# Management practices and opportunities in East African highland banana (*Musa* spp. AAA-EA) production in Uganda

Lydia Wanja Ireri Wairegi

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**Lydia Wanja Ireri Wairegi**

**Thesis committee**

**Thesis Supervisor**
Prof. Dr. K.E. Giller
Professor of Plant Production Systems
Wageningen University

**Co-supervisors**
Dr. Ir. P.J.A van Asten
Research Scientist
International Institute of Tropical Agriculture, Kampala, Uganda

Prof. Dr. M.A. Bekunda
Professor, Department of Soil Science
Makerere University

**Other members**
Prof. Dr. Bruno Delvaux, Université Catholique de Louvain, Belgium
Prof. dr. H.B. Meinke, Wageningen University
Prof. dr. L. Brussaard, Wageningen University
Dr. A.E. Hartemink, Wageningen University

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Lydia Wanja Ireri Wairegi
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# Abstract

The East African highland banana (*Musa* spp. AAA-EA) is a primary food and cash crop in Uganda. Despite its importance, yields are poor due to biotic and abiotic constraints. However, quantitative information on the importance, interactions, and geographic distribution of yields and constraints is scanty. On-farm quantification of the yield gap requires a tool for estimating bunch weight since quantification of production is very difficult as plants are at different stages of production at any given time. Diagnosis of nutrient deficiencies requires a tool for identification of plant nutrient imbalances. The overall objective of this thesis, therefore, was to generate technologies and information that researchers and farmers can use to improve the productivity, profitability, and sustainability of their banana-based systems. This study is based on data collected through monitoring of farmer plots, household surveys and group interviews in the banana growing belt of Uganda in 2006-2008. A tool for quantitative estimation of bunch weights, regardless of genotypic, developmental and spatial variations, was developed. Compositional Nutrient Diagnosis (CND) and Diagnosis and Recommendation Integrated System (DRIS) norms for diagnosing nutrient imbalance in bananas were derived. Actual yield levels observed in this study (averaged 9.7-25.5 t $ha^{-1}$ $year^{-1}$) were more than double the official national statistics (5.5 t $ha^{-1}$ $year^{-1}$). Biotic stresses (i.e. pests, weeds) were particularly important in the Central region, whereas abiotic stresses (i.e. nutrient deficiencies, drought) dominated in the South and Southwest regions. Poor soil fertility and drought seemed to be more important than suggested by past publication records and research investments. Fertilizer response was much higher where the tested blanket fertilizer application corresponded with the existing plant nutrient deficiencies. Application of external inputs (fertilizer and mulch) was very profitable (Marginal Rate of Return $\geq$1.00) in areas with good farm gate prices (e.g. Central region) and good crop response (e.g. Central and South regions), but was not profitable in areas far away (e.g. parts of the Southwest) and in areas with weak fertilizer response. High fertilizer prices were the most important constraint to adoption of fertilizer use. Other important constraints were poor availability, labour requirements for fertilizer application, and the belief that fertilizer negatively affected soil quality. This study concludes that that there is scope for increased input use in banana systems in Uganda, but that regional variations in crop response and input/output prices have to be taken into account. In addition, research efforts towards addressing poor soil fertility and drought should be increased. The study further concludes that demonstrating/testing of recommendations/ technologies in collaboration with farmers shortens and strengthens the adoption pathway by allowing for simultaneous participative evaluation, fine-tuning, adoption and adaptation of recommendations and technologies.

**Key words**: Yield gap analysis; Bunch weight; Compositional Nutrient Diagnosis; Diagnosis and Recommendation Integrated System; Soil fertility; Fertilizer; Mulch; Profitability; Constraints to adoption.

# Contents

Chapter 1

# General introduction

# 1. Background

Food production in sub-Saharan Africa (SSA) has continued to be below demand as population growth has continued to outstrip increase in food production (Dorward et al., 2004). Between 1990-92 and 2003-05, the number of undernourished people in SSA rose from 170.5 to 213.8 million (FAO, 2008). In recent years, climate change has further put pressure on food security due to non-regular weather patterns that impact on available water for crops (Gregory et al., 2005). Trade liberalization, resulting from globalization, has also affected food production in SSA by transmitting real world agricultural prices to the domestic markets as private traders have replaced parastatals in inputs supply (Ellis, 2005). Due to the increase in food shortages, SSA has become increasingly dependent on imports and food aid (USDA, 2009).

Small-scale farmers in Asia and Latin America increased production dramatically due to the Green Revolution, but most small-scale farmers in SSA continue to have poor production (Voortman et al., 2003). In the past, growth in overall agricultural production in SSA was achieved through an increase in area of cropped land (World Bank, 2000; FAO 2009). Further agricultural expansion is no longer feasible in many SSA countries as land has increasingly become a constraint due to increase in population. Future efforts to increase production should mainly be achieved through agricultural intensification (Alexandratos, 1995; Reardon, 1998, Reardon et al., 1999). Actual yields in SSA for most crops are still far below potential.

Low agricultural growth in Africa is due to a combination of poor economic policies, and geographical and ecological factors (Sachs and Warner, 1997; Rodrik, 1998). Compared to other continents, Africa has a larger number of landlocked countries; a higher fraction of area in tropical latitudes which makes climate related constraints (e.g. drought, diseases, pests, weed competition) more serious problems; and higher dependence on natural resources which is believed to contribute to low economic growth (Sachs and Warner, 1997). Conditions that need to improve to achieve sufficient agricultural development in SSA relate to access to markets, infrastructure, institutions (Dorward et al., 2004), and rural livelihood diversification (Ellis, 2005).

Evidently, the fact that eradication of extreme poverty and hunger was ranked as the first Millennium Development Goal implies that agricultural production merits greater investment in SSA. Uganda, where half of the population (51.5%) is estimated to live below the poverty line of US$ 1.25 $day^{-1}$ (UNDP, 2008), is one of the countries requiring such investment. Uganda's primary staple crop is the East African highland banana (*Musa* spp., AAA-EA). The crop is particularly important in the southern half of the country where a bimodal rainfall pattern dominates.

## 2. Banana production in East Africa

Banana is now a major food crop in Africa estimated to meet more than a quarter of the food energy requirements in the continent (Robinson, 1996). It is a primary food and cash crop for over 30 million people in East Africa. The fact that it produces fruit throughout the year adds to its importance as a food security crop in Africa. Uganda is Africa's largest producer while Rwanda and Burundi are the second and third largest producers in East Africa, respectively (FAO, 2009). The per capita production was estimated as 472, 383 and 236 kg in Uganda, Rwanda and Burundi, respectively (Frison and Sharrock, 1998). Banana has high carbohydrate content and is a good source of Vitamins A, B6 and C, and the nutrient K. Banana is cultivated in a wide range of ecological zones. Despite its importance, yields are low (<20 t $ha^{-1}$ $year^{-1}$) (FAO, 2009) compared with the potential yield of >70 t $ha^{-1}$ $year^{-1}$ (van Asten et al., 2005).

Bananas originate from Southeast Asian and Western Pacific regions (Robinson, 1996). With time, crosses of inedible sub-species of *Musa acuminata* Colla produced some hybrids that were edible. Karamura (1998) reported that the triploid AAA arose from the diploids through a process of meiotic chromosome restitution at meiosis. Simmonds (1966) suggested that triploid AAA bananas arrived at the East African coast with Arab traders centuries ago. The bananas then moved further inland into the East African highlands (Simmonds, 1959). Here, bananas evolved to suit the local conditions through a process of spontaneous somoclonal variation (Karamura, 1998) and subsequent farmer selection for mutants with desirable traits. The large variation in banana cultivars that subsequently emerged from this process makes that the East African highland region is regarded as a secondary diversity centre for bananas (Simmonds, 1966). In the past century, other *Musa* cultivars were introduced, such as dessert bananas (AAA, AB), plantains (AAB), and exotic beer and cooking bananas (ABB). The large majority of bananas grown are the East African highland (cooking and beer) that take up over 85% of all bananas in Uganda (Karamura, 1998). In Uganda, East African highland bananas are found at 1200-1800 meters above sea level (Pillay and Tripathi, 2007). Banana is mainly grown in relatively small plots, near the homestead, in multi-cultivar systems (Karamura et al., 1998) as a monocrop or intercropped with both perennials and annuals.

## 3. Constraints to banana production

During 1970s and 1980s, there was a reported general decline in banana yields and increase in production area in Uganda (Figure 1) (FAO, 2009). Banana production in traditional growing areas declined and was replaced by other food crops (Gold et al., 1993). This decline in production, coupled with increased reports on weevil and nematode damage to the crop in the mid-1980s (Sengooba, 1986; Sebasigari and Stover, 1988), raised fears that the production of Uganda's primary staple food crop was at stake. In response, Uganda developed a National Banana Research Programme (NBRP) in 1989 to address the problem of poor banana yields. Thereafter, a collaborative program was developed between the NBRP, Makerere University and the International Institute of Tropical Agriculture (IITA), with the support of the Rockefeller Foundation and the International Development Research Council, to: a) characterize Ugandan banana-based cropping systems, b) determine the principal production constraints, and c) prioritize research needs and directions. These research efforts have generated a lot of information on banana production, though often qualitative and descriptive in nature or limited in geographic or temporal spread. In the section below, we will outline the current state of art with regard to banana production constraints.

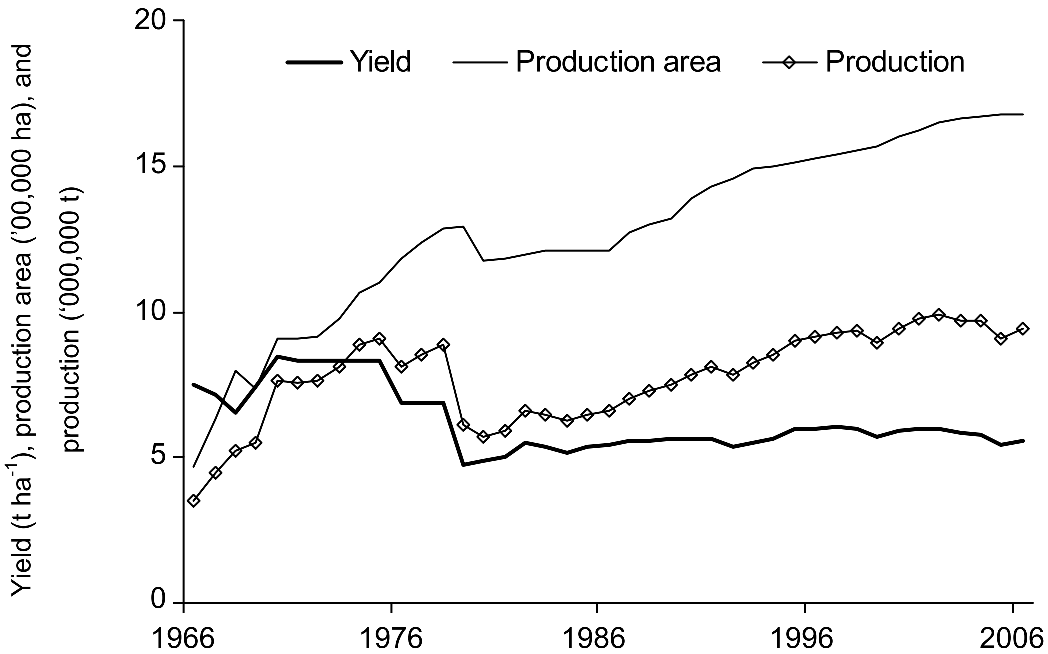


Figure 1: Yield, production area, and production of banana for the period 1966-2006, in Uganda (FAO, 2009)

Depletion of soil fertility, along with the related problems of rainfall, weeds, pests, and diseases, are the major causes of poor banana yields in the East African highlands. Soil net nutrient removal in banana production systems is high (Bazira et al. 1997) and the value of replacing the depleted nutrients, in banana growing areas, is estimated to be above 10% of household income obtained from agricultural production (Nkonya et al., 2005). In addition, soils in Uganda on which bananas are grown are often Ferralsols and Acrisols, which have poor inherent fertility (Jaetzold and Schmidt, 1982; Sanchez et al., 1989). Farmers commonly use organic amendments such as mulch, manure, and crop and kitchen residues (Bekunda and Woomer, 1996; Rufino, 2003), but little fertilizer is used. Mineral fertilizer improves plant nutrient availability (Byerlee et al., 1994) leading to rapid improved plant growth. This seems also true for banana production, as many studies have demonstrated that production substantially increased upon fertilizer use (e.g. Rubaihayo et al., 1994; Zake et al., 2000; Murekezi, 2005). However, profitability and risk associated with erratic rainfall are key drawbacks to fertilizer use in Africa (Adesina 1996; Mwangi, 1997; Enyong et al., 1999), particularly since fertilizer prices in Africa are 2-6 times higher than those in Europe, North America and Asia (Sanchez, 2002).

