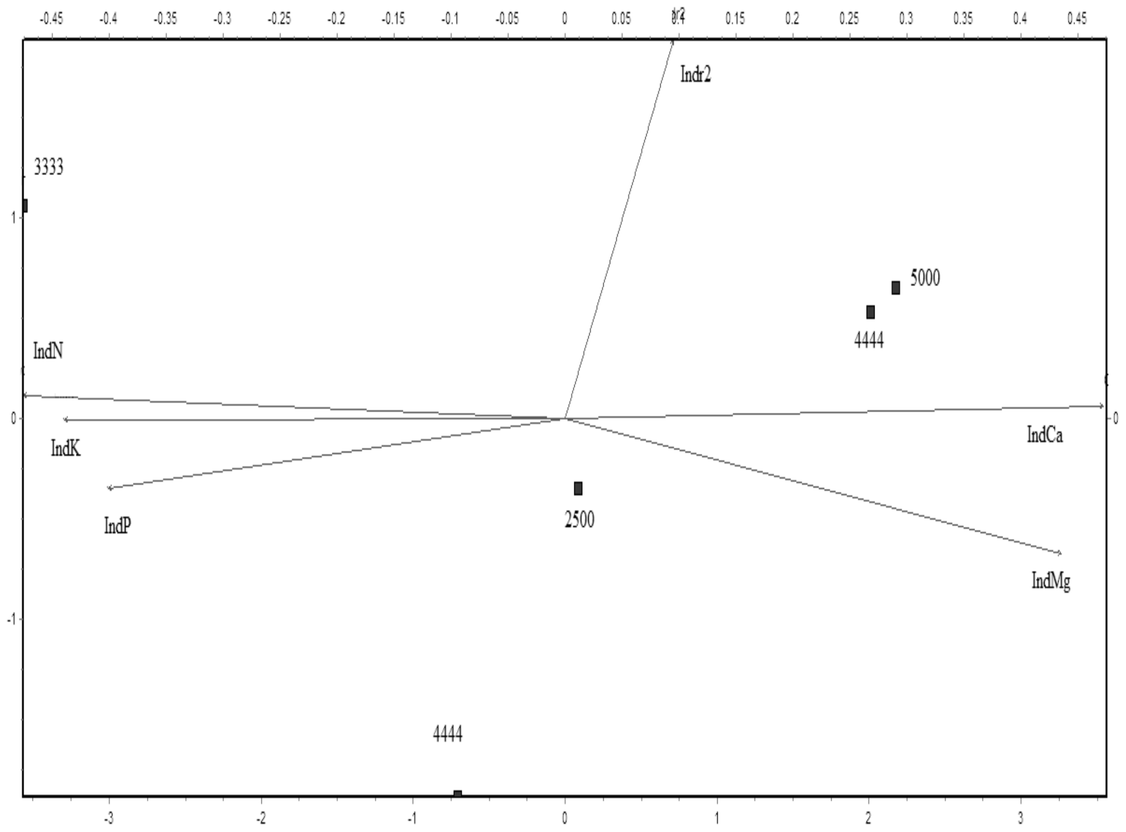


FIGURE 4.1 PCA score plot of PC1 and PC2 of derived CND indices at the Kibungo, Rubona and Ruhengeri sites. 1428, 2500, 3333, 4444 and 5000 are plant densities (plants ha^{-1}). Ind denotes indices and r2 refers to r^2 which is the global nutrient imbalance.

TABLE 4.2 Cumulative variance function [$F_i^c(V_x)$] for row-centered 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*
	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*
	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*
	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

An asterisk (*) means that the 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-centered ratio expressions for nutrients and Rd.

4.3.3 Yield gap and limiting factors

Bunch yield correlated positively with soil nutrient contents at Kibungo and Rubona (Table 4.3). 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}) (Figure 4.2). 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 4.4). At Rubona, the above mentioned correlations were negative, while positive at Ruhengeri, implying that high yield is associated with high water content in wet areas (e.g. Ruhengeri).

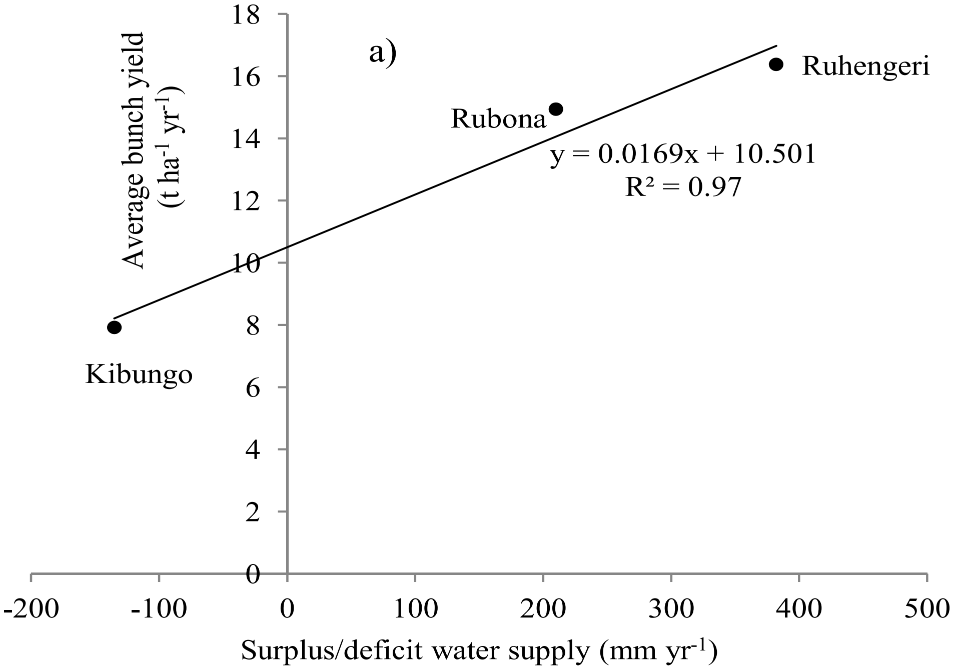


FIGURE 4.2 Relationship between surplus/deficit of water supply (mm yr^{-1}) and bunch yield (t ha^{-1} yr^{-1}), and above ground dry matter yield (t ha^{-1} cycle^{-1}) (b) at the Kibungo, Rubona and Ruhengeri sites. Surplus/deficit (i.e. difference between rainfall and water demand by bananas) refers to positive/negative balance respectively.

TABLE 4.3 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
	LAI	-0.08 NS	0.42 NS	0.04NS	0.03 NS	0.037NS
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

*and ** mean that all *r* values are significant at $p = 0.05$ and 0.01 levels respectively and NS = not significant ($p > 0.05$).

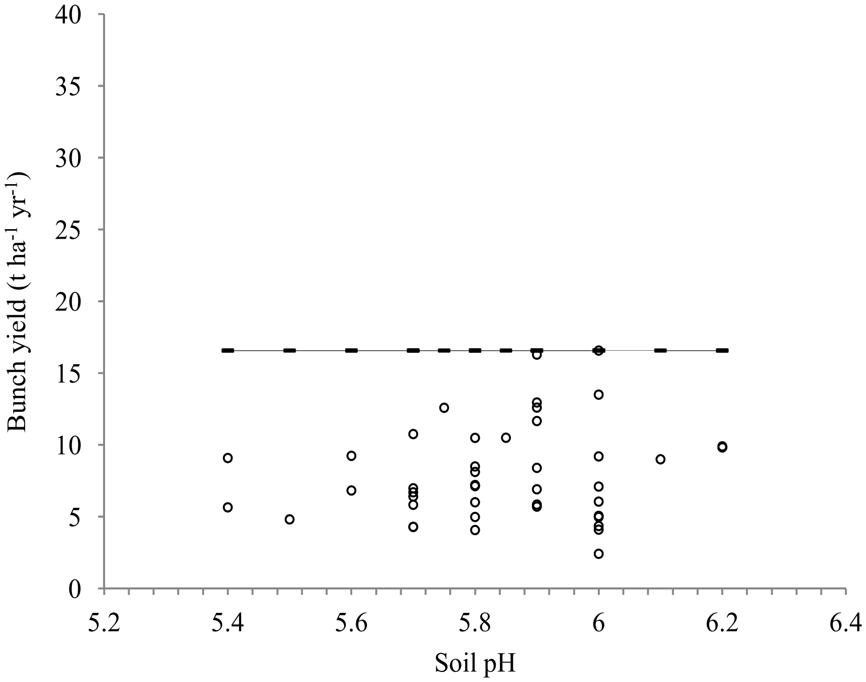
TABLE 4.4 Pearson correlation coefficients (n = 45, Pr > |r|) for bunch yield (t ha^{-1} year^{-1}) and cumulative soil water content (mm) at 40 and 60 soil depths (i.e. banana rooting zone) at different time intervals during a 12-month period before harvest at the experimental sites.

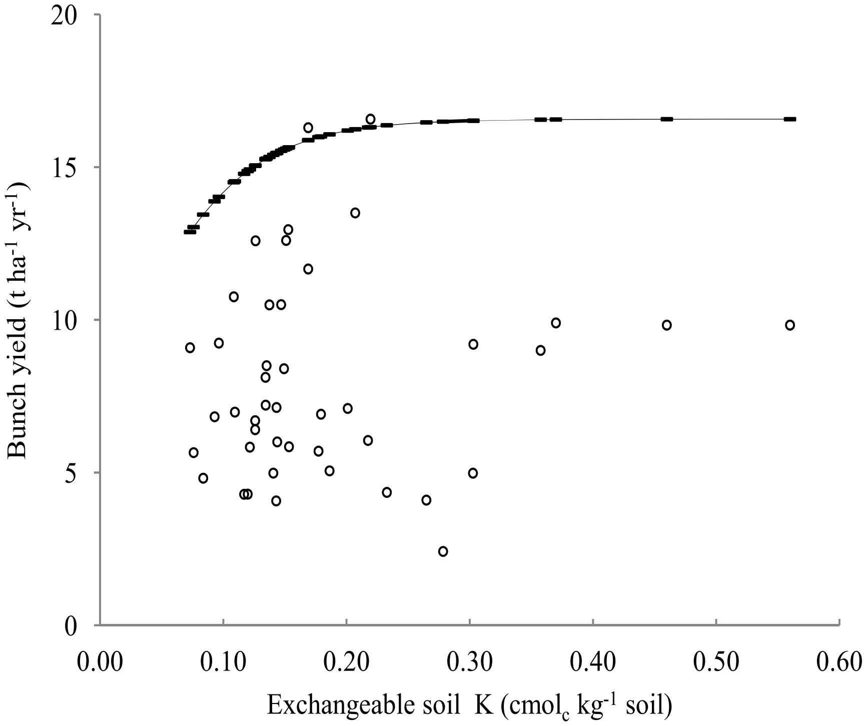
Site		Cumulative soil water content (mm) at different months after planting								
		Soil depth (cm)	12	13	14	16	20	21	23	24
Kibungo	Bunch yield	40	-0.095 NS	-0.083 NS	-0.015 NS	-0.073 NS	-0.013 NS	0.046 NS	0.085 NS	0.003 NS
		60	-0.082 NS	-0.048 NS	-0.071 NS	-0.097 NS	-0.099 NS	-0.042 NS	-0.032 NS	-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*	-

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

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 (Figure 4.3). At Ruhengeri, the boundary line points showed that bunch yield and ABG did not increase significantly after the LAI = 4.

a) Kibungo


40
35
30
25
20
15
10
5
0
Bunch yield (t ha-1 yr-1)
5.2
5.4
5.6
5.8
6
6.2
6.4
Soil pH