Since most of SSA's agriculture is rainfed, variations in rainfall amount and distribution are particularly important (Sivakumar and Wallace, 1991). Rainfall in most of Uganda's banana growing regions is between 1000 and 1300 mm (van Asten et al., 2005), which is well below the 1500-2500 mm considered as ideal by Purseglove (1985). Water availability may further be aggravated by run-off, which easily occurs in Uganda's hilly landscape. Runoff may also cause soil erosion (Magunda and Tenywa, 1999; Nkonya et al., 2004), although the banana canopy and self mulch are reported reduce run-off (INIBAP, 1986) and erosion by up to 65% (Lufafa et al., 2003). Yields are directly related to the amount of water transpired (Tanner and Sinclair, 1983). Soil water deficit slows down the rate of emergence of new banana leaves (Turner and Thomas, 1998) and bunch filling (Turner et al., 2008). Farmers have recognized these problems, and have developed and adopted various traditional water conservation technologies (Mutunga et al., 2001; SIWI, 2001).

Mulching, ridging and bench terraces are some of the practices used to conserve soil moisture (FAO, 2002). Numerous studies have documented the importance of mulch (e.g. Rubaihayo et al., 1994; Speijer et al., 1999; McIntyre et al., 2001) and mulch seems to be the commonest water conservation method used by farmers confirming the importance of this practice.

Weevils (*Cosmopolites sordidus*) and nematodes (*Radolpholus similis* and *Helicotylenchus multicinctus*) are the most important pests affecting banana production. Nutrient and water uptake is impaired when plant roots are infested by nematodes or corms damaged by weevils (Robinson, 1996). The banana weevil, found all over the world where bananas are cultivated (Robinson, 1996), has been identified as the most important insect pest on bananas in Uganda (Gold et al., 1999) causing yield losses of up to 60% (Gold et al., 2004). Parasitic nematodes have caused production losses of 30-50% in on-station trials (Speijer et al., 1999; Speijer and Kajumba, 2000). Since nematodes feed, multiply and migrate inside banana roots and corm (Gowen and Quénéhervé, 1990), they are spread via infected material. Integrated pest management (IPM) practices have been proposed (Blomme et al., 2005) but their use is hampered by the associated costs (Bagamba et al., 2005) and unwillingness of farmers to adopt them (Walker et al., 1984; Gold et al., 1993).

Technology adoption is influenced by biophysical and socio-economic factors. Some factors reported to influence fertilizer use are distance of farm from village, distance to market, gender of farmer (Adesina, 1996), fertilizer prices, commodity prices, access to capital, risks of crop losses (Camara and Heinmann, 2006). In Uganda, among the major constraints to adoption of fertilizer use is lack of availability (Sseguya et al., 1999; Dramadri et al., 2005), farmers' experience in fertilizer use, formal education of farmer, extension services received, household income, group membership and family labour (Dramadri et al., 2005).

Despite increasing effort from the agricultural research community in the region to try to understand what causes the poor yields, in an effort to formulate improved crop management recommendations (van Asten et al., 2005), there have been several shortcomings. Firstly, quantification of production in on-farm studies has proven to be very difficult, because production is continuous and most farmers do not use any formal way of monitoring production. Allometric relationships for predicting bunch weights have been proposed (e.g. Woomer et al., 1999; Yamaguchi and Araki, 2004) but these regressions cannot be used in rapid monitoring of production because they would either require destructive sampling or would be time consuming (e.g. using a ladder to count all fingers). On-farm studies on constraints to production were carried out in a few fields only, which may not be representative for the entire region. For the few studies that covered a larger geographical area (e.g. Bekunda and Woomer, 1996; Bagamba, 2007), production data used was based on farmer estimates collected during single visit surveys. Such surveys take a snapshot picture of production and constraints, whereas yields and constraints show large temporal variations (Birabwa et al., 2010). Most studies on pests (e.g. Rukazambuga et al., 1998; Speijer and Kajumba,

2000) were conducted on-station under controlled environments, where pest pressure was artificially increased in some plots and eliminated in others.

Site specific recommendations which target existing constraints are crucial to achieve yield increases in the developing countries (Cassman, 1999). Such recommendations should be specific to a geographical region having similar comparative advantages, based on similar agro-climatic conditions, access to markets and populations (Pender et al., 2004). Development of such recommendations requires identification of the most limiting constraints. Several authors suggested that some factors are more limiting than others (Smithson et al., 2001; McIntyre et al., 2000) but the effects of the different constraints on yield have not been partitioned.

Despite declining banana yields, soil nutrient mining due to increased banana commercialization, and the existence of blanket fertilizer recommendations, on-farm fertilizer use in Uganda is extremely low (<2 kg hectare$^{-1}$ of arable land in 2002, Camara and Heinmann, 2006). Since high fertilizer prices are the major bottleneck to its adoption (Omamo, 2003), there is need to develop more profitable fertilizer recommendations that target primary nutrient deficiencies. Development of such recommendations requires tools for identification of plant nutrient imbalances. The nutrient norms currently in existence for diagnosis of nutrient imbalance in AAA-EA cultivars, derived by Wortmann et al. (1994), were based on data that was limited to the Kagera region in Northwest Tanzania and may not be applicable for Uganda.

## 4. Study objectives

Although banana production systems are better understood due to the numerous studies carried out, information gaps still exist. Literature is scarce on the relative importance of biophysical constraints, interactions and geographic and temporal distribution. Furthermore, recommendations addressing these constraints do not take into account biophysical and socio-economic differences among farms. There is need, therefore, to identify sustainable agronomic interventions which are problem specific and take into account the existing biophysical and socio-economic limitations of producers.

The key hypothesis of this thesis is that biophysical constraints and interventions addressing these constraints differ in importance among major banana growing regions in Uganda while successful adoption/adaptation of interventions aimed at closing the yield gap is highly influenced by regional variations in their profitability and farmer-perceived opportunities and constraints. The overall objective of this thesis was to generate technologies and information that researchers and farmers can use to improve the productivity, profitability, and sustainability of banana-based systems. To achieve this, the following research questions were formulated:

1 What are the current yields and yield gaps in farmer fields in Uganda? This question required:
   a) Development of a tool for quantifying banana production.
   b) Monitoring on-farm banana production.
2 What are the important production constraints and what is their contribution to the yield gap? This question required :
   a) Development of a tool for diagnosing nutrient imbalances in *Musa* spp., AAA-EA.
   b) Use of a boundary line approach to calculate yield gaps.
3 How do current blanket recommendations/technologies demonstrated in farmers' fields by non-governmental organizations (NGOs) address these constraints?
4 What is the impact of these recommendations/ technologies on productivity and profitability?
5 What are the important factors that impact on adoption/ adaptation of these technologies/ recommendations?

The research questions listed above were addressed using a combination of on-farm monitoring, household and farm surveys, and focus group discussions in Central, South, Southwest and East, Uganda. Demonstration plots established in 2004 by the Agricultural Productivity Enhancement Program (APEP) and nearby control plots were monitored for a period of one year (2006-2007). Additional farmers' plots were surveyed during the same period in order to have a large dataset. Data from on-farm monitoring and farm surveys was useful in address the first four research questions. Carrying out household surveys and focus group discussions in 2008 provided information from farmers for use in addressing the fifth research question.

In Chapter 2, the tool for quantifying bunch weight is derived (Question 1a) based on data from on-farm monitoring (Question 1b). The reliability of the relationship in estimating bunch weights while taking into consideration genotypic, developmental and spatial variability is assessed. This relationship is then used in the calculation of yield data, where data are missing. Chapter 3 addresses Question 2a by developing Compositional Nutrient Diagnosis (CND) and Diagnosis and Recommendation Integrated System (DRIS) norms for use in diagnosing of nutrient imbalance in *Musa* spp., AAA-EA.

In Chapter 4, the first research question "What are the current yields and yield gaps in farmer fields in Uganda?" is discussed. The second research question "What are the important production constraints and what is their contribution to the yield gaps?" is addressed in Chapter 4 and 5. In Chapter 4, the boundary line approach (Question 2b) is used to identify the relative important of factors limiting banana production in Central, South and Southwest Uganda, the possible yield gap attributed to each of these factors is quantified and then proportions of farms in which these factors are limiting is calculated using data from on-farm monitoring. The constraints to production in East are not explored in this Chapter because the data from the region was inadequate for the boundary line analytical approach used in this chapter. In Chapter 5, CND norms are used to diagnose nutrient imbalances in the four regions. Chapter 5 also addresses the third research question "How current blanket recommendations/technologies demonstrated in farmers' fields by NGOs address these constraints?" and the fourth research question "What is the impact of these recommendations/ technologies on productivity and profitability?".

The fifth research question "What are the important factors that impact on adoption/ adaptation of these technologies/ recommendations?" is discussed in Chapter 6. We combined the results of household surveys and focus group discussions to identify the drivers of adoption of these technologies/recommendations.

Finally, in Chapter 7, the main findings of the thesis and their implications for sustainably increasing banana yields are discussed, and suggestions are made for future research.

# Chapter 2

## Quantifying bunch weights of the East African banana (*Musa* spp. AAA) using non-destructive field observations

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## Abstract

In banana on-farm studies in the East African highlands, quantification of production has been difficult because plants are at different stages of development at any given time. Production is continuous and quantification would therefore require permanent presence of an observer. Hence, most on-farm surveys have resorted to estimations from farmers or 'experts' through recall or visual qualitative observations. These methods are highly inaccurate. This study aims to develop and validate allometric relationships for quantitative estimation of bunch weights, based on rapid, inexpensive and non-destructive methods of data collection that take into consideration genotypic, spatial and developmental variability. The study was conducted in 179 farmer fields in Central, South, Southwest, and East Uganda. Bunch weights were estimated through linear regression with log-transformed girth of pseudostem at base and 1 m, number of hands, and number of fingers in the lower row of the second lowest hand. The number of hands and fingers relate to the potential sink size (i.e. bunch), and the girth at base and 1 m were used as a proxy for pseudostem volume, which relates to the potential of the plant to fill the sink. Bunch weight was significantly ($P \leq 0.001$) and positively ($R^2 = 0.73$) related to log-transformed pseudostem volume, and number of hands and fingers. When data were partitioned and regressed, regression coefficients did not differ significantly for cultivars (i.e. Enyeru, Kibuzi, Nakabululu and Nakitembe), developmental stages (flowering, early fruiting, late fruiting and full maturity), regions (Central, South, Southwest and East Uganda), foliar and soil N, P, K, Ca and Mg concentrations. Data partitioning improved the accuracy of prediction significantly for different cultivars, regions, and foliar Ca, but not for bunch developmental stages, foliar N, P, K and Mg and soil N, P, K, Ca and Mg concentrations. However, the residuals of all the regressions of partitioned data correlated highly ($R^2$ between 0.92 and 1.00) to those of the regression based on pooled data. On validation of the regression based on pooled data, the bias (-9.97%) and modeling efficiency statistic (0.64), suggested that predictions were not always accurate. Still, the total predicted bunch weights were higher than the observed bunch weight by only 2%. This study therefore concludes that the regression derived using pooled data is suitable for on-farm prediction of bunch weight, for the East African highland cooking banana, regardless of genotypic, developmental and spatial variations.


**Keywords:** General regression; Specific regressions; Banana cultivars; Regions; Soil nutrients; Foliar nutrients; Bunch development stages

# 1. Introduction

The East African highland bananas (AAA-EA) are the major banana groups in Uganda (Karamura, 1998), primarily used for cooking and juice extraction. Bananas are a primary food and cash crop (Edmeades, 2006) occupying up to 30% of the total area under cultivation in Uganda (Rojas, 1998), where they are primarily produced by millions of smallholder farmers. However, production is poor compared with potential yield (van Asten et al., 2005) and has been declining (FAO, 2007).

There has been an increasing effort from the agricultural research community in the region to try to understand what causes the poor yields, in an effort to formulate improved crop management recommendations (van Asten et al., 2005). Much of this research has been conducted on-farm. However, on-farm quantification of production has proven to be very difficult, because production is continuous; i.e. plants in farmers' fields are at different stages of development at any given point in time. If harvesting was synchronized and occurred during a particular time of the year, farm visits at time of harvesting, to capture production information, would be feasible. Since most farmers do not use any formal way of monitoring production (e.g. farmers rarely use weighing scales for bananas), quantification of production would require researchers to be permanently present at the farm, to capture bunch weights when farmers decide to harvest. Supplying farmers with scales, for data collection over a period of time, also has severe limitations; e.g. (i) farmers often have gaps in the data collected due to labour constraints, (ii) data are entered incorrectly either accidentally or on purpose (i.e. the latter often occurs if farmers are remunerated), and (iii) many smallholder farmers are illiterate. Limiting studies to farms managed by literate farmers only may severely bias the research results, since education level, access to resources, crop and soil management practices, and yields are often strongly positively correlated (van Asten et al., 2010a).

Despite the severe constraints related to quantifying production based on qualitative visual observations, most researchers have used this method, because no alternative rapid methods to quantify production were available. Production data used by Bekunda and Woomer (1996), Sseguya et al. (1999) and Bagamba (2007) among other studies were based on-farmer estimates. Estimation of bunch weights using visual assessment saves time but is prone to human error and can only be feasible for detecting large differences in production (Smith et al., 2001) on a semi quantitative basis.

An alternative approach would be to use allometric relationships between different plant parts and bunch weight to quantify production in a non-destructive way. Such relationships should be based on variables that can be quantified easily using rapid, inexpensive and non-destructive methods of data collection. The relationship between bunch weight and other plant characteristics has been explored previously. Bunch weight and circumference of pseudostem were positively ($r$ = 0.63–0.85) and highly correlated ($P$ < 0.01) for different varieties in a study by Mukasa et al. (2005). In Woomer et al. (1999), total number of fingers and bunch volume were observed to be good predictors of bunch weight for different management systems and years ($R^2$ = 0.80–0.96 for fingers and $R^2$ = 0.57–0.90 for volume). However, these regressions cannot be used in rapid monitoring of production because they would either require destructive sampling (i.e. volume) or would be time consuming (e.g. using a ladder to count all fingers). On the other hand, some of the parameters can be estimated to avoid destructive sampling. For example, the number of fingers can be estimated using the method devised by Turner et al. (1988). The method relates number of fingers on bunches to number of fingers in third hand from top of the bunch, number of fingers in the second hand from the bottom of the bunch, and number of hands.

Yamaguchi and Araki (2004) also derived allometric relations to predict bunch weight. Despite the high $R^2$ (0.93–1.00) of the regressions, their method had several shortcomings; i.e. (i) it was based on complete destructive sampling of the plant, (ii) the allometric relationships were based on a small sample size of 14 plants, (iii) spatial variability was not taken into account, and (iv) and the average bunch weight of 32 kg was relatively high compared with average weights of 9.8 (South Uganda) and 11.0 kg (Central Uganda) reported by Wairegi et al. (2007) in Uganda. Another shortcoming is that prediction of bunch weight required several steps.

It is likely that allometric relationships to estimate bunch weights are influenced by genotypic, developmental, spatial and environmental variations. It has been reported that pseudostem girth and number of hands and fingers vary with cultivar (Karamura, 1998) while pseudostem girth decreases as the developing bunch fills (Bosch et al., 1996). Climate and soil properties, which are known to vary with regions, have also been reported to affect plant parameters. Low temperature increased pseudostem girth and reduced number of hands (Arunachalam et al., 1976) while bunch weight was increased by N (Arunachalam et al., 1976; Weerasinghe et al., 2004).

The objectives of the study are to develop and validate allometric relationships for estimating bunch weight based on rapid, quantitative, and non-destructive measurements on standing plants in the field. This study also wishes to evaluate whether a general allometric relationship can be used, or whether relationships need to be developed that take into consideration genotypic, bunch developmental, and site variability (i.e. differences in climate and soil/plant nutrient concentrations).

## 2. Materials and methods

### 2.1 Study area

The study was carried out in179 plots, in mature plantations (5 to over 50 years), in Central, South, Southwest and East Uganda. The area lies approximately between latitudes 1º30’ N and 1º00’ S and longitude 29º52’ and 34º30’ E at an altitude of 1120–1700m above sea level. Of these plots, 95 were ‘demonstration’ from an extension programme (Wairegi et al., 2007), while the rest were ‘control’ plots, representing farmer practices. Control plots received animal manure (38% of the plots) and external mulch (13%) but no fertilizer, whereas demonstration plots received manure (46%), mulch (53%) and inorganic fertilizer (100%, with N, P and K averaging 71, 8 and 32 kg $ha^{-1}$ $year^{-1}$). Control plots were selected adjacent to demonstration plots, either within or near the farms that hosted such plots.

### 2.2 Data collection

Data on bunch weights and other plant characteristics were collected over a period of 12 months in 2006–2007. Within each plot, 30 mats of East African highland banana cooking varieties were randomly selected for monitoring. These mats were numbered and cultivars recorded. For bunch-bearing plants (flowering to harvest period) within these mats, girth of pseudostem at base ($G_{base}$, in cm) and 100 cm height ($G_{1m}$, in cm), number of hands (*Hands*), number of fingers in the lower row of the second lowest hand (*Fingers*) and bunch development stage were recorded. Here, $G_{base}$ was measured where the outer leaf sheaths of the pseudostem joined the corm. If the corm was below the soil surface, then $G_{base}$ would be measured at the soil surface. For $G_{1m}$ measurements, loose leaf sheaths with strongly shrivelled margins would be removed, while healthy loose leaf sheaths would be forced back onto the pseudostem and included in the measurement. The last group of flowers that appeared to develop at least three healthy fingers was considered as the last hand of a bunch. Bunch development stages were recorded as (1) flowering (flowers fresh to start of drying), (2) early fruiting (flowers dried up to finger filling started but spaces still visible between fingers), (3) late fruiting (finger filling continuing to lines on fingers start changing from angular to rounded) and (4) full maturity (ready for harvesting, finger lines more rounded than angular). Farmers were trained to record data on bunch weights (*Bwt*, in kg) at harvest using weighing scales provided free of charge. At harvesting, the pseudostem was partially cut to allow the bunch to descend slowly under its own weight. The peduncle was then cut off at the point where it entered the pseudostem. In order to avoid tampering of data, farmers did not receive payment for the records.

### 2.3 Analytical approach

A three-step analytical approach was used. In first step, models were evaluated to determine the most suitable form for the allometric regressions. Next, the performance of the selected model was evaluated across different variables (e.g. spatial and genotypic) using the same data set used to evaluate models. Finally, an independent data set was used to validate the model. A similar approach was used in cotton and grape studies by Akram-Ghaderi and Soltani (2007) and Castelan-Estrada et al. (2002), respectively.

The data from demonstration plots were first pooled and then grouped according to cultivars, bunch development stages, regions and foliar and soil nutrient concentrations. For each of the foliar and soil nutrients, high and low nutrient groups were formed with one group having concentrations below and including the median and the other concentrations above the median. The partitioning was done at the median because the data were not always normally distributed.

Next, the allometric relationships between *Bwt* and $G_{base}$, $G_{1m}$, *Hands* and *Fingers*, for the pooled non-transformed and transformed data, were first examined graphically. Thereafter, relationships were explored using the stepwise method of linear regression analysis. Stepwise regression analysis automatically selects all significant parameters (Miles and Shevlin, 2001). The best regression model was selected on the basis of the highest adjusted coefficient of determination (adjusted $R^2$) and low multicollinearity. High multicollinearity between regression parameters is not considered appropriate; some statisticians suggest that variance inflation factors (VIFs) exceeding 5 or 10 indicate high multicollinearity (Montgomery and Peck, 1992). This study decided to consider VIF values above 5 as high. The regression equation derived for pooled data using the selected model is from this point referred to as the ‘general regression’.

Using the selected model, specific regressions were derived for four selected cultivars, bunch development stages, regions, and low and high foliar and soil nutrient concentrations. Although cultivar selection primarily targeted those with high number of observations, attempts were made to select cultivars that represented the range of different EA-AAA banana clone sets (Karamura, 1998). Statistical and graphical methods were used to determine whether the specific regressions differed from each other and how well the general regression compared with these regressions. Different methods were used because there does not seem to be a set method for determining the suitability of a general regression when compared with specific regressions.

In the first method, specific regressions within a group were compared with each other using coefficient confidence intervals. Regressions were similar if the coefficients did not differ significantly based on confidence intervals (Akram-Ghaderi and Soltani, 2007).