20
15
10
5
0
Bunch yield (t ha-1 yr-1)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
Exchangeable soil K (cmolc kg-1 soil)

b) Rubona

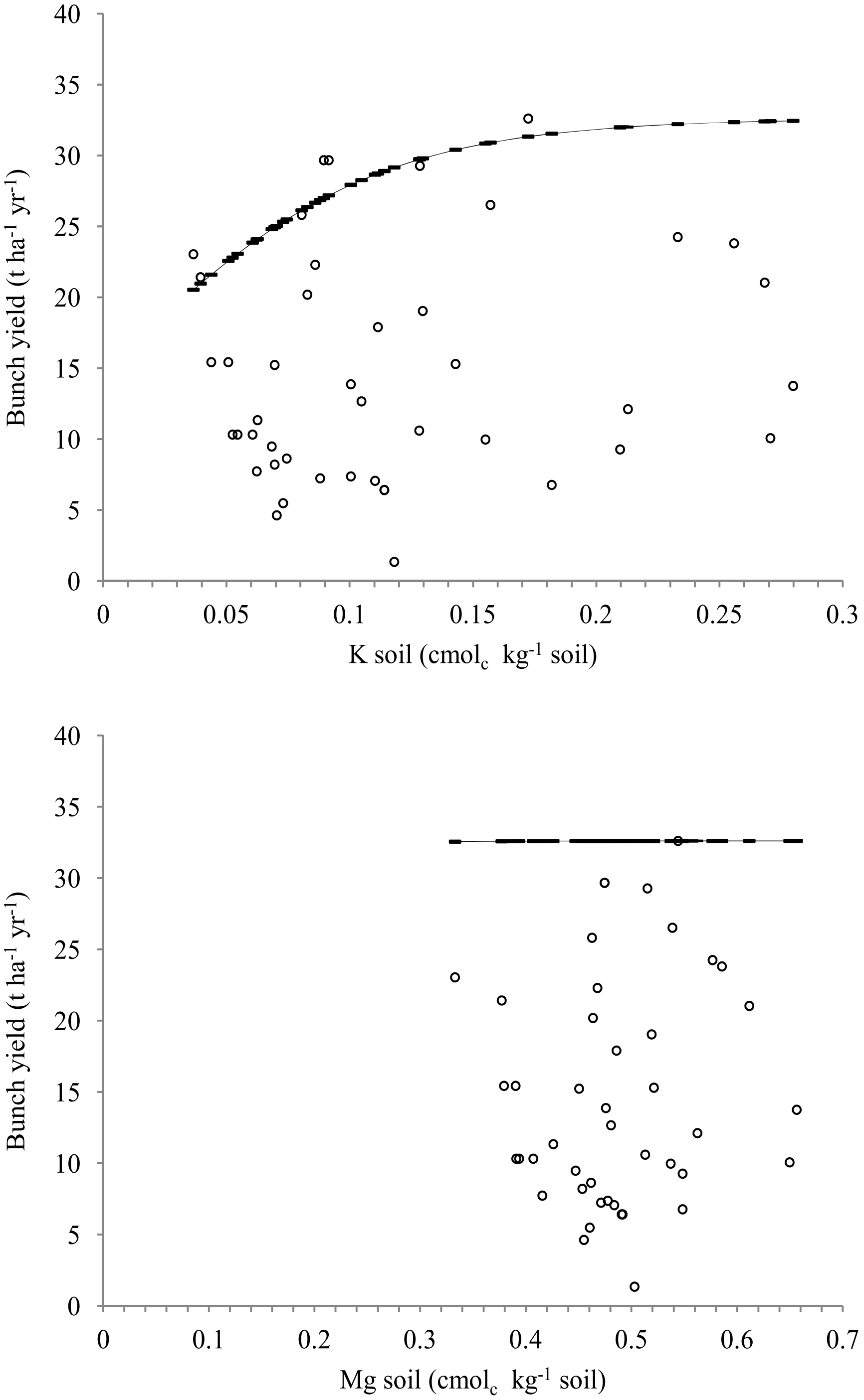


FIGURE 4.3 Relationships between bunch yield (t ha^{-1} yr^{-1}) and soil nutrient contents at the Kibungo, Rubona and Ruhengeri sites. The lines represent the boundary lines.

The average bunch yield gaps for soil pH, K, Ca and Mg content 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 (Figure 4.4). 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 (Figure 4.4). 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 (Figure 4.5).

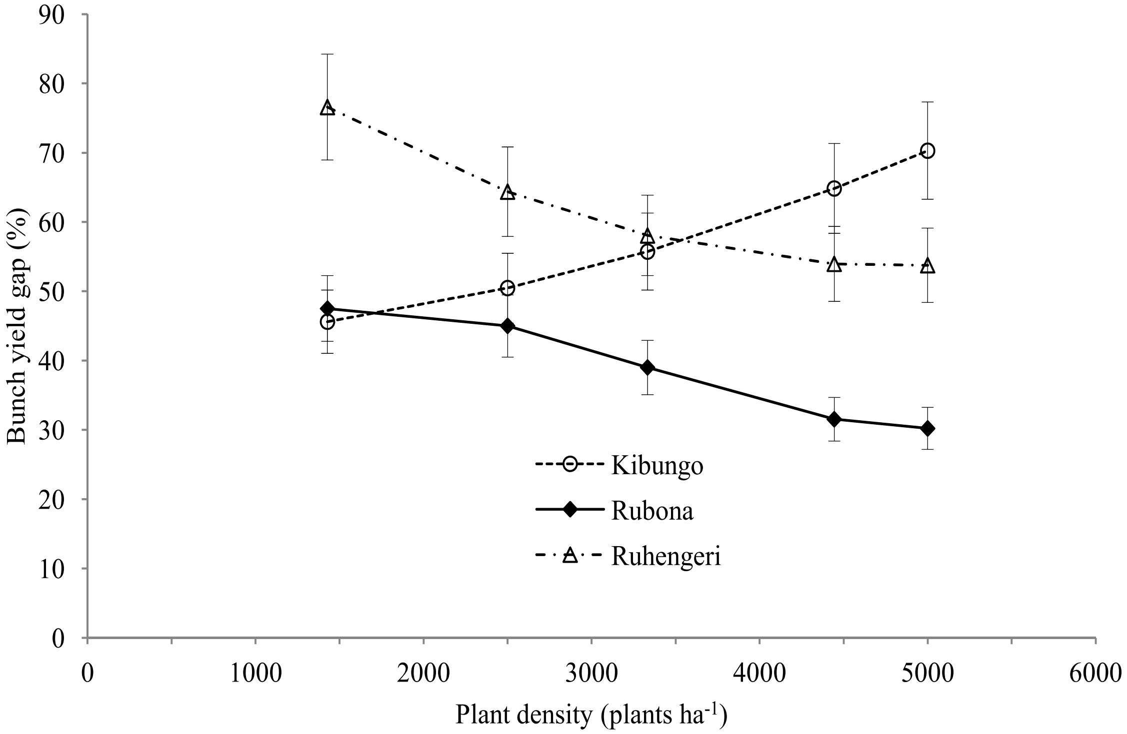
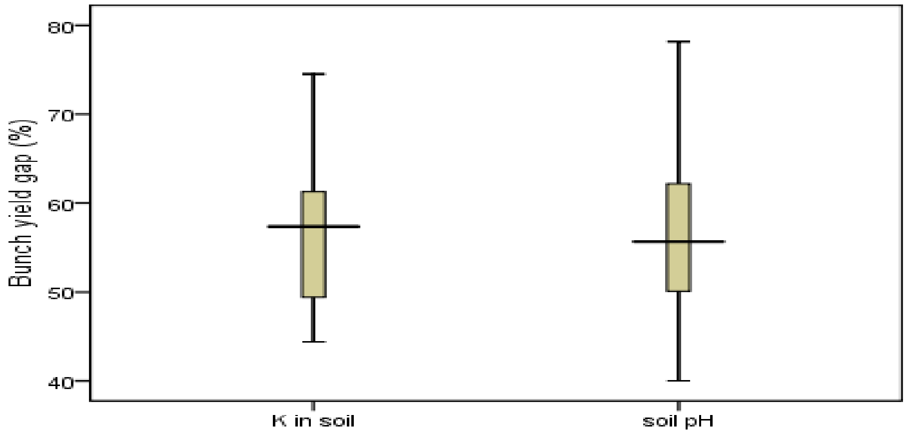
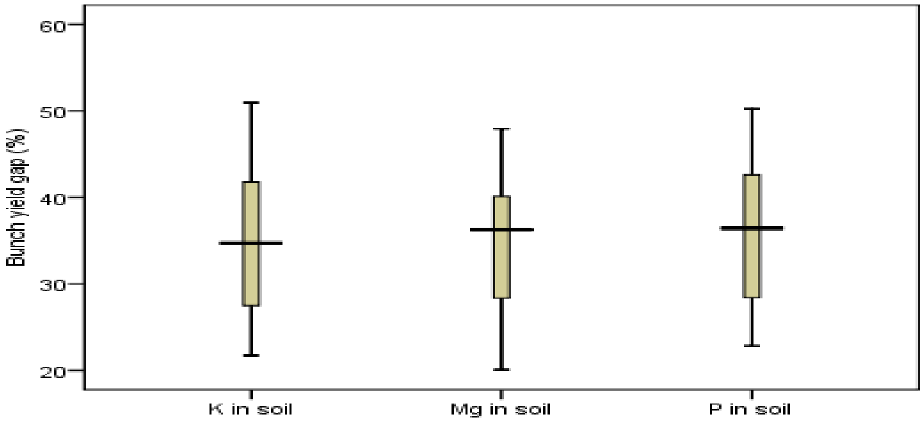


FIGURE 4.4 Predicted banana yield gap explained by plant density at the Kibungo, Rubona and Ruhengeri sites. Yield gap is expressed as percentage of maximum yield attained.

a) Kibungo



b) Rubona



c) Ruhengeri

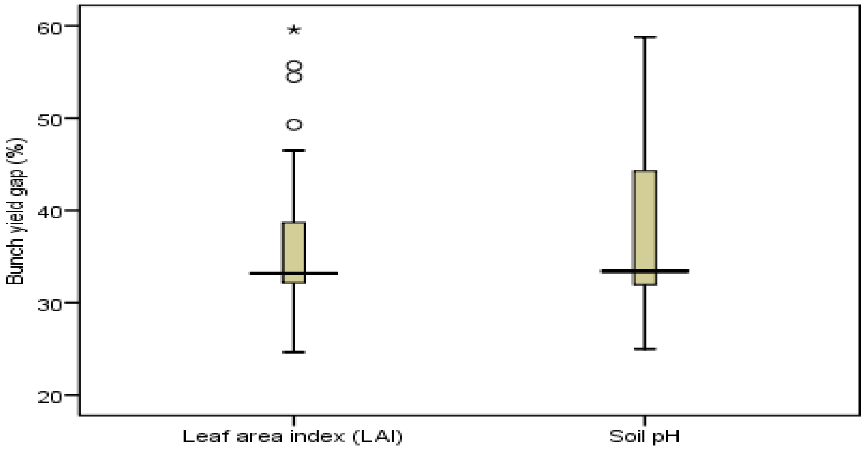
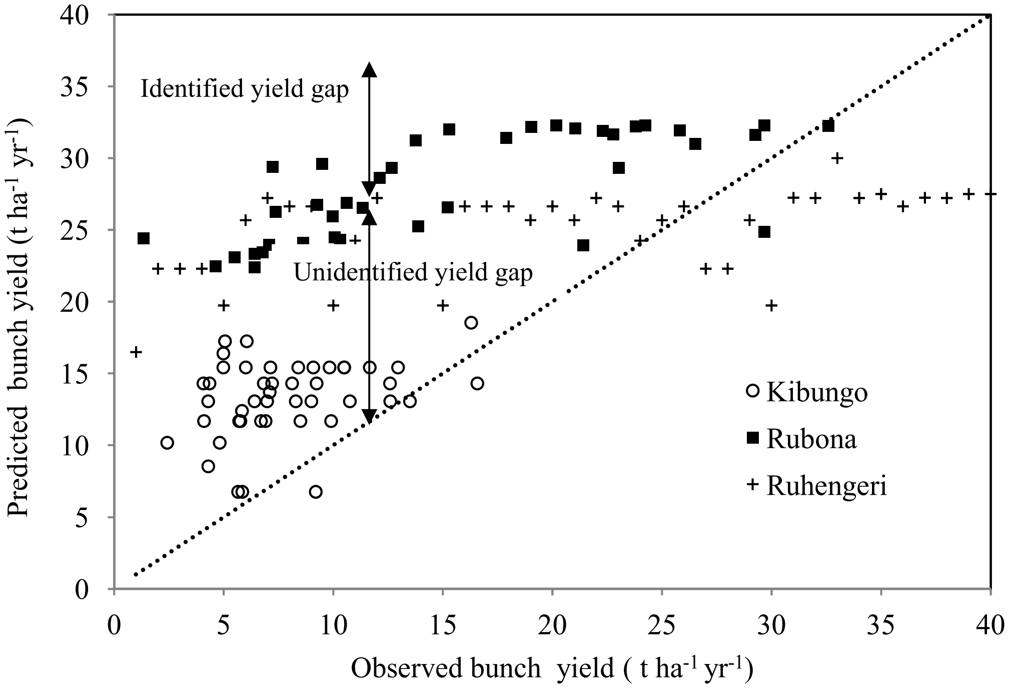


FIGURE 4.5 The yield gap explained by soil nutrient and LAI, expressed as percentage of maximum yield attained at the Kibungo, Rubona and Ruhengeri sites. The solid lines across boxes are medians. The boxes represent the inter-quartiles and bars represent the smallest and largest observations.