In the second method, the suitability of the general regression compared with specific regressions was determined using $F$-test according to the method described by Brahim et al. (2000) who derived his approach from Tomassone et al. (1983) and Fonweban and Houllier (1997). Residual sum of squares (RSS) of the general regression was compared with the summed RSS of the specific regressions. The observed $F$-value was calculated as

$$F\text{ observed}=\left[\left[\frac{\mathrm{RSS}-\sum_{i=1}^{r}\mathrm{RSS}_i}{\mathrm{df}-\sum_{i=1}^{r}\mathrm{df}_i}\right]\Big/\left[\frac{\sum_{i=1}^{r}\mathrm{RSS}_i}{\sum_{i=1}^{r}\mathrm{df}_i}\right]\right] \tag{1}$$

where RSS and df are the residual sum of square and degrees of freedom of the general regression, respectively, $\mathrm{RSS}_i$ and $\mathrm{df}_i$ are the residual sum of square and degrees of freedom of the $i^{\text{th}}$ specific regression, respectively, and $r$ are the number of specific regressions. The observed $F$-value was then compared with the theoretical $F$-value at $v_1$ and $v_2$ degrees of freedom, where

$$v_1=\mathrm{df}-\sum_{i=1}^{r}\mathrm{df}_i \tag{2}$$

$$v_2=\sum_{i=1}^{r}\mathrm{df}_i \tag{3}$$

Since our study assumed that specific regressions gave more accurate predictions than the general regression, the $F$-test was one-tailed.

The third method checked whether the general and specific regressions predicted the same values by plotting the residuals for the former ($x$-axis) against those of the latter ($y$-axis) and fitting a regression line. This regression line was evaluated for bias using the simultaneous $F$-test for zero intercept and unit slope (Dent and Blackie, 1979; Mayer et al., 1994). A major drawback of this method highlighted in Harrison (1990) is the fact that low residual variation, as would be the case if the $x$ and $y$ pairs were closely related, can lead to the test conclusion that the regressions are not closely related.

Some 320 observations from control plots were used for validation of the general regression. Untransformed predicted and observed bunch weight values were compared using graphical and statistical tests. First, these predicted values were plotted against observed values and a regression line showing relationship was fitted. This line was evaluated for bias (Dent and Blackie, 1979; Mayer et al., 1994). Next, the deviations of predictions from observations were further explored using percent bias (Arevalo et al., 2007) calculated as:

$$\%\,\text{Bias} = \left( \sum_{i=1}^{n} \frac{x_i - y_i}{x_i} \right) \times \frac{100}{n} \tag{4}$$

where $x_i$ and $y_i$ are the observed and predicted bunch weights for the $i^{\text{th}}$ observation, respectively, and $n$ are the number of $x$ and $y$ pairs. A positive bias indicates under estimation while a negative bias indicates overestimation.

Lastly, the general regression was evaluated using the modeling efficiency statistic (EF) (Loague and Green, 1991) calculated as:

$$EF = 1 - \frac{\sum_{i=1}^{n} \left( x_i - y_i \right)^2}{\sum_{i=1}^{n} \left( x_i - \bar{x} \right)^2} \tag{5}$$

where $\bar{x}$ is the mean of the observed bunch weight. The maximum value for EF is one while an EF less than zero indicates that the model predicted values are worse than simply using the observed mean (Loague and Green, 1991). Regression analyses were carried out using the SPSS for Windows 12.0 software. The $F$-tests, %Bias and EF were calculated with Microsoft Office Excel 2003.

# 3. Results

## 3.1 Descriptives and grouping variables

For the pooled data (Table 1), the $G_{base}$ and $G_{1m}$ averaged 72 and 57 cm, respectively while both *Hands* and *Fingers* averaged 8 and *Bwt* averaged 19 kg. Across the regions, the least and highest bunch weight was in Central and East, respectively.

Cultivar selection and partitioning of foliar and soil nutrients into low and high concentrations require mention. Three (Enyeru, Kibuzi and Nakitembe) out of the 39 cultivars that were in the database, had the highest number of observations (255, 138 and 143, respectively). Although Enyeru, Kibuzi and Nakitembe belong to Nfuuka, Nakabululu and Nakitembe clone sets, respectively, Kibuzi has some characteristics of the Nakitembe clone set (Karamura, 1998). Hence Nakabululu was selected, despite having low observations (40), because it distinctly belongs to the Nakabululu clone set. Median values used for N, P, K, Ca and Mg concentrations were 2.80%, 0.20%, 3.77%, 0.93% and 0.47%, respectively for foliar and 0.19%, 33.84 ppm, 1.71 $cmol_c$ $kg^{-1}$, 14.04 $cmol_c$ $kg^{-1}$ and 4.67 $cmol_c$ $kg^{-1}$ for soil.

## 3.2 Determination of the allometric regression model

Graphs depicting the relationship between *Bwt* and the other plant parameters suggested more of a 'power' than 'linear' relationship. Graphs relating *Bwt* to $G_{base}$ and $G_{1m}$ are presented in Figure 1. The $R^2$ value was 0.61 and 0.65 for $G_{base}$, 0.62 and 0.66 for $G_{1m}$, 0.47 and 0.52 for *Hands* and 0.33 and 0.38 for *Fingers*, for the linear and ''power'' relations, respectively. Although the $R^2$ for ''power'' relations were higher than those for linear relations for all parameters, the differences were not significant ($P \leq 0.05$).

After exploring several stepwise regressions using different combinations of non-transformed and transformed parameters, the models derived using transformed parameters (Table 2) were found to have better fit than those derived using non-transformed parameters (not presented). In the stepwise regression process, the first model related *Bwt* to $G_{1m}$, while the second, third and fourth models added *Hands*, *Fingers* and $G_{base}$, respectively, to the predictors. These results suggested that bunch weight would be best predicted using all four parameters. Interestingly, further exploration of data showed that the order in which parameters were added to subsequent models during stepwise regression differed with cultivars, bunch development stages, regions and foliar and soil nutrient concentrations (data not

Table 1: Descriptive statistics for bananas in demonstration plots in Central, South, Southwest and East Uganda

| Region | *n* | $G_{base}$ | | | $G_{1m}$ | | | *Hands* | | | *Fingers* | | | *Bwt* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Min. | Max. | Mean | Min. | Max. | Mean | Min. | Max. | Mean | Min. | Max. | Mean | Min. | Max. | Mean |
| Central | 184 | 43 | 105 | 71 | 28 | 88 | 56 | 3 | 14 | 7 | 4 | 10 | 8 | 2 | 60 | 17 |
| South | 196 | 35 | 92 | 66 | 30 | 84 | 53 | 4 | 12 | 7 | 3 | 10 | 7 | 2 | 35 | 15 |
| Southwest | 308 | 50 | 105 | 75 | 37 | 95 | 59 | 4 | 14 | 8 | 5 | 10 | 8 | 4 | 46 | 22 |
| East | 38 | 66 | 102 | 82 | 51 | 82 | 64 | 6 | 12 | 10 | 4 | 10 | 8 | 10 | 47 | 27 |

n, $G_{base}$, $G_{1m}$, *Hands*, *Fingers* and *Bwt* denote number of observations, pseudostem girth at base (cm), pseusostem girth at 1m (cm), number of hands, number of fingers in the lower row of the second lowest hand and bunch weight (kg), respectively shown). Hence, the following regression model, which used all parameters to predict bunch weight, was assumed to have had the best prediction ability:

$$\ln(B_{wt}) = k + a \ln(G_{base}) + b \ln(G_{1m}) + c \ln(Hands) + d \ln(Fingers) \quad (6)$$

where $k$ is the intercept and $a$, $b$, $c$ and $d$ are parameter coefficients.

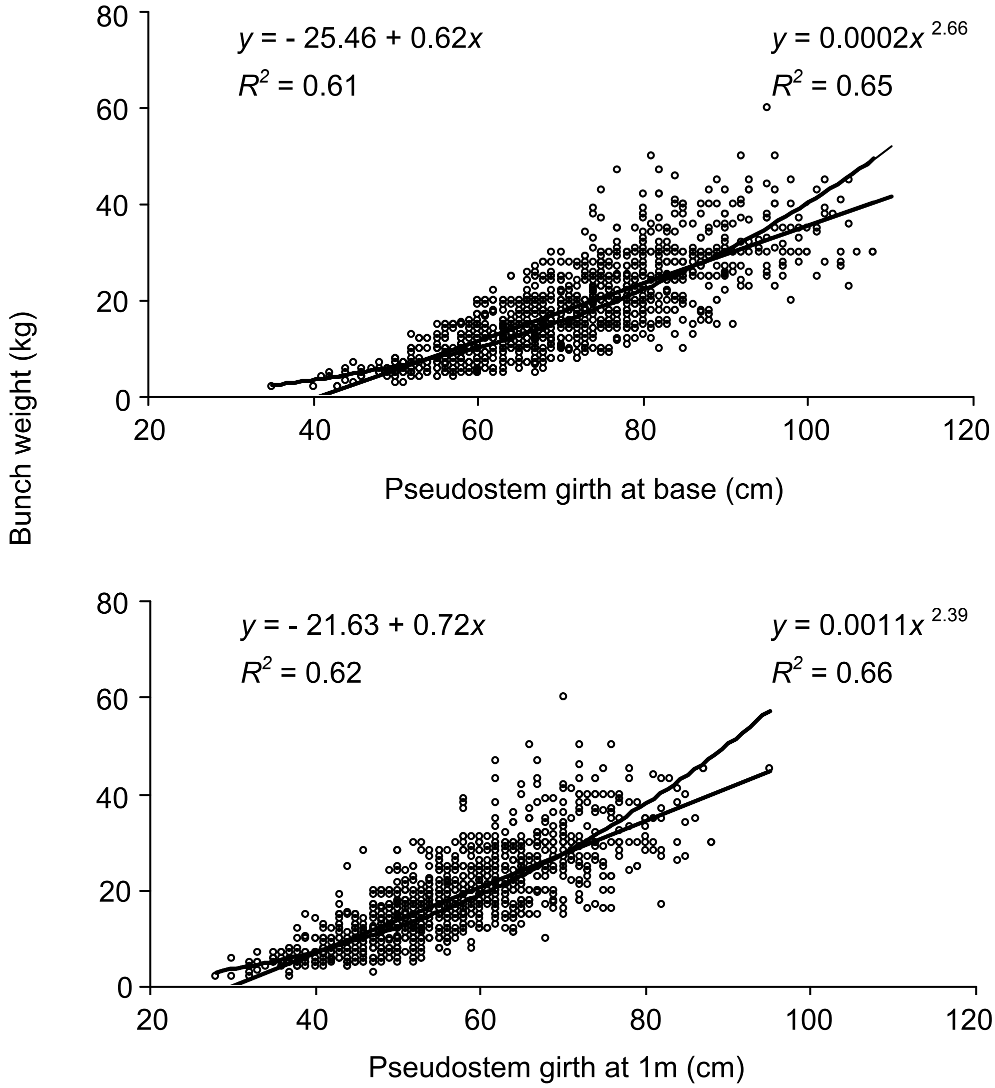


Figure 1: The relationship between bunch weight and pseudostem girth at base and 1 m. Linear and ‘‘power’’ relations lines are shown.

Table 2: Regression coefficients and adjusted $R^2$ for successive linear regression equations, for the pooled data, derived using stepwise method

| Model | *k* | *a* | *b* | *c* | *d* | $R^2$ |
|---|---|---|---|---|---|---|
| 1 | - 6.832 | | 2.395 | | | 0.66 |
| 2 | - 5.844 | | 1.770 | 0.759 | | 0.71 |
| 3 | - 6.022 | | 1.616 | 0.636 | 0.511 | 0.73 |
| 4 | - 6.795 | 0.755 | 1.059 | 0.569 | 0.478 | 0.73 |

*k* is the intercept and *a, b*, *c* and *d* are coefficients of the regression.
$\ln(B_{wt}) = k + a \ln(G_{base}) + b \ln(G_{1m}) + c \ln(Hands) + d \ln(Fingers)$ where *Bwt*, $G_{base}$, $G_{1m}$, *Hands* and *Fingers* are bunch weight (kg), pseudostem girth at base (cm), pseudostem girth at 1 m (cm), number of hands and number of fingers, respectively. All models were significant at $P \leq 0.001$.

Using the VIF, higher co-linearity was observed for $G_{base}$ (7.76) and $G_{1m}$ (7.26) compared with Hands (2.13) and Fingers (1.66). Instead of omitting one of the girth parameters from the regression, both were used to estimate the volume of the pseudostem from the base to 100 cm height ($Vol_{stem}$, in $cm^3$). This volume was assumed to be that of a truncated cone, whose circumferences were the two pseudostem girths, and was therefore calculated as:

$$Vol_{stem} = \frac{100}{12\pi}\left[G_{base}^2 + G_{1m}^2 + (G_{base} \times G_{1m})\right] \tag{7}$$

$Vol_{stem}$ subsequently replaced the two girth parameters giving a refined model

$$\ln(B_{wt}) = k + c \ln(Hands) + d \ln(Fingers) + f \ln(Vol_{stem}) \tag{8}$$

where $f$ is the coefficient for $Vol_{stem}$. This parameter had low co-linearity (2.19) with other parameters. The regression coefficients *k*, *c, d* and *f* had values of -8.908, 0.561, 0.482, and 0.925, respectively, 95% confidence intervals of 0.725, 0.133, 0.165, 0.090, respectively and were highly significant ($P \leq 0.001$). The adjusted $R^2$ for the model remained 0.73. The regression equations presented and discussed in this paper, from this point onward, are based on this model. We will refer to the regression based on all pooled data as the 'general regression'.

### 3.3 Comparison of the general regression with regressions specific to cultivars

The regressions of the four cultivars (Table 3) did not differ significantly based on the confidence intervals (95%) of the coefficients. However, the observed $F$-value was greater than the theoretical $F$-value for the comparison between the general regression and cultivar specific regressions ($P \leq 0.05$) as presented in Table 4. When the relationship between residuals of the general and cultivar specific regressions was compared graphically (Figure 2), the slope and $R^2$ of the fitted regression line were high for Enyeru (both parameters had values of 0.97) and low for other cultivars (slopes had values of 0.93, $R^2$ ranged 0.92-0.93). The absolute value of intercept was highest and lowest for Nakabululu (0.20) and Enyeru (0.05), respectively. The fitted lines for all cultivars differed significantly from the line of zero intercept and unit slope ($P \leq 0.05$).

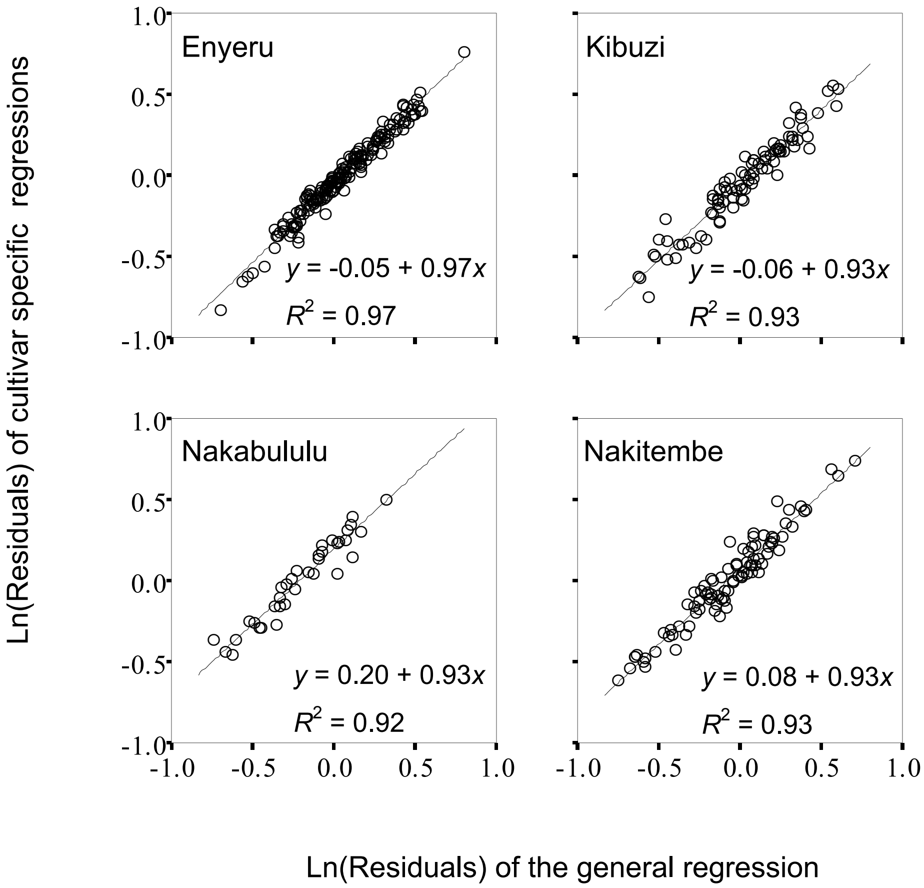


Figure 2: The relationship between the residuals of the general regression and cultivar specific regressions for Enyeru, Kibuzi, Nakabululu and Nakitembe. The fitted lines differ significantly from the $y = x$ line ($P \leq 0.05$).

Table 3: Regression coefficients (±95% confidence intervals) and adjusted $R^2$ of regressions for selected cultivars, stages of bunch development and regions.

| Variable | *k* | *c* | *d* | *f* | $R^2$ | *n* |
|---|---|---|---|---|---|---|
| Cultivars | | | | | | |
| Enyeru | - 7.205 ±1.500 | 0.619±0.317 | 0.513±0.371 | 0.750±0.203 | 0.69 | 176 |
| Kibuzi | - 11.014±2.497 | 0.688±0.387 | -0.009±0.555 | 1.207±0.296 | 0.71 | 89 |
| Nakabululu | - 7.266±4.584 | 0.429±0.641 | 0.361± 0.665 | 0.793±0.553 | 0.57 | 35 |
| Nakitembe | - 9.615±2.048 | 0.847±0.425 | 0.560±0.496 | 0.916±0.273 | 0.81 | 89 |
| Stages | | | | | | |
| Flowering | - 11.506±3.175 | 0.252±0.607 | 0.229±0.730 | 1.279±0.410 | 0.72 | 51 |
| Early fruiting | - 8.121±1.062 | 0.487±0.208 | 0.567±0.258 | 0.847±0.127 | 0.68 | 323 |
| Late fruiting | - 8.745±1.387 | 0.540±0.261 | 0.665±0.368 | 0.878±0.176 | 0.74 | 214 |
| Full maturity | - 9.898 ±1.744 | 0.593±0.327 | 0.360±0.329 | 1.039±0.217 | 0.78 | 138 |
| Regions | | | | | | |
| Central | - 9.924±1.362 | 0.280±0.258 | 0.659±0.347 | 1.035±0.171 | 0.75 | 184 |
| South | - 8.453±1.523 | 0.609±0.262 | 0.257±0.298 | 0.913±0.181 | 0.66 | 196 |
| Southwest | - 8.064±1.151 | 0.544±0.238 | 0.590±0.275 | 0.830±0.149 | 0.67 | 308 |
| East | - 7.231±4.033 | 0.414±0.581 | 0.391±0.592 | 0.821±0.383 | 0.44 | 38 |

*k* is the intercept and *c*, *d* and *f* are coefficients of the regression
$\ln(B_{wt}) = k + c\ \ln(Hands) + d\ \ln(Fingers) + f\ \ln(Vol_{stem})$, where *Bwt*, *Hands*, *fingers* and $Vol_{stem}$ are bunch weight (kg), number of hands, number of fingers and volume of pseudostem ($cm^3$), respectively. All regressions were significant at $P\leq0.001$.

### 3.4 Comparison of the general regression with regressions specific to developmental stages

The confidence intervals (95%) for the coefficients for all the developmental stage specific regressions indicated that there were no significant differences between the regressions (Table 3). Also, for the comparison between the general and specific regressions, the observed *F*-value ($P \leq 0.05$) was less than the theoretical *F*-value, when these regressions were compared with the general regression (Table 4). The fitted lines depicting the relationship between the residuals of the general and developmental stage specific regressions had intercepts ranging -0.01 to 0.06 while both gradients and $R^2$ ranged 0.94–1.00 (Figure 3). These fitted lines differed significantly from the line of zero intercept and unit slope ($P \leq 0.05$).

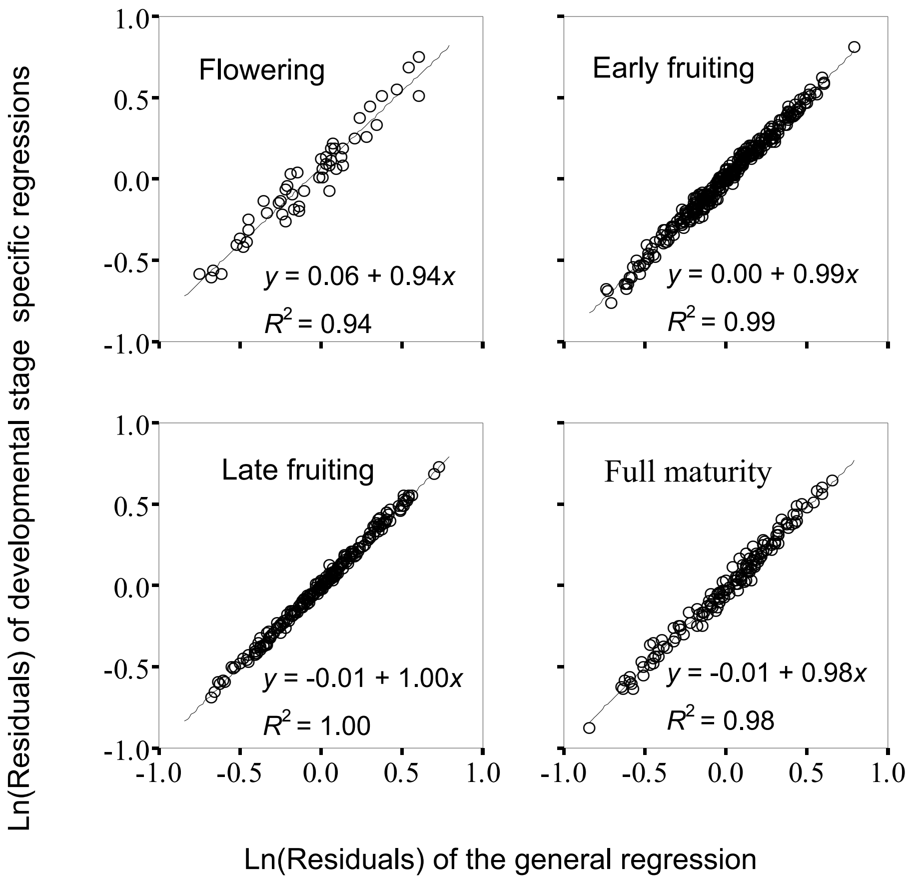


Figure 3: The relationship between the residuals of the general regression and developmental stage specific regressions for flowering, early fruiting, late fruiting and full maturity. The fitted lines differ significantly from the $y = x$ line ($P \leq 0.05$).