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 (Figure 4.6). 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 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}).

a) Bunch yield



b) ABG

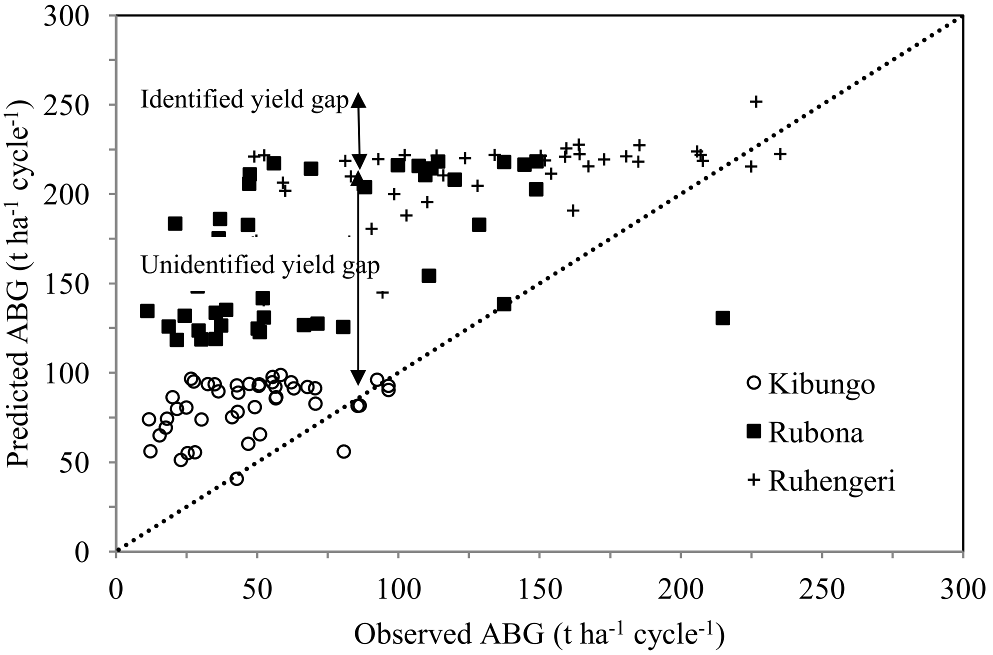


FIGURE 4.6 Observed and predicted bunch yield and above ground dry matter yield at the Kibungo, Rubona and Ruhengeri sites. The dotted diagonal line depicts the relationship y = x. The predicted yield was the minimum prediction based on biophysical factors.

4.4 DISCUSSION

4.4.1 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, resulting in 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. As K is essential nutrient for banana fruit filling, 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 to 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 & 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.*, 2005)

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 to 8.0 (Turner *et al.*, 1989).

4.4.2 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 & 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 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 & 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 & 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 & van Asten, 2010).

4.4.3 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 (≤ 40 cm soil depth) compared with Rubona (≤ 80 cm soil depth) and Ruhengeri (≤ 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.

4.4.4 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 & 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 & 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 & van Asten, 2010; Wairegi & van Asten, 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 × 3 m blanket recommended plant spacing with different farmers adaptations (Tushemereiwe *et al*., 2001), low rates of inorganic fertilizer use (Wairegi & van Asten, 2010), and scarcity of crop residue for mulch (Nankinga *et al*., 2005).

4.5 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.

CHAPTER 5

INFLUENCE OF PLANT DENSITY ON VARIABILITY OF SOIL FERTILITY AND NUTRIENT BUDGETS IN LOW INPUT EAST AFRICAN HIGHLAND BANANA (*MUSA* SPP. AAA-EA) CROPPING SYSTEMS

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ABSTRACT

The productivity of East African highland (EAH) banana cropping systems is declining, particularly in areas with low inherent soil fertility. Soil fertility management requires knowledge of nutrient flows at the interface between above and below ground surface. The magnitude of soil fertility dynamics and nutrient depletion was studied for a short-term banana plant density trial in three contrasting agro-ecological sites of Rwanda (Kibungo low rainfall with medium soil fertility, Rubona high rainfall with low soil fertility and Ruhengeri high rainfall with high soil fertility) using nutrient stock and partial nutrient balance calculations. Plant density did not significantly influence nutrient mass fractions in plant parts (fruit, leaves and pseudostems), but nutrients retained through leaves and pseudostems and those removed through crop harvest (bunch dry matter) increased with plant density. Plant density responses to variation in soil fertility and partial nutrient balance seemed to depend on diversity in climate and soil type. Partial N and K balances (kg ha^{-1} yr^{-1}) were estimated to be strongly negative at Rubona and Ruhengeri, while partial Ca and Mg balances were positive at Kibungo and Ruhengeri but negative at Rubona. This study showed that partial nutrient balances associated with soil nutrient stocks can provide a first order of magnitude estimate of nutrient depletion in low input EAH banana cropping systems. This should direct the attention of agricultural researchers and farmers to develop options that can improve the productivity of these systems, where resource availability for improved nutrient management is scarce.

Keywords: Agro-ecological sites, East African highland bananas, nutrient depletion.

5.1 INTRODUCTION

East African highland (EAH) banana (*Musa* spp.) is a key staple and cash crop for smallholder farmers in Rwanda, Uganda, parts of DR Congo, Tanzania, and Kenya. However, yields have been low and reported to be declining, with soil fertility problems often cited as the primary cause (Okumu *et al.*, 2011). Soil fertility management strategies require knowledge of soil fertility dynamics of cultivation systems. To replenish nutrients in banana farms while conserving soil water, most banana growers use banana self-mulch, household wastes, compost and farmyard manure, and residues of annual crops (Baijukya & De Steenhuijsen Piters, 1998; Briggs & Twomlow, 2002).

However, rates of nutrient returns and external input application are generally insufficient to meet the nutrient requirements to maintain or improve yields. Numerous studies have reported nutrient deficiencies (e.g. N, P and K; Gaidashova *et al.*, 2010, and K and Mg; Smithson *et al.*, 2001, Smithson *et al.*, 2004). This is associated with insufficient manure being available to farmers and the perceived high cost or unavailability of inorganic fertilizers (Wortmann *et al.*, 1994; Wairegi & van Asten, 2010). Nutrient recycling in banana cropping systems is highly dynamic (Baijukya & De Steenhuijsen Piters, 1998; van Asten *et al.*, 2004), due to the large biomass turnover and relatively low harvest-index of the crop (Hauser & van Asten, 2010). However, there is relatively little understanding of nutrient fluxes and balances of these systems (Nyombi *et al.*, 2010; Delstanche, 2011).

Bananas are a perennial crop, with stools successively regenerated by suckers every 6-18 months. Biomass production is highly dynamic over time (Birabwa *et al.*, 2010) as a consequence of variation in rainfall, but fruit can be harvested all year round (Dorel *et* al., 2008). Bananas require a continuous and relatively large supply of nutrients, particularly K, high total K uptake by aboveground biomass easily exceeding 500 kg ha^{-1} annually (Nyombi *et al*., 2009). While predicting nutrient depletion under EAH banana cropping systems, there is a need to focus on existing knowledge and practices of farmers when it comes to their ability to replenish soil nutrient stocks to maintain or even improve yields. Large regional variations exist in terms of EAH banana yields, agro-ecological characteristics such as soil and rainfall, and crop management practices such as plant density, mulching, and weeding (Gaidashova *et al*., 2009; Delstanche, 2011; Ndabamenye *et al*., 2012). However, these variations have a tremendous impact on nutrient balances and sustainability of these important food production systems. Smallholder producers require site-specific crop and soil management agrotechniques to improve productivity and sustainability. This requires an understanding of nutrient balances and the underlying determining factors in terms of crop management and agro-ecological conditions in major banana production zones.

Computing nutrient flows and balances (Smaling *et al*., 1993) in a farming system can increase understanding of nutrient management and environmental impact (Oenema *et al*., 2003). The method has also been found to be a valuable tool to assess sustainability of agro-ecosystems and to provide information to account for changes in productivity over time (Haileslassie *et al*., 2007). Nutrient balance studies involve computation of differences between nutrient inflows and outflows in a farming system, whereby a negative balance indicates nutrient mining and a positive value indicates nutrient accumulation (Nandwa & Bekunda, 1998; Cobo *et al*., 2010). In East Africa, numerous studies reported assessments of N balances but not much attention has been given to P and K and few have considered Ca and Mg (Cobo *et al*., 2010). Reviewing nutrient balances in African land use systems, Cobo *et al*. (2010) reported an overall negative trend. In smallholder banana systems, the bulk of the annual nutrient supply originates either from recycling of crop residues or external organic nutrient inputs (very limited amounts of manure and mulch) and mineral fertilizers or mineral weathering (only a very small percentage) (Delstanche, 2011).

The objectives of this study were to assess the magnitude and variability of nutrient depletion in smallholder banana systems that are characterized by low external input use, but large variability in agro-ecological conditions and crop density management. We studied plant nutrient uptake and recycling under contrasting agro-ecological sites but with similar crop management conditions across Rwanda in a series of researcher-managed banana density experiments.

5.2 MATERIALS AND METHODS

5.2.1 Experimental sites, plant material, treatment structure and cultural practices

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 as described in the previous sections 3.2.1 (i.e. experimental sites) and 3.2.2 (i.e. plant material, treatment structure and cultural practices).

5.2.2 Soil and plant analyses

Prior to experimental establishment, five soil subsamples were collected per plot at 0-30 cm depth and mixed to make single composite samples per plot. For each plant density plot, a quadrant of 4 m^2 (2 m × 2 m) was marked in the centre using labelled sticks that remained throughout the period of the experiment. At flowering and the first harvest (i.e. 21.5 months), soil subsamples were also collected at 0-30 cm in the above mentioned quadrant and mixed to make single composite samples. Subsequent subsamples were also collected at the end of the trial (i.e. 3.5 years) and mixed as previously. Soil samples were oven dried at 105°C for 48 hours, ground and passed through a 2.0 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).

At the harvest of the plant crop, plant subsamples were collected from the pseudostem, leaves, peduncle and fingers to determine the total nutrient mass fractions in the different plant parts. Pseudostem subsamples (a pie of a 5cm wide pseudostem disk) were taken at upper, middle and lower parts of harvested pseudostems, so as to get an appropriate composite sample representing the entire pseudostem. Leaf subsamples of 10 by 10 cm were collected from the entire upper third leaf of three randomly selected harvested plants and composited for each density treatment. Peduncle subsamples (a piece of 10 cm length) were chopped and a composite sample was made. Banana finger subsamples were obtained from upper, middle and lower hands. The skin and pulp of the fingers were not separated. Finger subsamples of each part were bulked, weighed, chopped and dried in an oven at 105°C for 48 hours. All dried plant samples were ground and sieved to < 2 mm particle size. The analytical methods used were as described by Okalebo *et al*. (2003). Total nutrient content in plant parts was calculated from N, P, K, Ca and Mg mass fractions (g kg^{-1}) in the pseudostem, finger, peduncle and leaf biomass and the dry weights of the plant parts. Total above ground biomass (t ha^{-1} yr^{-1}) was consisted of leaves + pseudostems and bunch yield (t ha^{-1} yr^{-1}) was consisted of peduncle + fingers.

5.2.3 Calculation of nutrient stocks and partial nutrient balances

The nutrients N, P, K, Ca and Mg were considered in the input-output model because they are the most limiting in the East African highland region (Wairegi *et al*., 2010). Soil nutrient stocks were the nutrients present in the top 30 cm of soil and considered as the total amount of nutrients present in the organic matter fraction, the adsorbed phase and in the soil solution (van den Bosch *et al*., 1998). Partial nutrient balances were calculated using input and output calculation model which is adapted from Smaling *et al*. (1993) (Table 5.1). In this study, no mineral fertilizer was applied. The nutrient inputs were cattle manure (IN1) added at planting time. Those inputs were calculated from the nutrient content in the manure and the quantity applied per hectare for a 30 cm soil depth (Table 5.2). The outputs in the harvested bunches (OUT1) were calculated by multiplying the quantities of dry matter with the nutrient mass fractions for N, P, K, Ca and Mg. The partial nutrient balances (kg ha^{-1} yr^{-1}) were calculated from IN1-OUT1.

TABLE 5.1 Nutrient flows for the calculation of partial nutrient balances at plant density plot level (adapted from Smaling *et al.,* 1993).