### 3.5 Comparison of the general regression with regressions specific to regions

Based on the confidence intervals for the coefficients (95%), the regressions for all regions did not differ significantly (Table 3). The observed *F*-value was greater than the theoretical *F*-value ($P \leq 0.05$) for the comparison between the general and specific regressions for these regressions (Table 4). The fitted lines of the graphs showing the relationship between the residuals of the general and region specific regressions (Figure 4) had the lowest absolute value of intercept in the Central (0.02) and the highest in East (0.05). The slope and $R^2$ values were high in South (1.01) and Southwest (0.99), respectively, and low in Central and East (both parameters had values of 0.97). All the fitted lines differed significantly from the line of zero intercept and unit slope ($P \leq 0.05$).

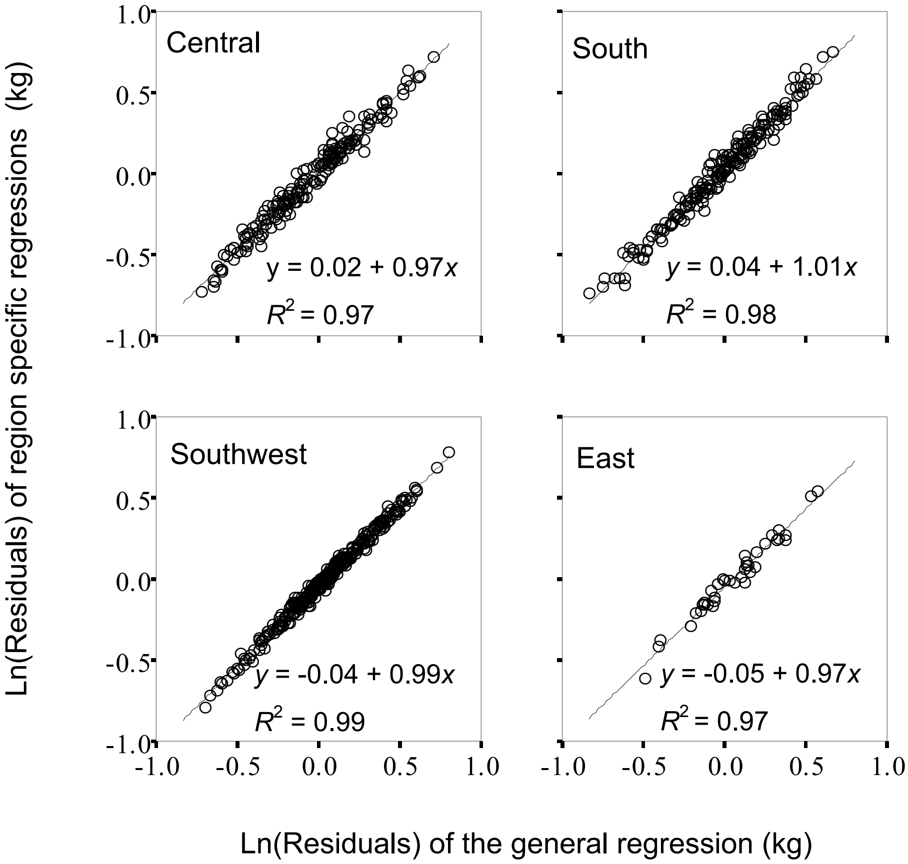


Figure 4: The relationship between the residuals of the general regression and region specific regressions for central, south, southwest and east. The fitted lines differ significantly from the $y = x$ line ($P \leq 0.05$).

Table 4: Comparison of the general regression with specific regressions for cultivar (1 = Enyeru, 2 = Kibuzi, 3 = Nakabululu, 4 = Nakitembe), stage of bunch development (1 = flowering, 2 = early fruiting, 3 = late fruiting, 4 = full maturity), and region (1 = Central, 2 = South, 3 = Southwest, 4 = East)

| Variable | Specific regression1 | | Specific regression2 | | Specific regression3 | | Specific regression4 | | observed *F* |
|---|---|---|---|---|---|---|---|---|---|
| | $RSS_1$ | $df_1$ | $RSS_2$ | $df_2$ | $RSS_3$ | $df_3$ | $RSS_4$ | $df_4$ | |
| Cultivars | 11.08 | 172 | 6.91 | 85 | 2.24 | 31 | 7.33 | 85 | 1.38* |
| Stages | 5.19 | 47 | 24.25 | 319 | 17.84 | 209 | 12.88 | 134 | 2.60 |
| Regions | 16.72 | 180 | 17.87 | 191 | 22.39 | 304 | 2.14 | 34 | 4.75* |

RSS and df are residual sum of squares and degrees of freedom, respectively. The general regression RSS and df are 61.465 and 721, respectively. * denotes significant difference ($P≤0.05$) between the general and specific regressions.

### 3.6 Comparison of the general regression with regressions specific to foliar nutrient concentrations

For foliar nutrient concentrations, adjusted $R^2$ for specific regressions ranged 0.71–0.76 and there were no significant differences in regression coefficients between low and high nutrient concentrations based on confidence intervals (95%) for all nutrients (data not shown). The observed *F*-value was lesser than the theoretical *F*-value ($P≤0.05$) for N, P, K and Mg, and greater for Ca, when the general regression was compared with specific regressions (Table 5). Although the graphs showing the relationship between residuals of the general and specific regressions are not presented here, the fitted lines in these graphs had intercepts ranging -0.02 to 0.02, while slopes and $R^2$ both ranged 0.99–1.00. The fitted lines all differed from the line of zero intercept and unit slope ($P≤0.05$).

### 3.7 Comparison of the general regression with regressions specific to soil nutrient concentrations

For soil nutrient concentrations, adjusted $R^2$ for specific regressions ranged 0.67–0.77 and there were no significant differences in regression coefficients between low and high nutrient concentrations based on confidence intervals (95%) for all nutrients (data not shown). The observed *F*-value ($P≤0.05$) was lesser than the theoretical *F*-value, for all nutrients, when the general regression was compared with specific regressions (Table 6). Although the graphs are not presented here, the regression lines showing the relationship betweens the residuals of the general and nutrient concentration groups had intercepts of -0.01 to 0.03 while slopes and $R^2$ ranged 0.99–1.00. All lines except for low Ca concentrations differed from the line of zero intercept and unit slope ($P \leq 0.05$).

Table 5: Comparison of the general regression with specific regressions for foliar nutrient concentrations (1 = low nutrient concentrations, 2 = high nutrient concentrations).

| | Specific regression1 | | Specific regression 2 | | observed *F* |
|---|---|---|---|---|---|
| | $RSS_1$ | $df_1$ | $RSS_2$ | $df_2$ | |
| N | 29.731 | 351 | 31.198 | 362 | 0.97 |
| P | 31.926 | 395 | 28.674 | 318 | 1.40 |
| K | 31.428 | 359 | 29.197 | 354 | 1.37 |
| Ca | 34.325 | 380 | 25.811 | 333 | 2.03* |
| Mg | 33.791 | 362 | 26.541 | 351 | 1.76 |

RSS and df are residual sum of squares and degrees of freedom, respectively. The general regression RSS and df are 61.465 and 721, respectively. * denotes significant difference ($P \leq 0.05$) between the general and specific regressions.

Table 6: Comparison of the general regression with specific regressions for soil nutrient concentrations (1= low nutrient concentrations, 2 = high nutrient concentrations).

| | Specific regression1 | | Specific regression 2 | | observed *F* |
|---|---|---|---|---|---|
| | $RSS_1$ | $df_1$ | $RSS_2$ | $df_2$ | |
| N | 35.686 | 409 | 25.140 | 298 | 0.66 |
| P | 28.947 | 359 | 31.976 | 348 | 0.58 |
| K | 31.213 | 385 | 28.914 | 322 | 1.21 |
| Ca | 30.975 | 359 | 29.843 | 348 | 0.66 |
| Mg | 30.125 | 359 | 30.225 | 348 | 1.03 |

RSS and df are residual sum of squares and degrees of freedom, respectively. The general regression RSS and df are 61.465 and 721, respectively. * denotes significant difference ($P \leq 0.05$) between the general and specific regressions.

### 3.7 Validation

The general regression was validated using data from the control plots. The observed and predicted bunch weights ranged 2– 44 and 3–47 kg, respectively, with means of 16 and 17 kg, respectively, while the total sum was 5244 and 5348 kg, respectively. The regression line showing the relationship between observed and predicted bunch weights had an intercept, slope and $R^2$ of 3.59, 0.80 and 0.67, respectively (Figure 5). The line differed significantly from the line of zero intercept and unit slope ($P \leq 0.05$). The bias and EF were -9.97% and 0.64, respectively.

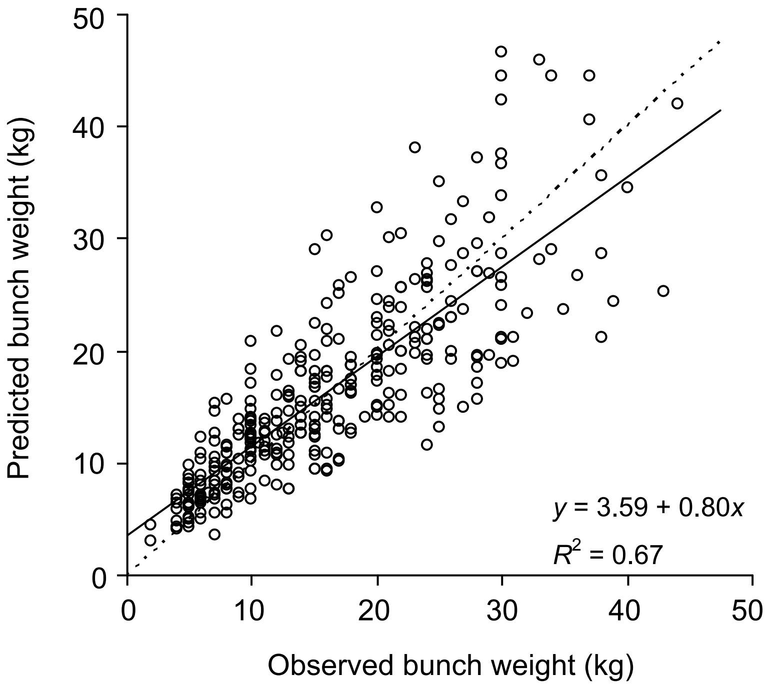


Figure 5: Comparison of observed and predicted bunch weight (kg) from validation data. The dotted line depicts the $y = x$ relationship while the solid line depicts the relationship between observed and predicted values. The fitted line differs significantly from the $y = x$ line ($P \leq 0.05$).

## 4. Discussion

The objectives of the study were to develop and validate a tool that can be used for rapid and non-destructive estimation of bunch weights. In the paragraphs below we will discuss the model structure and fit, then evaluate whether there is a need to take into consideration genotypic, bunch developmental, spatial, and plant and soil nutrient status variability when estimating bunch weights, and finally evaluate how the model works on an independent data set.