Flows	Calculations
Inputs	
IN1: Organic input (cattle manure)	Nutrient content of manure × quantity applied
Outputs	
OUT1: Harvested product (bunches)	Nutrient content in harvested bunches × yield

TABLE 5.2 Cattle manure analysis and its nutrient inputs (IN1) at the Kibungo, Rubona and Ruhengeri trial sites.

Plant density plot	Applied manure (kg ha^{-1})	Mean values of cattle manure nutrient content (%)				
		N	P	K	Ca	Mg
		0.49	0.31	1.65	0.85	0.51
		Nutrient inputs (IN1) (kg ha^{-1} yr^{-1}) for 0-30 cm soil depth				
		N	P	K	Ca	Mg
1428	8,568	28.0	17.7	94.2	48.6	29.1
2500	15,000	49.0	31.0	165.0	85.0	51.0
3333	19,998	65.3	41.3	220.0	113.3	68.0
4444	26,664	87.1	55.1	293.3	151.1	90.7
5000	30,000	98.0	62.0	330.0	170.0	102.0

5.2.4 Statistical analyses

Data sets on nutrient mass fractions and nutrient balances were subjected to analysis of variance using JMP statistical discovery software version 10.0 (SAS Institute Inc., NC, USA). All data were firstly analyzed for three way interaction (site × cultivar × density). We have chosen this statistical model because densities are nested within sites, and included site in the same statistical analysis to be able to know whether the differences between sites are significant statistically. Significant effects for most observations (i.e. site, density and site × density interaction) were discussed and Student's test at p = 0.05 was used to separate the means of significantly different parameters. Using SPSS 16.0 (Statistical Package for Social Sciences) for Windows, data on nutrient stocks over a trial period were subjected to repeated measures with time as the repeated factor to look at significances between times.

5.3 RESULTS

5.3.1 Initial soil nutrient contents and stocks

All soils had an optimum pH for banana cultivation, ranging from 5.7 to 6.2 (Table 5.3). Average soil organic matter and total N values were higher at Kibungo (6.1% and 0.3%) than Rubona (2.7% and 0.2%) and Ruhengeri (2.9% and 0.2%). Ca, Mg and K were higher at Kibungo compared with other sites. The high N content (at 0-30 cm soil depth) at Kibungo sites can partially be explained by the fact that site was under natural fallow (for over six years) with species with perennial grass and shrubs such as *Tithonia diversifolia* and *Lantana camara* which might have a high content of C and N, resulting in soil organic matter accumulation from aboveground organic inputs, root residues and exudates (Puttaso *et al*., 2011). Furthermore, the difference in soil organic matter (SOM) content between sites might be due to differences in environmental conditions (e.g., rainfall and temperature), soil characteristics, chemical composition of the residues and presence of decomposer organisms. High and low SOM contents at Kibungo and Rubona, respectively, can also be associated with high percentage of clay particles with SOM encapsulated in micro- and meso-aggregates, and high sand fraction with non-protected organic material (Puttaso *et al*., 2011) due to low cation exchange capacity (CEC). The Ruhengeri site was cultivated with maize and Irish potatoes prior to the trial installation. The ratio of exchangeable K to Mg at Ruhengeri is 0.4:1 and higher than the optimal of 0.3:1 (Delvaux, 1995), but lower at Rubona (0.1:1) and equals to the optimum at Kibungo (0.3:1). Nitrogen stocks are higher at Kibungo, followed by Rubona and lastly Ruhengeri while the reverse occurred for phosphorus. Potassium, Ca and Mg stocks are higher in Kibungo compared to other sites.

TABLE 5.3 Mean values of soil properties in the 0-30 cm layer, prior to experimental establishment at the Kibungo, Rubona and Ruhengeri sites.

Parameters	Kibungo	Rubona	Ruhengeri
Soil pH (1:2.5 sediment-water)	5.7 (0.2) b	5.8 (0.1) b	6.2 (0.0) a
OM (%)	6.1 (1.8) a	2.7 (0.1) b	2.9 (0.0) b
N (%)	0.3 (0.1) a	0.2 (0.0) b	0.2 (0.0) b
P (mg kg^{-1})	4.4 (0.5) c	9.9 (2.0) b	37.8 (3.1) a
Ca (cmol kg^{-1})	3.3 (0.3) a	2.4 (0.5) c	3.0 (0.1) b
Mg (cmol kg^{-1})	1.2 (0.1) a	0.7 (0.2) b	0.6 (0.0) c
K (cmol kg^{-1})	0.3 (0.1) a	0.1 (0.1) c	0.2 (0.0) b
K/Mg (-)	0.3 (0.1) b	0.1 (0.1) c	0.4 (0.1) a
Sand (%)	11.4 (0.0) c	64.4 (0.0) a	50.4 (0.0) b
Clay (%)	71.3 (0.0) a	22.3 (0.0) c	23.3 (0.0) b
Silt (%)	17.3 (0.0) b	13.3 (0.0) c	26.3 (0.0) a
Soil textural classification	Clay loam	Sandy clay	Sandy clay loam
Soil bulk density (kg m^{-3})	1418	1256	1207
Soil nutrient stocks (kg ha^{-1})			
N	12686.4 (2992.2) a	6665.8 (181.2) b	5712.0 (8.3) c
P	18.8 (2.2) c	44.0 (9.1) b	136.9 (11.2) a
K	560.0 (124.6) a	176.3 (113.5) c	332.6 (30.2) b
Ca	5631.4 (479.4) a	4310.7 (931.5) b	4419.7 (175.9) b
Mg	1194.4 (145.5) a	718.2 (261.4) b	488.3 (13.8) c

Mean values with the same letter within the row are not significantly different at $p = 0.05$. Standard deviations are in parentheses.

5.3.2 Internal flow through above ground biomass

Site × density interactions differed significantly ($p < 0.05$) in terms of nutrients (kg ha^{-1} yr^{-1}) contained in above ground biomass (ABG = Pseudostems + leaves). Nutrients retained in ABG differed significantly between sites, amounts being significantly greater at the Ruhengeri high rainfall site (Figure 5.1), where ABG is higher compared to the other sites (data not shown). At all sites, an increase in plant density was associated with a significant increase in nutrients contained in ABG, whereby high plant densities (4444-5000 plants ha^{-1})

recorded nutrients roughly double those of lower densities (1428-2500 plants ha^{-1}) (Figure 5.1). As plant densities did not differ significantly for the nutrient mass fractions of N, P, K, Ca and Mg (Table 5.4), the significant differences between plant densities probably result from larger amounts of ABG caused by the increase in plant density.

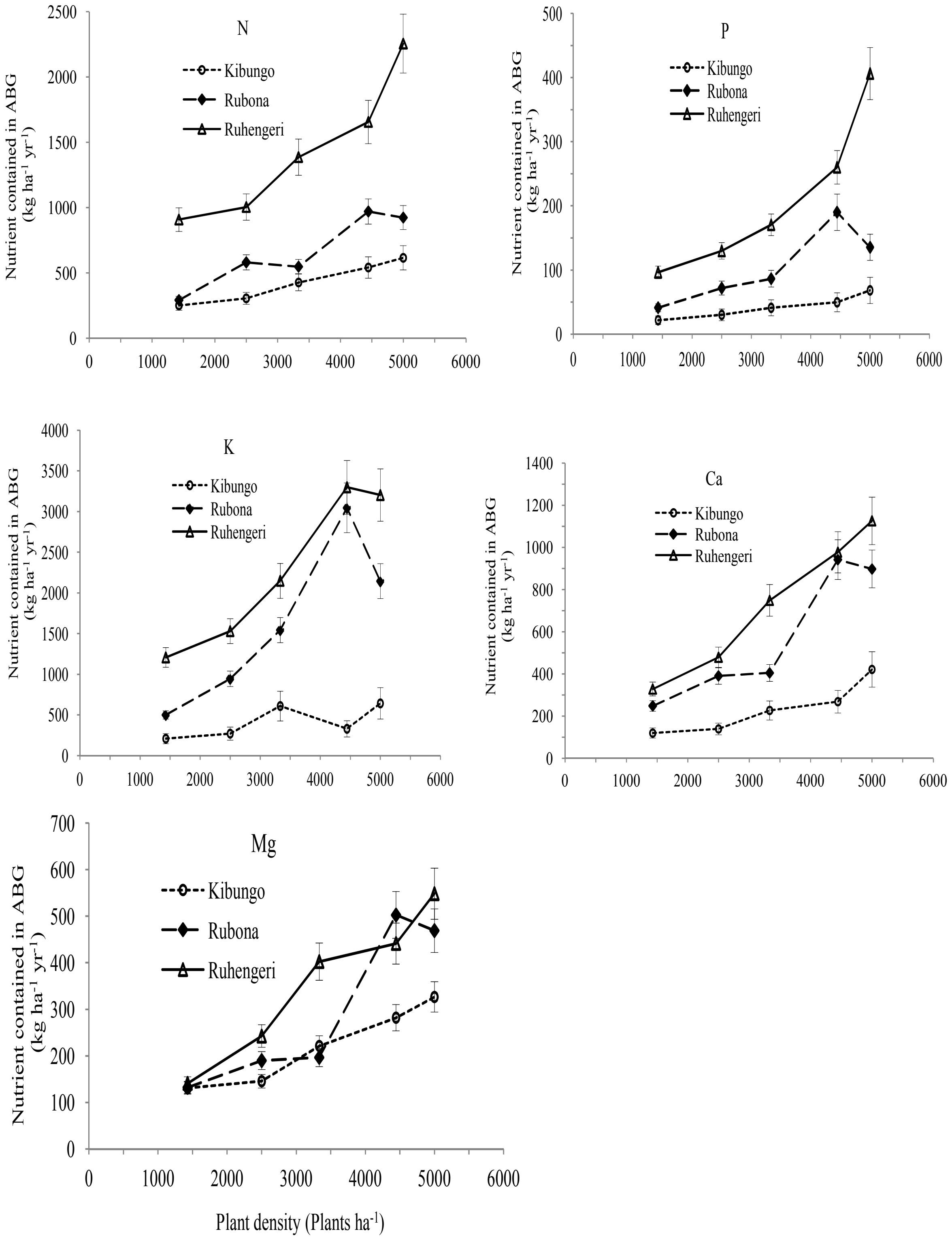

FIGURE 5.1 Nutrients (kg ha^{-1} yr^{-1}) retained in above ground biomass (pseudostems + leaves) (ABG) for site × density interaction level at the Kibungo, Rubona and Ruhengeri sites.

TABLE 5.4 Mean values for the effect of site and plant density on nutrient mass fraction in plant parts.

Effect	Nutrient content in ABG (g kg^{-1})$^{(*)}$					Nutrient content in fruit (g kg^{-1})$^{(**)}$				
	N	P	K	Ca	Mg	N	P	K	Ca	Mg
Site										
1	21.1 b	1.9 c	17.6	10.5	10.3 a	18.3 b	1.8 c	52.3 c	8.8 b	3.8 b
2	21.1 b	2.8 b	38.4	15.1	7.4 b	26.3 a	2.7 b	73.3 b	23.4 a	8.9 a
3	30.0 a	3.8 a	64.7	13.0	6.3 c	17.3 b	4.6 a	84.6 a	4.1 c	4.8 b
Density										
1428	26.7 a	2.9 a	38.9 a	12.7	8.2 a	22.8 a	3.1 a	68.7 a	10.7 a	6.0 a
2500	24.1 a	2.7 a	37.2 a	12.4	7.9 a	21.3 a	2.8 a	70.1 a	12.9 a	6.0 a
3333	21.2 a	2.7 a	45.2 a	12.8	7.6 a	18.7 a	3.4 a	73.7 a	12.1 a	5.8 a
4444	23.0 a	2.7 a	40.5 a	12.9	8.5 a	19.7 a	3.0 a	68.6 a	12.1 a	5.6 a
5000	25.2 a	3.1 a	39.5 a	13.4	7.7 a	20.7 a	3.0 a	69.1 a	12.8 a	6.0 a
p										
Site	0.0011*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*
Density	0.5783	0.5828	0.6384	0.9450	0.3206	0.1045	0.4474	0.7360	0.0850	0.8633
S × D	0.6450	0.0948	0.5298	0.9815	0.5167	0.5232	0.2111	0.7662	0.7714	0.7276

$^{(*)}$ = Leaves + pseudostems. $^{(**)}$ = Peduncle + fingers. AGB = Above ground biomass dry matter. S×D = Site × density interaction. 1 = Kibungo, 2 = Rubona and 3 = Ruhengeri. An asterisk (*) means significant effect (Pr > *F*, $p \leq 0.05$). Mean values with the same letter within the column for each category (i.e. site and density) are not different significantly at $p = 0.05$. Site effect is averaged over all cultivars and all plant densities and plant density effect is averaged over all cultivars and sites.