### 4.1 The allometric model

Using pooled data, stepwise regression analysis was used to determine the most suitable form for the allometric regressions. The process retained all four parameters in a regression which had an adjusted $R^2$ of 0.73. The parameters retained in order of importance were $G_{1m}$, *Hands*, *Fingers*, and $G_{base}$ (see Table 2). The model based on $G_{1m}$ and *Hands* only already achieved a good adjusted $R^2$ (= 0.71), so it could be considered as a slightly less labour intensive alternative for bunch weight estimations. However, stepwise regression analysis of distinct groups of cultivars, sites, and bunch development stages showed that the model that included all four parameters was the most robust. Use of simpler models based on fewer parameters (e.g. $G_{1m}$ and *Hands*) would not consistently yield good predictions for certain data sets that differed in sites, cultivars, and bunch development stages (data not shown). For example, some cultivar groups would give better predictions with $G_{base}$ instead of $G_{1m}$ (data not shown), contrary to what we found for the model derived using pooled data. We therefore believe that for certain conditions (i.e. for certain sites, cultivars and bunch development stages), a model with fewer parameters would have reduced predictive value compared with a model in which all parameters are included. Although combining $G_{base}$ and $G_{1m}$ into a pseudostem volume parameter did not lead to a further increase in the adjusted $R^2$, it is generally considered inappropriate to keep two parameters with high co-linearity in one regression function (Montgomery and Peck, 1992).

The fact that logarithmic transformation of data improved the fit of the regression is in agreement with findings in other biological studies such as West et al. (1997), Niklas and Enquist (2002) and Castelan-Estrada et al. (2002). Further improvement of the fit may be difficult; although the number of hands and fingers indicate the potential size of the sink, while pseudostem volume could be considered as a proxy for the potential of the plant to fill the sink, translocation of resources to the bunch is not only depending on pseudostem volume, but also on the number and size of the functional leaves. At mat level, the mother plant normally translocates resources to developing suckers, although after flowering bunch filling has priority over the sucker (Dens et al., 2008). Better fits ($R^2 > 0.73$) for our general and site specific regressions may also be difficult to achieve because the time of harvest is subject to farmer perceptions on maturity and the opportunity for sale; i.e. some farmers harvested bunches before full physiological maturity had been reached.

### 4.2 Cultivars

Although the confidence intervals of the regression coefficients showed that the regressions for the four cultivars are similar (Table 3), the fact that the observed $F$-value differed from theoretical $F$-value (Table 4) suggested that the accuracy of prediction could be improved by using specific regressions instead of the general regression. Still, graphic comparison of the residuals (Figure 2) implied that the two regressions were closely related ($R^2 \geq 0.92$) for the four cultivars. On the other hand, comparison of the fitted lines with the line of zero intercept and unit slope showed that the two regressions may not always predict similar values. Although these findings suggested that specific regressions may give more accurate predictions compared with the general regression, it may not be possible to develop cultivar specific regressions where resources are limiting. There are more than 80 banana cultivars in Uganda (Karamura, 1998) and high cultivar diversity has been reported in banana plantations (Gold et al., 2002a). Hence, the general regression could be used for estimation of production in banana plantations. Akram-Ghaderi and Soltani (2007) made similar conclusions for cotton. However, the need for cultivar specific allometric regressions has been demonstrated for oat (Semchenko and Zobel, 2005) and soybean (Reddy et al., 1998).

### 4.3 Stage of bunch development

Surprisingly, the stage of bunch development did not seem to have a notable effect on the allometric relationship. The confidence intervals of the coefficients of specific regressions (Table 3) implied that the regressions were similar while the observed $F$ (Table 4) suggested that these regressions did not differ from the general regression. Further, graphs of residuals (Figure 3) showed that the general and specific regressions were closely related ($R^2 \geq 0.94$) although the fact that the fitted lines differed from the line of zero intercept and unit slope suggested that they did not always predict similar values. On the whole, the study concludes that the general regression could be used for plants with bunches at different stages of development. Since there is reduction in pseudostem girth in the period between flowering and harvesting (Bosch et al., 1996) possibly due to the fact that no new leaves emerge after flowering but senescence of leaves continues (Turner et al., 2008), the stage of bunch development would have been expected to affect the allometric relationship. It is possible that girth changes are not uniform along the pseudostem and hence the overall changes in pseudostem volume from 0 to 1 m height may have been minimal.

### 4.4 Agroecologies

Although the observed *F*-values for regions (Table 4) and foliar Ca (Table 5) suggested the need for specific regressions, the confidence intervals of the regression coefficients for regions (Table 3) and low and high foliar and soil nutrient concentrations (data not shown) suggested otherwise as they showed that specific regressions did not differ significantly. Furthermore, the fitted lines of the graphs relating residuals of general and specific regression showed that the general and specific regressions were closely related ($R^2 \geq 0.97$). Surprisingly, the simultaneous *F*-test for slope and intercept suggested that the two regressions differed even when intercept and slope were close to zero and one, respectively. For example, although the line for low foliar N concentration had 0.00 intercept and 1.00 slope, it differed significantly from the $y = x$ line. Harrison (1990) showed that low residual variation, when x and y pairs are closely related, can lead to the incorrect test conclusion that the regressions are not closely related. Overall, the results of this study suggested that the general regression can be used to predict bunch across different regions with varying plant and soil nutrient concentrations. Previous studies have suggested that the environment may have an effect on allometric relationships. Ssali et al. (2003) reported significantly higher ($P \leq 0.05$) bunch weight in plots which received much compared with those plots without external inputs while the circumference of the pseudostem remained similar. The increase in bunch weight could be related to a higher number of hands and fingers.

### 4.5 General versus specific regressions

The general regression, which was not specific to cultivar, region or stage of development, had a very good adjusted $R^2$ of 0.73. Regressions presented by Woomer et al. (1999) had $R^2$ ranging 0.57–0.96, but these regressions were based on destructive methods and were specific to cultivar, region and stage of development. The fact that the general regression had such a good fit might have been because three log-transformed variables were used to predict bunch weight. In the study of Woomer et al. (1999), only one variable was used in the predictions and data were not transformed.

### 4.6 Validation

The fact that the line depicting the relationship between observed and predicted bunch weights differed significantly from the perfect fit suggests that predictions made using general regression can differ from actual bunch weights. Furthermore, the negative bias implied that the regression tended to overestimate bunch weights. On the other hand, although the EF was below one, the fact that it was well above zero and actually closer to one than to zero suggests that the model is fairly good at making predictions. This was further supported by the fact that the total of the predicted bunch weights deviated <2% from the observed bunch weights. These findings imply that the regression may actually be more efficient in predicting total production where observations are numerous than in predicting individual bunch weights.

In addition to its importance in predicting production during single farm visits, for example in surveys, the general regression is even more important in predicting production in monitoring studies, particularly at distant sites where travel time and costs are high. Since bunch development from flowering to maturity can range 91–151 days as reported in Lemchi et al. (2005) (in this study the range was 81–159 days), it can be assumed that farm visits at intervals of 75 days would ensure that no bunch would be harvested without the researcher collecting data on it. In comparison, using the current methods of data collection where mature bunches are either harvested and weighed, or if not harvested their weights are visually estimated, it is likely for a researcher to miss out on some bunches especially where field visits are made at intervals of more than two weeks. Hence, it can be assumed that by using the regression to predict bunch weight instead of the current methods, the costs (i.e. labour and transport) associated with data collection can be reduced by 80%.

## 5. Conclusions

Highland banana bunch weights can be rapidly and fairly accurately estimated based on non-destructive plant parameter measurements. The general regression presented in this paper is suitable for bunch weight predictions across a range of genotypic, developmental, agro-ecological variables. We conclude that a general regression can be used when it is not possible to continuously monitor weights of individual bunches harvested and when resources to develop site and cultivar specific regressions are limiting. The regression is particularly relevant for on-farm studies on the productivity of East African highland bananas. Although the study focused itself on highland cooking bananas, the general regression may also be used for highland juice banana. Studies by Tugume et al. (2002) suggested that juice banana cultivars were not a distinct clone set (Mbidde) as proposed by Karamura (1998), but rather fell into the same clone sets as the cooking bananas. Given the fact that the highland banana systems extend well beyond Uganda's borders into Tanzania, Kenya, Rwanda, Burundi and the Democratic Republic of Congo, our findings can have a large application in further studies on this crop in this region. We also believe that our approach could be used to develop similar functions for other types of bananas (e.g. dessert bananas and plantains) since it is based on the general crop physiology of banana plants whereby the final banana bunch weight is a function of the potential sink size (number of hands and fingers) and the ability of the plant to fill this sink (i.e. pseudostem volume). These findings will strongly increase the quality of on-farm research, allowing more rapid progress to close the large yield gaps in African smallholder systems and beyond.

# Chapter 3

# Norms for multivariate diagnosis of nutrient imbalance in the East African highland bananas (*Musa* spp. AAA)

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## Abstract

Despite poor yields and soil fertility problems, fertilizer use in the East African highland banana (AAA-EA) production is absent. High fertilizer costs increase the need for site-specific fertilizer recommendations that address deficiencies. This study aimed to derive and compare norms for AAA-EA bananas, using Compositional Nutrient Diagnosis (CND), Diagnosis and Recommendation Integrated System (DRIS), and a DRIS that includes a filling value (DRIS-$R_d$), and study nutrient interactions. Data on foliar nitrogen, phosphorus, potassium, calcium, and magnesium concentrations, and plant performance were obtained from 300 plots in Uganda. CND indices were closely related to DRIS and DRIS-$R_d$ indices ($R^2$ > 0.97). Four nutrient interactions were common in both low and high bunch weight sub-populations. Although the three approaches can be used to determine nutrient imbalances in AAA-EA bananas, we recommend CND for ease of use. Diagnosis of nutrient deficiencies should be based on methods that identify plant nutritional imbalances.

**Keywords:** Compositional nutrient diagnosis (CND); Diagnosis and Recommendation Integrated System (DRIS); Foliar nutrient concentration; Nutrient imbalances; Nutrient interactions.

# 1. Introduction

Banana is an important food crop in the world (Samson, 1992) widely grown in the Caribbean, Asia, Africa and Latin America (FAO, 2009). In East Africa, the highland bananas (AAA-EA) are a primary food and cash crop for over 30 million people. In Uganda, bananas are the primary staple crop (Edmeades, 2006). However, actual production (<30 t $ha^{-1}$ $year^{-1}$) is poor compared with potential yield (>70 t $ha^{-1}$ $year^{-1}$) (van Asten et al., 2005). Poor soil fertility is a major production constraint (Wairegi et al., 2007). Despite declining banana yields, soil nutrient mining due to increased banana commercialization, and the existence of blanket fertilizer recommendations, on-farm fertilizer use in Uganda is extremely low (<2 kg $ha^{-1}$ of arable land in 2002; Camara and Heinmann, 2006). Farmers reported high fertilizer prices as the major bottleneck to its adoption (van Asten et al., 2010b). The recent (2007-2008) sharp rise (50-100%) in fertilizer prices in Uganda puts further pressure on the profitability and adoptability of fertilizer, with consequent negative impact for the long term food security in the densely populated East African highlands. There is a strong need to develop more profitable fertilizer recommendations that target primary nutrient deficiencies.

Plant nutrient deficiencies are more directly diagnosed using foliar analysis as opposed to soil analysis (Hallmark and Beverly, 1991) since the correlation between soil and plant nutrient status is often poor (Hanson, 1987). Since nutrient uptake and distribution are affected by interactions within the plant, multi-nutrient approaches have been derived. Two common methods used to diagnose nutritional imbalances are the Diagnosis and Recommendation Integrated System (DRIS) (Walworth and Sumner, 1987) and Compositional Nutrient Diagnosis (CND) (Parent and Dafir, 1992).