5.3.3 Nutrient retained in bunch yield

Plant densities did not differ significantly for the nutrient mass fractions of N, P, K, Ca and Mg in the fruit (Table 5.4). However, nutrient retained in bunch yield (fingers + peduncle) differed significantly ($p < 0.05$) and the amounts of nutrients increased with plant density at Rubona and Ruhengeri whilst nutrient content decreases at Kibungo (Figure 5.2). In general, the higher densities of 4444 and 5000 plants ha^{-1} registered larger nutrient exports than the lower densities. Potassium was exported in large amounts, followed by N, Ca, Mg and lastly P at all sites. Bunch yield also correlated positively with nutrient exports with the strongest correlation at Rubona (*r* = 0.76-0.92), followed by Kibungo (*r* = 0.64-0.90) and lastly Ruhengeri (*r* = 0.49-0.80) (data not shown). High correlations between bunch yield and nutrient exports at Rubona suggest the latter can rapidly be depleted than others if nutrient exports are not offset by recycled nutrient-rich biomass or by other means of replenishing soil fertility.

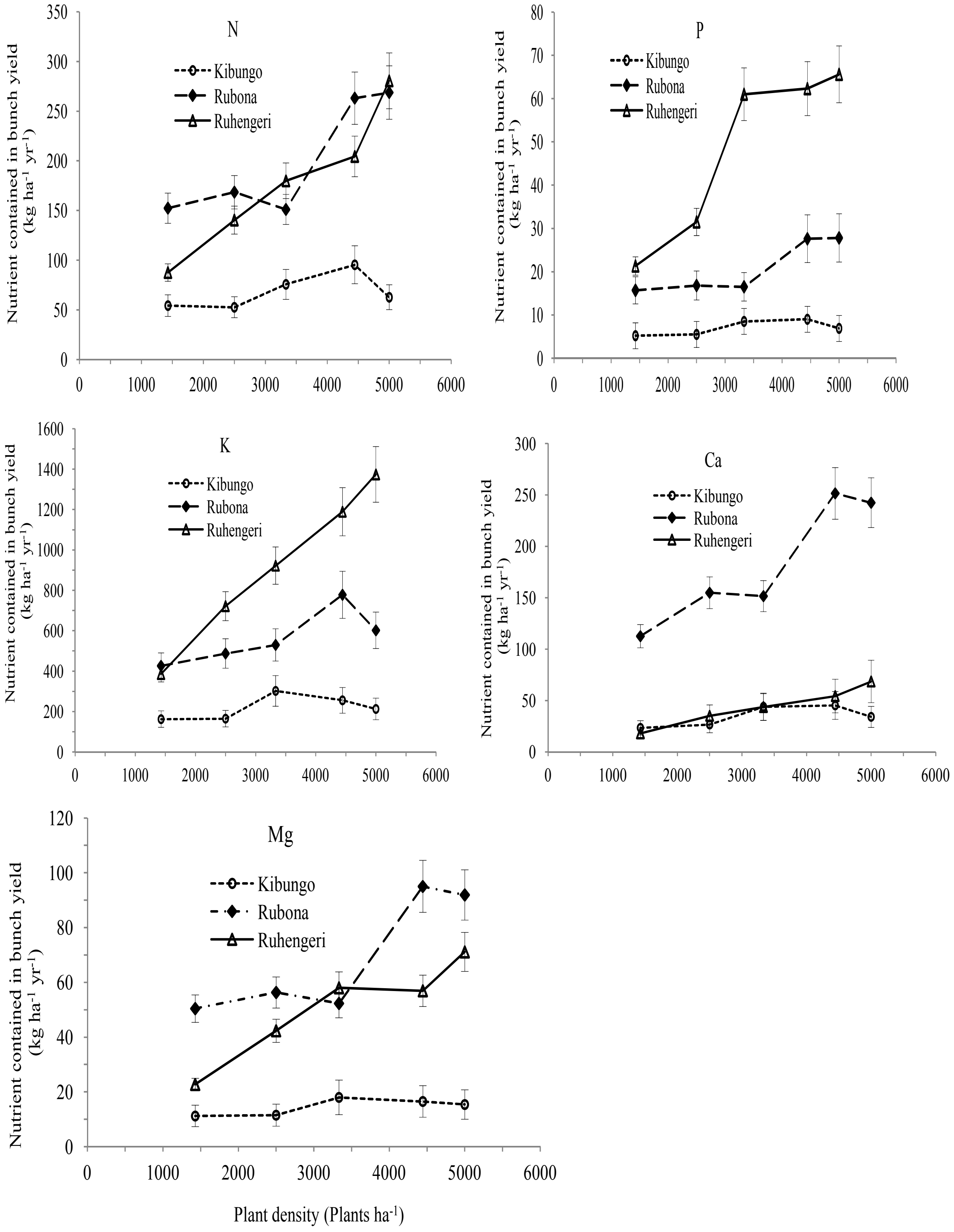

FIGURE 5.2 Nutrients (kg ha^{-1} yr^{-1}) retained in bunch yield (fingers + peduncle) for site × density interaction level at the Kibungo, Rubona and Ruhengeri sites.

5.3.4 Nutrient stocks over a experimentation period

Figure 5.3 shows that over a trial period (i.e. at the end of the trial), nutrient stocks differed significantly between sites but were not influenced by plant density (Table 5.5) despite larger amount of nutrients contained in leaves and pseudostems. Nitrogen stocks were considerably higher on soils that have high clay content (e.g. Kibungo), probably due encapsulated SOM in micro- and meso-aggregates, followed by soils with sandy soils with less clay content (e.g. Ruhengeri and Rubona). Calcium, Mg and K were strongly lower in sandy soils of Rubona compared with the other sites. In general, N stocks were considerably higher, followed by Ca, Mg and K. Phosphorus stocks were dramatically lower at Kibungo compared with the other sites, implying that significant P deficiency.

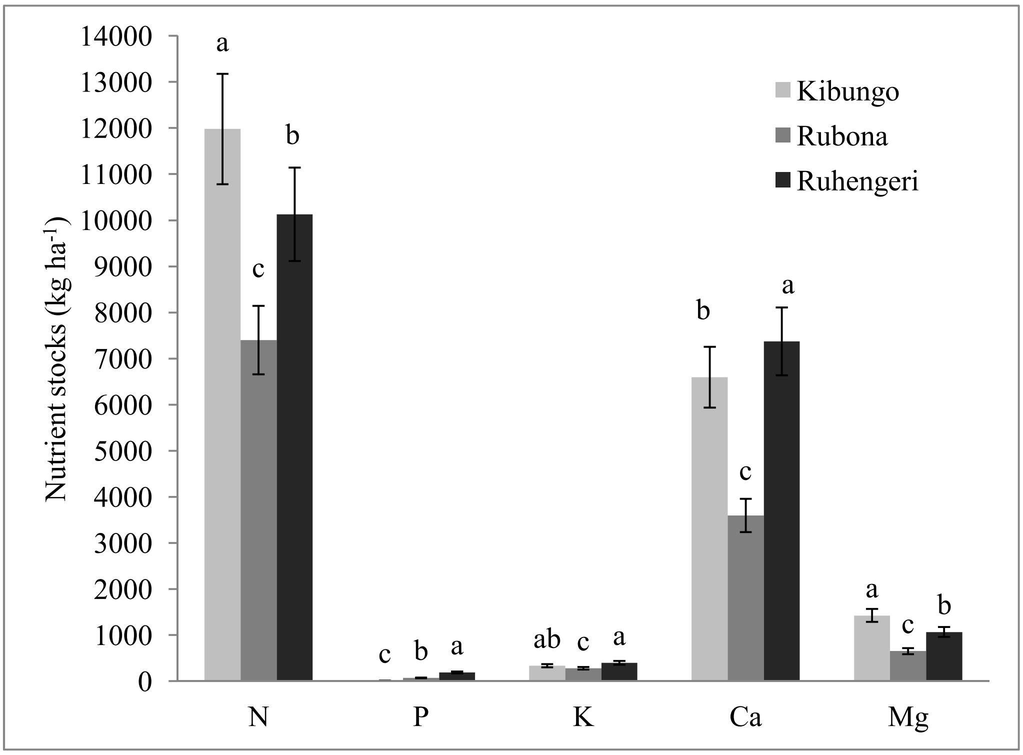

FIGURE 5.3 Nutrient stocks (kg ha^{-1}) over a trial period (i.e. at the end of the experiment) at the Kibungo, Rubona and Ruhengeri sites. Values are averages over all plant densities and all cultivars.

TABLE 5.5 Effect of plant density on soil nutrient stocks (kg ha^{-1}) at flowering, harvest of the plant crop and end of the experiment.

Site	Density	Flowering					Harvest					End of trial				
		N	P	K	Ca	Mg	N	P	K	Ca	Mg	N	P	K	Ca	Mg
Kibungo	1428	11869	3	255	3921	851	11260	5	150	10384	1600	10952	1	374	6743	2276
	2500	11559	5	313	3942	859	10703	4	171	11549	1630	13262	1	272	5968	1889
	3333	11133	7	354	3997	905	10713	4	190	10188	1490	12744	1	398	5825	1864
	4444	11328	4	272	4177	987	11722	5	123	10802	1587	12215	2	217	5936	2195
	5000	11191	4	315	3777	809	12413	4	137	10614	1579	13035	3	294	5982	2022
	p = 0.05	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rubona	1428	7721	50 B	182	2802	489	6107	36 B	118	3579 C	574 B	7514	102	307	2520	566
	2500	8073	57 B	199	2821	502	6970	68 AB	174	4265 AB	702 AB	8101	66	474	3022	720
	3333	7850	67 B	202	2999	520	6056	45 B	130	3798 BC	604 AB	8933	107	614	3220	673
	4444	7374	127 B	258	2992	557	6797	92 B	216	4390 A	743 A	9024	132	852	3097	710
	5000	8246	84 AB	189	3023	551	6858	69 AB	156	4362 AB	672 AB	9071	77	549	3517	852
	p = 0.05	NS	0.048*	NS	NS	NS	NS	0.05*	NS	0.020*	0.007*	NS	NS	NS	NS	NS
Ruhengeri	1428	12664	162	325	9712	1031	10973	356	108	12864	2302	11835	179	1048	4958	861
	2500	11758	110	255	10056	1038	9926	286	79	10932	1875	10871	145	712	4849	935
	3333	12057	213	194	7119	742	10387	375	111	12370	2224	11476	150	807	4391	794
	4444	12734	149	228	8814	853	11150	315	98	11089	1985	11666	174	1051	4958	919
	5000	13144	98	194	9100	872	11543	247	75	9262	1514	11762	135	945	4854	887
	p = 0.05	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

An asterisk (*) means significant effect (Pr > *F*, $p < 0.05$) of plant density and NS = not significant ($p > 0.05$. Mean values with the same letter within the column for are not different significantly at $p = 0.05$.

5.3.5 Partial nutrient balances

Results in Table 5.6 show that partial nutrient balances differed significantly between sites. In general, N and K partial balances were negative and considerably higher at the Ruhengeri high rainfall site, with its good soil and high yields, followed by the Rubona moderate rainfall site which is characterized by lower inherent soil fertility. This implies differences in the magnitude of nutrient depletion between sites. Table 5.6 also shows that an increase in plant density was associated with increasing negative N and K partial balances (i.e. outflows were much higher than inflows), which highlights the detrimental effect of high plant density system in nutrient mining, whilst P, Ca and Mg partial balances were positive. Table 5.7 shows nutrient mining at three sites and under plant densities based on partial nutrient balances. In general, N and K were strongly mined for up to 2% for N and more than 200% at Rubona and Ruhengeri whilst high P accumulation was found first at Kibungo, followed by Rubona. Calcium and Mg were generally accumulated.

TABLE 5.6 Mean values for the effect of site, plant density and the interaction site × plant density on partial nutrient balances.

Effect	Partial nutrient balance (kg ha^{-1} yr^{-1}) IN1-OUT1				
	N	P	K	Ca	Mg
Site					
1	-2.6 a	34.4 a	1.0 a	79.0 a	53.6 a
2	-135.2 b	20.6 b	-344.1 b	-69.0 b	-1.0 c
3	-113.0 b	-6.9 c	-697.9 c	69.7 a	18.0 b
Density					
1428	-70.0 a	3.6 d	-230.4 a	-2.7 c	1.0 d
2500	-71.4 a	13.1 c	-292.8 ab	12.8 bc	14.3 cd
3333	-70.2 a	12.7 c	-364.7 ab	33.7 ab	25.2 bc
4444	-100.5 a	22.1 b	-447.6 b	34.1 ab	34.5 ab
5000	-106.0 a	28.5 a	-399.5 b	55.0 a	42.6 a
Site × density					
1 1428	-26.3 abc	12.5 de	-67.9 ab	25.2 cd	17.9 cdef
1 2500	-3.5 ab	25.5 b	-20.2 ab	58.4 bc	39.5 bc
1 3333	-10.3 ab	32.8 b	-82.2 ab	69.4 bc	50.0 b
1 4444	-8.2 ab	46.1 a	37.8 a	105.9 ab	74.2 a
1 5000	- 35.4 abc	55.1 a	117.3 a	135.9 a	86.6 a
2 1428	-124.3 def	2.0 ef	-332.0 bcd	-63.9 e	-21.3 g
2 2500	-119.4 def	14.2 cd	-322.1 bcd	-69.8 e	-5.3 fg
2 3333	-85.7 cd	24.8 bc	-309.7 bcd	-38.2 de	15.7 def
2 4444	-176.0 ef	27.5 b	-484.7 cde	-100.4 e	-4.3 fg
2 5000	-170.7 ef	34.2 b	-272.0 bc	-72.4 e	10.1 ef
3 1428	-59.5 bcd	-3.6 f	-291.3 bcd	30.6 c	6.5 f
3 2500	-91.3 cd	-0.5 f	-556.5 de	49.9 bc	8.7 ef
3 3333	-114.5 de	-19.6 g	-702.0 ef	69.8 bc	10.0 ef
3 4444	-117.2 def	-7.2 f	-895.7 fg	96.8 b	33.8 bcd
3 5000	-182.5 f	-3.6 f	-1043.7 g	101.5 b	30.9 bcde
p for the effect of:					
site	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*
Density	0.154NS	<.0001*	0.0460*	0.0240*	<.0001*
Site x density	0.0117*	<.0001*	0.0003*	0.0468*	0.0203*

1 = Kibungo, 2 = Rubona and 3 = Ruhengeri. An asterisk (*) means significant effect (Pr > *F*, $p \leq 0.05$) and NS = not significant. Mean values with the same letter within the column for each category (i.e. site, density and site × density) are not different significantly at $p = 0.05$. Site effect is averaged over all cultivars and all plant densities and plant density effect is averaged over all cultivars and sites.

TABLE 5.7 Relative nutrient gain or losses (%) at the Kibungo, Rubona and Ruhengeri trial sites. Values are calculated based on initial nutrient stocks and partial nutrient balances.

Effect	Gains/ losses (%)				
	N	P	K	Ca	Mg
Site					
1	-0.4 a	185.0 a	0.2 a	1.4 a	4.5 a
2	-2.0 b	48.8 b	-283.0 b	-1.6 b	0.1 b
3	-1.9 b	-5.1 c	-211.5 c	1.6 a	3.7 a
Density					
1428	-1.0 a	23.1 d	-148.3 a	-0.2 c	0.1 c
2500	-1.1 a	56.8 c	-157.9 a	0.2 bc	1.4 bc
3333	-1.1 a	73.5 c	-131.4 a	1.5 bc	3.1 ab
4444	-1.6 ab	102.8 b	-194.0 b	0.6 ab	4.3 a
5000	-1.8 b	125.4 a	-193.0 b	1.0 a	5.1 a
p					
site	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*
Density	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*

1 = Kibungo, 2 = Rubona and 3 = Ruhengeri. Mean values with the same letter within the column for each category (i.e. site and density) are not different significantly at $p = 0.05$. Site effect is averaged over all cultivars and all plant densities and plant density effect is averaged over all cultivars and all sites.

5.4 DISCUSSION

5.4.1 Nutrients contained in above ground biomass

This study showed that nutrients contained in above ground biomass (ABG) indicate their large contribution to nutrient balances as sinks of nutrients, so that a high plant density plays a considerable role in nutrient recycling. The quantities of nutrients contained in leaves and pseudostems in this study are similar to those reported in the region under traditional banana farming systems, but considerably lower than those reported under well fertilized conditions

(Nyombi *et al*., 2010). Lekasi *et al*. (2001) reported about 1.0% N and 7.7% K in banana stalks and 2.8% N and 4.9% K in leaf dry matter. Delstanche (2011) reported the total foliar nutrient contents for N, P, K, Ca and Mg between 1.49-3.11% N, 0.06-0.47% P, 1.95-4.74% K, 0.27-1.41% Ca and 0.18-0.79% Mg. Obviously, decomposing leaves and pseudostems may represent a large (2.1-3.0%) fraction of N in total biomass, which is important to N recycling for subsequent ratoon crops under high plant density.

5.4.2 Nutrient removal through bunches

Effect of site × density on nutrient removal through harvested bunches highlights the detrimental effect of high plant density on soil fertility in low input systems. Exported nutrient masses (mainly for N and K) were consistently higher than those reported in the literature worldwide, including that for the East African region. The greatest amounts of N (400 kg N ha^{-1} yr^{-1}) and K (1000 kg K ha^{-1} yr^{-1}) were found to be incorporated in the banana fruit (Turner *et al*., 1989). The current study showed that a proportion of 13.8-22.5% of the N is exported in bunches at harvest. Teixeira *et al*. (2008) and Raphael (2006) reported a figure of 30%. Bazira *et al*. (1997) reported removal of 52.6, 9.3 and 58.0 kg ha^{-1} yr^{-1} of N, P and K, respectively in banana farms in central Uganda. Lopez (1999) estimated from published data that a highly productive plantation (70 t ha^{-1} yr^{-1}) exports 126 kg N, 15 kg P and 399 kg K per hectare annually. Based on average literature values for AAA-genomic group bananas worldwide, the calculated quantity of nutrient removed by the fruit (in kg ha^{-1}) was 104 kg N, 10 kg P, 285 kg K and 13 kg Mg (van Asten *et al*., 2004). In fact, banana is a perennial crop which assimilates large amounts of nutrients that are recycled back to the soil; results from this study imply that increasing plant density may hasten nutrient depletion due to greater nutrient export through the harvested bunches. Under high banana planting density system, bunch yields consistently increased with an increase in plant density (Ndabamenye *et al*., 2013).

5.4.3 Nutrient balances and the sustainability of the cropping system

The strongly negative partial nutrient balances encountered suggest that nutrient input is less than nutrient removal in bunches and other nutrient losses from the system. These differences in partial nutrient balances are consistently high, suggesting that soil fertility replenishment measures should be undertaken as a significant management strategy that reduces nutrient mining to ensure sustainability. In Uganda (e.g. the Lake Victoria region), Bekunda (1999) reported the 82% of the farmers sell banana fruits, which results in net resource outflows. Calculated negative N and K partial balances at Rubona and Ruhengeri are alarming compared with the estimated nutrient depletion rate for all African countries, which range from -14 kg NPK ha^{-1} yr^{-1} to -136 kg NPK ha^{-1} yr^{-1} (Smaling *et al*., 1993). Haileslassie *et al.* (2005) reported values of 122 kg N, 13 kg P and 82 kg K per hectare per year as national depletion rates in Ethiopian mixed farming systems. Partial P balances were positive and significantly higher at Kibungo than Rubona. This difference might be attributed to the fact that soils with a high clay content (e.g. Kibungo) tend to fix more P than sandy soils (e.g. Rubona) (Chattha *et al*., 2007), so that P is strongly adsorbed to soil particles and less subjected to leaching (Brady & Weil, 2002). Applied manure as external input was the main P source. Nevertheless, the fact that partial P balances were found to be positive at Rubona, highlights the weaknesses of this approach. The amount of dust in the air will determine largely the deposits occurring with rains and these amounts (and their composition) are unlikely to be homogeneous in space and time within the region. Therefore, studies to quantify and validate the influxes in nutrient balance models need verification. Despite the presence of volcanic ash soils at Ruhengeri, negative P partial balances were recorded, probably due to larger amounts being exported through bunches compared with other sites and relatively lower inputs.

Differences in magnitude of partial nutrient balances are probably also associated, to a certain extent, with inherent soil properties (e.g. high percentage of sand with less soil organic matter at Rubona) and climatic conditions (e.g. rainfall). Continuous nutrient depletion due to a loss of soil organic matter was also reported by Baijukya & De Steenhuijsen Piters (1998) for households without livestock in a high rainfall zone in Tanzania. Both N and K are essential nutrients for both growth and banana fruit filling, therefore substantial export of N and K require particular attention for sustainable soil fertility management. If no soil fertility-replenishing measures are taken, the banana system must be regarded as unsustainable in the longer term. However, previous studies have reported that well managed banana fields in the East African highland region (e.g. Rwanda, Uganda and Tanzania) continue to remain relatively productive without replanting for more than 100 years (Gold *et al*., 1999). This is because farmers replace dead plants (Ndabamenye *et al*., 2012) and maintain soil fertility by adopting systems where plant nutrient flow (e.g. biomass transfer) from distant fields and grazing areas to banana fields (Bekunda & Woomer, 1996).

Although internal flows were not included in the nutrient budget, there are substantial amounts of nutrients being recycled to the soil through leaves and pseudostems. Depending on the number of banana plants per unit area, differences in nutrient recycling between agro-ecological sites are expected to occur. This can probably result in positive nutrient balances that are comparable to those calculated in different banana-based land use systems (Bazira *et al*., 1997; Baijukya & De Steenhuijsen Piters, 1998) where farmers apply external mulch, kitchen residues and ashes, and livestock manure to their fields with the assumption that atmospheric deposition may occur. There is evidence that nutrient mining is a major threat to many African farming systems (Smaling *et al*., 1993) and organic amendments are no longer available to satisfy nutrient needs due to intensification of land use (Probert *et al*., 1992). Therefore, negative nutrient balances are expected to be more critical on highly weathered soils due to the fact that nutrient release from mineral weathering (and organic matter breakdown) is minimal (i.e. 5%) (Delstanche, 2011). Caution should be taken to maximize the use of external organic inputs on a large scale in order not to deplete crop fields of nutrients. Previous studies report that farmers can still maintain nutrient levels by recycling senesced leaves and pseudostems, which are continuously present on-farm, as well as banana peels (Yamaguchi & Araki, 2004). It is envisaged that detailed investigation should reveal more about diversity of soil management strategies required at farm level to support farmer decision-making in prioritizing options for nutrient recycling. As nutrient inputs through biomass dry matter are considerably high, farmers who employ high banana plant densities can still use banana residues as extra-source of nutrients for their home gardens and outfields that are generally characterized by low inherent soil fertility. However, there is a need to better understand the usefulness of banana residues as means to offset fertilizer application for smallholder farmers.

Although increasing plant density showed that bunch yields per unit area were consistently higher compared with lower plant densities (data not shown), findings from this study suggest that increasing plant density accelerates soil nutrient depletion with more acute losses in areas with moderate to relatively high inherent soil fertility. Negative nutrient balances and relative nutrient gains or losses of N and K at Rubona and Ruhengeri support this. Furthermore, an ‘order of magnitude’ estimate of depletion rates by quantifying available N, P and K in the top 30 cm of the profile (by assuming that all these nutrients are easily accessible) and their depletion rates (by considering nutrient export in bunches), illustrates that K is a key nutrient and that must be recycled to ensure sustainability (e.g. K soil stocks will be depleted in five years at Kibungo, in three at Rubona and in four at Ruhengeri) (data not shown). Therefore, as bananas require large amounts of potassium (Lahav, 1995), and recycling banana mulch is not just considered a promising practice for soil and water conservation, but absolutely essential to maintaining K levels. Ulrich & Ohki (1973) report that fertility of soils with less than 100 kg ha^{-1} of exchangeable potassium in the root zone should be improved by potassium fertilizer; an option not available to many resource poor farmers in the East African highland region.

Regarding the large amounts of nutrients contained in decomposing shredded leaves and pseudostems, there is an assumption that they get released and are subsequently available to the root systems and assimilated by ratoon crops. Wortmann *et al*. (1994) report that six to nine weeks after harvest are needed to account for 50-70% of N, K and Mg released from harvested banana leaves and pseudostems. There is evidence that some immediate nutrient losses may occur, especially through leaching, which will therefore deplete soil nutrient stocks. This suggests that efficient soil fertility management requires a critical understanding of nutrient recycling of post-harvest residues. Conducting studies on how to maximize responses to applied banana residues for the productivity of low input EAH banana cropping systems is of importance. Therefore, more research on quality and quantity of banana residues should be a priority.

5.4.4 Implications of findings and research outlook

Previous studies have reported on soil fertility management under banana systems (e.g. Bekunda & Woomer, 1996; Baijukya *et al*., 2005) but little attention was placed on plant density management. This study attempted to show first order estimates of nutrient balances (i.e. partial nutrient balances) by exploring potential temporal effects of plant density on nutrient mining. Numerous studies have also reported partial nutrient balances using primary data collected at plot or farm level (e.g. inorganic fertilizer, organic manure and crop removal). Often, these studies include inputs and outputs through natural processes (Smaling *et al*., 1996). However, due to uncertainties in transfer functions that are often used (Faerge & Magid, 2004), this study did not evaluate full nutrient balances which are supposed to provide potential effects of resource management on soil nutrient stocks (van den Bosch *et al*., 1998) and show trends in nutrient depletion or enrichment. The study explored the potential role of plant density in nutrient mining, where optimal plant density for bunch and biomass production was taken into consideration. In the current study, Ca and Mg, macronutrients that are often neglected, were also considered.

Results from this study are of importance for the sustainable management of resources such as organic inputs in banana-based systems in the East African highland region. It is important to consider that the decomposition of shredded banana leaves and pseudostems may be affected by ecological characteristics that can result in nutrient losses from the agro-ecosystem. Therefore, increasing losses through leaching in high rainfall areas should receive more attention of researchers, as banana residues are subjected to rapid decomposition under wet conditions (e.g. Ruhengeri site). These residues conserve soil water (Bananuka *et al*., 2000) and accelerate biological activity (Zake *et al*., 2000; Bananuka *et al*., 2000). Furthermore, East African highland bananas are often intercropped with annual crops

(Baijukya & De Steenhuijsen Piters, 1998), mostly established on lower slopes, valleys and in between-hill depressions where soil water is more available during dry periods (Rockström, 2000). Shifting from small scale plots to large scale studies, large differences in nutrient depletion or enrichment are of importance to streamline options that can improve the productivity of EAH banana cropping systems. Agricultural researchers, farmers and policy makers should develop management options that minimize nutrient losses and improve organic matter management (e.g. use of inorganic and organic nutrient resources). At high yield levels, depletion rates are so fast that it will be difficult to match these through organic inputs alone, since these materials are quite limited and therefore some degree of inorganic fertilizer adoption to counterbalance nutrient mining will be inevitable.

5.5 CONCLUSIONS

This study showed that nutrient depletion in banana production systems is very high, due to the large amount of nutrients exported through bunches. This will result in an unsustainable system if the amounts removed are not offset by soil fertility replenishing means. Large negative balances for N and K should receive attention by agricultural researchers, farmers and policy makers in seeking better ways to redress soil fertility decline, particularly for soils in Rubona and Ruhengeri. It is concluded that partial nutrient balances provide basic data to guide soil fertility replenishing measures that could be undertaken to ensure long-tem productivity of EAH banana cropping systems. Studies on how farmers should improve banana yield through external organic and/or in combination with inorganic inputs (i.e. manure and inorganic fertilizers) and ways to prioritize investments to increase profitability are urgently needed.

CHAPTER 6

GENERAL CONCLUSIONS AND RECOMMENDATIONS

6.1. OVERVIEW

Soil fertility decline in the East African region has been reported as a major cause of poor yields of most staple crops and much of the East African highland banana (*Musa*, spp.) cropping systems. This affects income generation and food security for most smallholder farmers. These systems are characterized by highly weathered soils with inherent poor soil fertility and limited capacity to supply nutrients. Farmers continue to grow crops with high nutrient demand such as bananas, but the insufficient supply of nutrients often limits yields. The use of fertilizers would lead to yield improvement, but the problem of high cost limits its use by smallholder farmers. Available soil fertility management practices include recycling of crop residues, biomass transfer and use of cattle manure, but these are mostly insufficient to compensate for nutrient mining. Several scientists have considered soil fertility evaluation as an entry point for soil fertility improvement of these systems. This study was conducted to give an insight to the productivity of EAH bananas in the East African highland region, with more emphasis on interactive effects of ecological characteristic, cultivar and managerial practice with planting density, receiving specific attention.

Taking into account continuous soil fertility mining and complex interactions between abiotic factors, this study investigated the effectiveness and profitability of having plant density as a management strategy in contrasting agro-ecological sites that differed distinctly in terms of altitude, temperature, annual rainfall and soil type, to understand direct and/or indirect influences of ecological characteristics on nutrient dynamics and productivity of EAH bananas. Different scenarios with respect to changes in soil fertility, on-farm practices (e.g. variations in on-farm plant densities), crop performance and the magnitude and variability of nutrient availability are addressed that may be important in developing policies for sustainable production of East African highland bananas in the region. The results from this study are useful for researchers and extension agents working to improve the productivity of East African highland bananas.

6.2. GENERAL CONCLUSIONS

6.2.1. On-farm plant density and banana productivity

This study showed that variation in plant density generally followed agro-ecological class, but overall regional plant density varied greatly, with soil fertility status and water supply being the predominant determining factors. Average banana plant densities varied from 1006 to 2326 mats ha^{-1} in Rwandan agro-ecological regions where average rainfall varied between 950 and 1400 mm yr^{-1} and altitude between 1400 and 1960 m a.s.l. Plant density was positively correlated with surplus/deficit water supply with highest plant densities found in high rainfall areas with a positive water balance and lowest plant densities found in lower rainfall areas with a negative water balance. Heaviest bunches were found at lowest plant densities and medium sized bunches at highest plant densities. Across regions, trends in bunch mass also followed soil fertility status. The choice of plant density varied with region and depended on whether the field was intercropped or whether the grower desired large bunch size to meet market preference.

6.2.2. Banana performance under contrasting environments

The study tested on-station, farmer's knowledge of plant density options using the most widely grown cultivars in the region. Site altitude and corresponding higher rainfall and soil fertility level had a positive effect on crop performance (i.e. the number of fingers, bunch mass, annual bunch yield and total above ground dry matter yields). An increase in plant density resulted in a linear increase in bunch yield per surface soil area, as soil fertility and water become non limiting factors from low to high altitudes.

It was interesting that yields of beer cultivars increased with density, but those of cooking cultivars decreased. Furthermore an increase in plant density resulted in high above ground biomass production (leaves + pseudostems), indicating that low densities should be recommended in order to increase bunch mass and yields, especially in dry and less fertile areas. It was observed that an increase in density leads to an increase in yield and the optimal agronomic density reaches the yield "plateau". This study confirmed that the optimal density for bananas depends on water availability, soil fertility and cultivar, whereby it is lower in low rainfall and less fertile areas and higher in areas with high fertility which also receive high rainfall.

6.2.3. Soil fertility as major constraint to banana productivity

To optimize fertilizer use, researchers advise that fertilizer recommendations should be based on specific nutrients which are most limiting (usually macronutrients) and to take into account site-specific nutrient deficiency rather than use blanket recommendations for the whole region (Wairegi *et al.*, 2010). Along these lines, this study explored variability in soil and plant nutrient status, and to some extent, water availability under low input systems and contrasting environments. Generally, an increase in plant density resulted in overall faster nutrient depletion of inherently poor soils than relatively fertile soils, whereby larger negative nutrient balances were accompanied with lower yield. The fact that expected yield gaps are higher when an increase in plant density is coupled with low inherent soil fertility, leads one to conclude that plant density management might be considered at as an entry point to be looked at, if one has to optimize the productivity of East African highland bananas.

The fact that soil fertility continues to decline, shows that there is a greater need for farmers to have knowledge on limiting factors, rather than the exact magnitude of nutrient depletion. As often voiced, this study revealed that soil fertility is still a challenge to EAH banana cropping systems. Subsequent short-term evaluations of trends in nutrient depletion (output > input) or enrichment (output < input) for macronutrients (N, P, K, Ca and Mg) also showed that nutrient depletion in banana production systems is very high, due to the large amount of nutrients exported through bunches. This can result in unsustainable systems if the amounts removed are not offset by soil fertility replenishing means. Large negative balances for K should receive attention from agricultural researchers, farmers and policy makers in seeking better ways to replenish soils with low inherent fertility.

6.3. GENERAL RECOMMENDATIONS AND RESEARCH OUTLOOK

6.3.1. Optimal banana plant density in the East African highland region

In the past, researchers and extension bodies, as well as banana growers have played an important role in setting up managerial strategies, and have always tried to improve banana production through different approaches. However, not much attention was given to plant density management as an entry point to maximize yield potential of a given plantation. The results on on-farm plant density assessment showed that plant densities generally recommended by extension bodies (3 × 3 or 2 × 3 m; i.e. 1111 and 1666 mats ha^{-1}) are seldom practiced by farmers, nor do they seem to be very appropriate, as higher densities seem to be more productive in areas with high rainfall and relatively good soil fertility. On-station trials also showed that the optimal density for bananas depends on water availability, soil fertility and cultivar. To maximize yield potential of a given banana plantation, plant density management requires some knowledge and the understanding of complex interactions of abiotic factors and farmer decision making, bearing in mind prevailing ecological characteristics. We recommend that:

- Agronomic optimal plant density should be lower (< 4444 plants ha^{-1}) in low rainfall (< 1000 mm yr^{-1}) and less fertile areas, but higher (> 5000 plants ha^{-1}) in areas with high fertility which receive high rainfall (> 1300 mm yr^{-1}), and
- Beer banana cultivars should be subjected to a high planting density (even > 4444 plants ha^{-1}) and still produce high yields, whereas cooking banana cultivars reach their maximum yields at somewhat lower densities (< 4444 plants ha^{-1}).

6.3.2. Addressing declining soil fertility of low input EAH banana cropping systems

Given that farmers continue to grow crops on soils with inherent poor soil fertility, which continues to decline, crop production should rely on efficient management of crop residues, and a search for fertilizer use strategies based on the most limiting nutrient. In fact, nutrient cycling in banana systems is highly dynamic due to the large amount of nutrients contained in the banana biomass and bunches. Being aware of soil fertility problems, farmers adopt different practices that integrate the use of banana residues, cattle manure and compost. However, these strategies are insufficient to sustain soil fertility which of banana cropping systems. In this study, plant density responses seemed to depend on diversity in climate and soil type and large negative balances for N and K were found in soil with low inherent soil fertility and to some extent in relatively fertile soils. In line with the above findings, the following actions are recommended:

- Identification of the most deficient element is of importance to help farmers to prioritize investments for purchasing fertilizer. This can increase fertilizer use rate in the East African highland region, especially in banana cropping systems where adapted plant densities in different regions may cause nutrient imbalance either over the short or long term.
- Studies on how farmers should improve banana yield through external organic and/or in combination with inorganic inputs (i.e. manure and mineral fertilizers) and ways to prioritize the investments to increase the profitability are needed.
- Banana productivity might be correlated with the amount of nutrients released during mineralization and those taken up by bananas, as well as those lost from the system through erosion and leaching. Under these circumstances, full nutrient balance studies would be promising tools to provide potential effects of resource management on soil nutrient stocks and show trends in nutrient depletion or enrichment.
- Exploring long-term nutrient dynamics, coupled with large scale investigation of limiting nutrients, should be undertaken to tell more about diversity of soil management strategies at farm level to support farmer decision-making in prioritizing options of nutrient management.

- Although the study highlighted the importance to consider all factors to optimize cultural practices such as plant density, some statistic/mechanistic quantification of the relative effect of natural processes requires further investigation. Furthermore, in order to account for the long term sustainability of these banana cropping systems, larger scale quantitative evaluation of nutrient balances, while accounting for inputs and outputs from natural processes (e.g. loses by leaching) will help in prioritizing alternative options for sustainable management. Thus, conceptualization model will help to give more generic value on the obtained results.

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APPENDICES

TABLE A.1 Monthly and cumulative rainfall during the experimentation period.

Year	Month	Monthly rainfall (mm)			Cumulative monthly rainfall (mm)		
		Kibungo	Rubona	Ruhengeri	Kibungo	Rubona	Ruhengeri
2007	April	159.0	186.4	209.2	159.0	186.4	209.2
2007	May	94.8	143.5	146.5	253.8	329.9	355.7
2007	June	14.4	24.9	46.9	268.2	354.9	402.6
2007	July	5.0	10.0	23.6	273.2	364.9	426.1
2007	August	15.8	30.8	58.9	289.0	395.7	485.1
2007	September	48.8	75.4	118.6	337.8	471.1	603.7
2007	October	89.6	117.3	168.6	427.4	588.4	772.3
2007	November	118.2	130.1	162.0	545.6	718.5	934.3
2007	December	96.0	111.3	110.5	641.6	829.8	1044.8
2008	January	78.8	114.8	92.8	720.4	944.5	1137.6
2008	February	92.8	120.3	124.6	813.2	1064.8	1262.2
2008	March	117.4	144.0	139.8	930.6	1208.8	1402.0
2008	April	151.2	195.5	188.2	1081.8	1404.3	1590.2
2008	May	86.2	145.8	142.6	1168.0	1550.0	1732.8
2008	June	12.6	15.5	47.8	1180.6	1565.5	1780.6
2008	July	4.0	5.3	24.8	1184.6	1570.8	1805.4
2008	August	18.0	33.3	65.6	1202.6	1604.0	1871.0
2008	September	46.8	71.5	124.4	1249.4	1675.5	1995.4
2008	October	77.6	114.5	155.8	1327.0	1790.0	2151.2
2008	November	110.0	131.8	166.4	1437.0	1921.8	2317.6
2008	December	100.0	126.8	119.0	1537.0	2048.5	2436.6
2009	January	77.4	112.4	95.1	1614.4	2160.9	2531.8
2009	February	91.7	118.2	124.2	1706.1	2279.1	2656.0
2009	March	164.6	57.0	104.2	1870.7	2336.1	2760.2
2009	April	152.6	40.6	159.4	2023.3	2376.7	2919.6
2009	May	153.4	118.6	153.6	2176.7	2495.3	3073.2
2009	June	16.6	13.0	24.4	2193.3	2508.3	3097.6
2009	July	25.2	5.6	20.8	2218.5	2513.9	3118.4
2009	August	31.2	1.4	43.0	2249.7	2515.3	3161.4
2009	September	12.0	40.0	148.2	2261.7	2555.3	3309.6
2009	October	5.0	13.8	178.0	2266.7	2569.1	3487.6
2009	November	99.8	85.6	130.4	2366.5	2654.7	3618.0
2009	December	140.2	101.2	91.8	2506.7	2755.9	3709.8
2010	January	63.6	124.6	76.4	2570.3	2880.5	3786.2
2010	February	192.8	224.8	160.6	2763.2	3105.4	3946.8
2010	March	125.6	93.8	280.0	2888.8	3199.2	4226.8
2010	April	163.6	268.9	196.6	3052.4	3468.0	4423.4
2010	May	12.0	80.6	203.6	3064.4	3548.6	4627.0

TABLE A.2 Monthly and cumulative temperature during the experimentation period.

Year	Month	Monthly temperature (°C)			Cumulative monthly temperature (°C)		
		Kibungo	Rubona	Ruhengeri	Kibungo	Rubona	Ruhengeri
2007	April	19.4	19.0	16.1	19.4	19.0	16.1
2007	May	19.4	18.8	15.9	38.8	37.8	32.1
2007	June	19.0	18.6	15.9	57.8	56.4	47.9
2007	July	19.2	19.1	16.2	77.0	75.5	64.1
2007	August	20.0	19.8	16.5	96.9	95.3	80.6
2007	September	20.2	19.8	16.5	117.1	115.2	97.1
2007	October	19.7	19.3	16.2	136.8	134.4	113.3
2007	November	19.0	18.7	15.9	155.8	153.2	129.2
2007	December	19.2	18.8	16.1	174.9	172.0	145.3
2008	January	19.2	18.8	16.0	194.1	190.8	161.3
2008	February	19.0	18.8	16.0	213.2	209.6	177.3
2008	March	19.0	18.8	15.9	232.1	228.5	193.2
2008	April	19.0	18.8	15.9	251.1	247.3	209.1
2008	May	19.1	18.6	15.9	270.2	265.9	225.0
2008	June	18.8	18.4	16.0	288.9	284.3	241.0
2008	July	19.0	18.8	16.0	308.0	303.1	257.0
2008	August	19.7	19.6	16.0	327.7	322.7	273.0
2008	September	19.8	19.6	16.0	347.5	342.4	289.0
2008	October	19.3	19.1	15.9	366.8	361.4	305.0
2008	November	18.6	18.4	15.9	385.4	379.9	320.9
2008	December	18.8	18.7	15.9	404.2	398.6	336.8
2009	January	19.3	19.0	16.2	423.6	417.6	353.0
2009	February	19.2	18.9	16.1	442.7	436.5	369.0
2009	March	19.5	19.1	16.8	462.3	455.6	385.8
2009	April	18.7	18.3	16.6	480.9	473.9	402.4
2009	May	19.0	18.4	16.8	499.9	492.3	419.2
2009	June	19.8	19.1	16.7	519.7	511.4	436.0
2009	July	20.0	19.0	16.4	539.7	530.4	452.4
2009	August	21.0	20.5	17.5	560.7	550.9	469.9
2009	September	20.9	20.5	17.5	581.7	571.4	487.5
2009	October	20.1	19.1	16.2	601.8	590.5	503.6
2009	November	20.1	18.6	16.4	621.8	609.1	520.0
2009	December	19.0	18.5	16.5	640.8	627.6	536.6
2010	January	19.8	19.6	17.3	660.6	647.2	553.9
2010	February	19.8	19.6	18.0	680.4	666.9	571.9
2010	March	19.8	19.2	17.8	700.2	686.0	589.6
2010	April	20.1	19.5	17.7	720.2	705.5	607.3
2010	May	19.9	19.1	15.8	740.1	724.6	623.2

TABLE A.3. Estimated effects of plant density on the height of the ratoon crop from planting to flowering at Kibungo, Rubona and Ruhengeri sites.

Interaction		Estimate	t Value	Pr > |t|
Site x cultivar				
1	1	-7.000	-2.510	0.04600*
1	2	0.669	0.220	0.8325ns
1	3	-4.813	-1.660	0.1485ns
2	1	-14.902	-4.810	<.0001*
2	2	-4.577	-1.380	0.1816ns
2	3	-5.065	-1.480	0.1527ns
3	1	-0.114	-8.070	<.0001*
3	2	-0.090	-6.990	<.0001*
3	3	-0.035	-2.340	0.0194*
Site x density				
1	1428	9.402	2.830	0.0092*
1	2500	15.088	4.660	<.0001*
1	3333	8.436	2.510	0.0191*
1	4444	1.597	0.470	0.6455ns
1	5000	-	-	-
2	1428	14.292	4.110	0.0004*
2	2500	-0.599	-0.170	0.8662ns
2	3333	5.039	1.410	0.1721ns
2	4444	-9.808	-2.570	0.0166*
2	5000	-	-	-
3	1428	8.779	2.590	0.01600*
3	2500	0.957	0.280	0.7800ns
3	3333	3.230	0.940	0.3566ns
3	4444	-0.864	-0.240	0.8089ns
3	5000	-	-	-

Site 1 = Kibungo, Site 2 = Rubona, Site 3 = Ruhengeri, Cultivar 1= “Ingaju”, Cultivar 2 = “Injagi” and Cultivar 3 = “Intuntu”. An asterisk (*) means significant effect (Pr > |t|, $P < 0.05$) for cultivar or plant density, and NS = not significant ($P > 0.05$). Empty brackets mean that no value was selected by the model.

TABLE A.4 Linear regressions between different growth and yield parameters (n = 45) for the mother and ratoon crops at the Kibungo, Rubona and Ruhengeri sites.

	Site	Equations	*r* value
Plant crop	Kibungo	$BM = -3.78 + 0.00043PSV$	$r = 0.50$
		$BM = -5.79 + 0.03879\ HT$	$r = 0.45$
		$BM = -3.091 + 14.624GGR$	$r = 0.41$
		$HT = 89.03 + 338.72GGR$	$r = 0.73$
		$TNL = 44 - 10.56\ GGR$	$r = 0.16$
	Rubona	$BM = -8.05 + 0.00068PSV$	$r = 0.83$
		$BM = -12.82 + 0.0675\ HT$	$r = 0.67$
		$BM = -11.952 + 32.78GGR$	$r = 0.76$
		$HT = 50.74 + 419.98GGR$	$r = 0.86$
		$TNL = 43.98 - 10.58GGR$	$r = 0.45$
	Ruhengeri	$YLD = -0.485 + 0.005\ DENS$	$r = 0.91$
		$HT = 81.75 + 398.9GGR$	$r = 0.66$
		$TNL = 23.3 + 13.9\ GGR$	$r = 0.28$
Ratoon crop	Kibungo	$BM = 3.439 + 0.00026PSV$	$r = 0.28$
		$BM = 0.478 + 0.0302\ HT$	$r = 0.38$
		$HT = 43.054 + 483.6GGR$	$r = 0.90$
	Rubona	$BM = 1.297 + 0.00048PSV$	$r = 0.32$
		$HT = 300.82 - 43.82GGR$	$r = 0.20$
	Ruhengeri	$BM = 26.169 - 0.00043PSV$	$r = 0.14$
		$BM = 31.28 - 0.026\ DFL$	$r = 0.35$

All *r* values are significant at $p = 0.05$ level. BM = Bunch mass (kg fresh weight), PSV = Pseudostem volume (cm^3 plant^{-1}), DENS = Plant density (plants ha^{-1}), YLD = Yield (t ha^{-1} year^{-1}), HT = Plant height (cm) at flowering, GGR = General growth rate (cm day^{-1}), DFL = Number of days to flower (days), TNL = Total number of leaves (nr plant^{-1}).

TABLE A.5. Regression analysis for yield response surface of mother crop at Kibungo, Rubona and Ruhengeri sites.

		Kibungo					Rubona					Ruhengeri				
Cultivar	Parameter	*F* value	Pr > *F*	Slope	t value	Pr > |t|	*F* value	Pr > F	Slope	t value	Pr > |t|	*F* value	Pr > *F*	Slope	t value	Pr > |t|
1	Intercept			1.116625	0.27	0.7882			15.24431	1.98	0.0497			16.9823	5.11	<.0001
	Density	5.51	0.0204	0.011842	1.93	0.0555	**10.59**	**0.0014***	-0.00752	-0.65	0.5146	**46.42**	**<.0001***	-0.0098	-2.00	0.0478
	Density^2	**14.05**	**0.0003***	-0.000006	-1.99	0.0481	0.09	0.7638	0.0000030	0.51	0.6078	3.04	0.0842	0.000004	1.84	0.0681
	Density^3	7.50	0.0070	0.000000	2.13	0.0346	7.91	0.0056	-0.00000	-0.35	0.7246	7.72	0.0064	-0.00000	-1.65	0.1016
	Density^4	5.33	0.0225	0.000000	-2.31	0.0225	0.04	0.8438	0.000000	0.20	0.8438	2.18	0.1424	0.00000	1.48	0.1424
2	Intercept			36.0126900	6.58	<.0001			1.311013	0.21	0.8320			16.2405	3.37	0.0013
	Density	1.59	0.2097	-0.03915354	-4.81	<.0001	**44.02**	**<.0001***	0.014162	1.53	0.1290	0.06	0.8087	-0.0071	-0.99	0.3281
	Density^2	1.47	0.2278	0.00001971	4.73	<.0001	24.88	<.0001	-0.000008	-1.72	0.0877	**37.81**	**<.0001***	0.000003	0.82	0.4177
	Density^3	5.56	0.0203	-0.00000000	-4.62	<.0001	3.99	0.0484	0.000000	1.89	0.0611	0.36	0.5487	-0.00000	-0.72	0.4713
	Density^4	**20.04**	**<.0001***	0.00000000	4.48	<.0001	4.02	0.0474	-0.00000	-2.01	0.0474	0.48	0.4904	0.00000	0.69	0.4904
3	Intercept			23.57270043	4.12	<.0001			6.133665	1.42	0.1566			3.641401	1.04	0.3004
	Density	**13.11**	**0.0005***	-0.02138055	-2.51	0.0138	**46.46**	**<.0001***	0.004443	0.69	0.4930	**78.86**	**<.0001***	0.00874	1.68	0.0963
	Density^2	1.67	0.1991	0.00001074	2.46	0.0157	19.72	<.0001	-0.0000019	-0.59	0.5551	1.17	0.2815	-0.000004	-1.55	0.1241
	Density^3	0.98	0.3253	-0.00000000	-2.40	0.0186	0.78	0.3776	0.00000	0.60	0.5527	3.01	0.0862	0.00000	1.45	0.1506
	Density^4	5.49	0.0215	0.00000000	2.34	0.0215	0.41	0.5208	-0.00000	-0.64	0.5208	1.79	0.1848	-0.00000	-1.34	0.1848

Terms in the model appeared as Density, Density^2, Density^3 and Density^4. * means that response surface is either, linear, quadratic (one bend), cubic (two bends) or quartic (three bends).