DRIS is based on dual ratio functions while CND is based on row-centred log ratios where each nutrient is adjusted to the geometric mean of all nutrients and to a filling value ($R_d$). Hallmark et al. (1987) proposed a modified DRIS which includes ratios of nutrient concentrations to dry matter (e.g. N/DM, where N and DM denote nitrogen and dry matter, respectively) for identifying limiting nutrients. Khiari et al. (2001a) used $R_d$ instead of DM (e.g. N/$R_d$) because the dry matter content includes nutrient concentrations already defined in the tissue simplex. The modified DRIS can identify situations where nutrients are not limiting unlike DRIS where at least one nutrient will always have a negative index (Hallmark et al., 1987).

Holland (1966) suggested use of Principal Component Analysis (PCA) to explain the effects of fertilizer application on foliar nutrient concentrations. Since CND is related to PCA (Parent et al., 1994a), PCA has been applied to CND derived row-centred log ratios to explore nutrient relationships (Parent et al., 1993; 1994a; Raghupathi et al., 2002). PCA has also been conducted on DRIS indices (Raghupathi et al., 2005; Parent et al., 1994a) to further explore plant nutrient interactions. PCA conducted on row-centred log ratios was easier to interpret compared with PCA conducted on DRIS indices (Parent et al., 1994a)

The DRIS method is reportedly inferior to CND in diagnosing imbalances as it assumes additivity of dual ratios, and does not directly take higher order interactions into account (Parent and Dafir, 1992). Compared with DRIS, CND appeared to be more sensitive for early detection of N stress in sweet corn (Khiari et al., 2001a) and for projecting nutrient imbalances in turmeric (Kumar et al., 2003). In studies on tomatoes (Parent et al., 1993) and potatoes (Parent et al., 1994b), DRIS and CND provided similar results.

There have been several studies on nutrient imbalances in bananas. Angeles et al. (1993) calculated DRIS norms primarily based on Cavendish cultivars. Wortmann et al. (1994) developed DRIS norms for AAA-EA cultivars in a study restricted to the Kagera region of Northwest Tanzania. Raghupathi et al. (2002) derived CND norms for Ney Poovan and Robusta banana cultivars grown in India. DRIS norms for a crop may differ between regions (Walworth and Sumner, 1987). Studies on nutrient imbalances in East African bananas have neither covered a wide range of agro-ecological conditions, nor have norms been developed using CND.

The objectives of this study were: (i) to investigate how foliar nutrient concentrations relate to yield, (ii) to derive and compare CND and DRIS norms for East African highland bananas, and (iii) to investigate the significance and direction of nutrient interactions using data derived a wide range of agro-ecologies in Uganda. The norms are compared with those developed in previous studies. Nutrient interactions are investigated using Principal Component Analysis (PCA).

## 2. Materials and methods

### 2.1 Study area

The study was carried out in 300 plots, in mature plantations (5-50 years old), in Central, South, Southwest and East Uganda. The area lies approximately between latitude 1º30' North and 1º00' South and longitude 29º52' and 34º30' East at an altitude of 1120-1700 m above sea level. The soils are mainly Acrisols and Ferralsols according to the FAO classification. The parent rocks underlying the soils sampled in this study have been described Archaean Gneissic-Granulitic-Complex, Proterozoic sediments and Cenozoic volcanic outcrops (Schlüter, 2008). The East African Meteorological Department (1963) generalized the rainfall pattern as bimodal with rains occurring in March-May and September-November. Annual rainfall (mm year$^{-1}$) at the study sites estimated using the local climate estimator (*LocClim)* (FAO, 2006) ranged between 782 and 1797 mm year$^{-1}$. *LocClim* rainfall estimates were assumed to be reliable because the mean annual rainfall predicted by *LocClim* for specific sites in Central and Southwest was not significantly different from actual observations reported for these sites in previous studies (e.g. Smithson et al., 2004; Okech et al., 2004a). In addition, farmers and local agricultural staff observed that the actual rainfall amount and distribution during the study period was normal. The *LocClim* has been used in other studies to estimate rainfall (e.g. Heaton et al., 2004; Mokany et al., 2006).

Nitrogen (N), phosphorus (P) and potassium (K) fertilizer averaging 71, 8 and 32 kg ha$^{-1}$ year$^{-1}$, respectively, was applied to 28, 34, 24 and 9 of the plots in Central, South, Southwest and East, respectively, (Wairegi et al., 2007) while the rest (25, 64, 42 and 71 plots in Central, South, Southwest and East, respectively) received no fertilizer. Since all plots were fully managed by farmers, other management practices (e.g. use of animal manure, mulch) were those commonly used by farmers. Banana production in all plots was rain-fed.

## 2.2 Data collection

The data used in this study was collected over a period of 12 months in 2006-2007. In order to generate a large dataset, data from a monitoring study (176 plots) and a multiple visit survey (124 plots) were combined. In the monitoring study, 30 randomly selected mats were monitored for the year while in the survey, data was collected from 20 randomly selected mats with bunch-bearing plants. During the study period, field visits were made at 3-5 month intervals in the monitoring study and at 4-6 month interval in the survey. In the monitoring study, farmers were given weighing balances to record bunch weights of marked mats. In both studies, data on girth of stem at base and 1 m, number of hands, number of fingers in the bottom row of the second lowest hand were collected from fruiting plants and used to estimate bunch weights using the general allometric regression derived by Wairegi et al. (2009), where data on bunch weights were missing.

Foliar sub-samples of 10 by 20 cm were collected from both sides of the midrib in the midpoint of the lamina from the third most fully expanded leaf of a flowering plant (Lahav, 1995) and composited for each plot. Composite samples consisted of 3 to 7 plants per plot. Since plots were not uniform in size, efforts were made to collect more samples in larger plots than in smaller plots. Samples were analysed using standard methods as described by Okalebo et al. (1993). The samples were oven dried at 72ºC for 48-96 hours, ground to < 2mm, digested in a sulphuric and selenium acid mixture. The samples were analysed colorimetrically for N and P while K was analysed using a flame photometer, and calcium (Ca) and magnesium (Mg) were analysed using an atomic absorption spectrophotometer.

**2.3 Analytical approach**

The production data was collected during a 12-month period over a wide range of agro-ecological conditions across the entire country. Banana production is continuous; i.e. plants in farmers' fields are at different stages of development at any given point in time. Therefore, the data presented in this study are assumed to be representative for the study regions encompassing temporal and spatial variation in banana production systems. This was further emphasized by the fact that banana production in Uganda is rainfed and the rainfall amount and distribution during the study period was close to the long term average. The intra-annual rainfall variation has impact on production variation (bunch weight and frequency of harvesting) (Birabwa et al., 2010) and this variation was captured by monitoring plants for 12 consecutive months and collecting data in 2-3 spaced visits in the case of the survey. The effects of inter-annual variation in rainfall were not captured, but a wide range of annual rainfall conditions was covered (782 -1797 mm year$^{-1}$) by the geographic spread of the study sites. Although Walworth and Sumner (1987) proposed that a survey approach is desirable for determination of norms, estimating banana production through single visit surveys is difficult because production is continuous and most farmers do not use any formal way of monitoring production. We used a novel technique to quantify bunch weights non-destructively during farm surveys. Since our study avoids temporal and spatial bias, we believe that the data collected in this study can be used to derive norms for bananas in Uganda, with potential applicability of these results in the other East African highland banana production areas (i.e. Burundi, Rwanda, eastern Democratic Republic of Congo, north-western Tanzania, and western Kenya)

The selection of the high bunch weight sub-population and calculation of CND norms was based on methods outlined by Khiari et al. (2001b). Plant tissue composition forms a $d$-dimensional nutrient arrangement; i.e. simplex ($S^d$) made of $d$ + 1 nutrient proportions including $d$ nutrients and a filling value ($R_d$) defined as (Parent and Dafir, 1992):

$$S^d = [(N, P, K, \ldots, R_d): N>0, P>0, K>0, \ldots R_d>O, N + P + K + \ldots + R_d = 100] \quad (1)$$

where 100 is the dry matter concentration (%); N, P, K,…. are nutrient proportions (%); and $R_d$ is the filling value computed as:

$$R_d = 100 - (N + P + K + \ldots) \quad (2)$$

A geometric mean (G) computed as:

$$G = (N \times P \times K \times \ldots \times R_d)^{\frac{1}{d+1}} \quad (3)$$

is used to divide nutrient proportions to derive row-centred log ratios as follows:

$$V_N = \ln\left(\frac{N}{G}\right), V_P = \ln\left(\frac{P}{G}\right), V_K = \ln\left(\frac{K}{G}\right), \ldots, V_{Rd} = \ln\left(\frac{R_d}{G}\right) \quad (4)$$

and

$$V_N + V_P + V_K + \ldots + V_{Rd} = 0 \quad (5)$$

where $V_x$ is the CND row-centred log ratio expression for nutrient $X$.

The data was next partitioned into low and high bunch weight sub-populations using the procedure described by Khiari et al., (2001b). The procedure identifies the optimum partition between the two sub-populations. The variance ratio must be low when comparing the variance of a nutrient expression for lower yields with that of the remainder of the population.

The observations were ranked according to decreasing bunch weight and the Cate-Nelson procedure was used to iterate a partition of the data between the two sub-populations (Khiari et al., 2001b). In the first partition, the two highest bunch weight values formed one group, and the remainder of the yield values formed another group; thereafter, the three highest bunch weight values formed one group, and the remainder of the yield values formed the other. This process was repeated until the two lowest bunch weight values formed one group, and the remainder of the bunch weight values formed the other. At each iteration, the numbers of observations were $n_1$ and $n_2$ for the first and second sub-population, respectively. For the two sub-populations obtained at each iteration, the variances of the row-centred log ratios were computed. The variance ratio of component *X* was then computed as:

$$fi(V_x) = \frac{\text{Variance of } V_x \text{ of } n_1 \text{ observations}}{\text{Variance of } V_x \text{ of } n_2 \text{ observations}} \tag{6}$$

where $fi(V_x)$ is the ratio function between two sub-populations for nutrient *X* at the $i^{th}$ iteration. The first variance ratio computed from the two highest bunch weight was put on the same line as the highest bunch weight.

The cumulative function, which is the sum of the variance ratios at the $i^{th}$ iteration from the top, was then computed as:

$$F_i^c(V_x) = \frac{\sum_{i=1}^{n_1-1} f_i(V_x)}{\sum_{i=1}^{n-3} f_i(V_x)} \times 100 \tag{7}$$

The relationship between the cumulative function $F_i^c(V_x)$ and bunch weight (*Y*) was defined as:

$$F_i^c(V_x) = aY^3 + bY^2 + cY + h \tag{8}$$

where *h* is the intercept and *a, b,* and *c* are parameter coefficients. The optimum partition, which is the inflection point, was obtained by equating the second derivative of the previous equation to zero. The bunch weight cut off value was $-b/3a$. The highest bunch weight cut-off value among the $d + 1$ nutrient computations was then selected as the lowest bunch weight in the high bunch weight sub-population.

From the high bunch weight sub-population, CND norms, which are the means and standard deviations of row-centred log ratios, denoted as $V_N^*$, $V_P^*$, $V_K^*$, …. $V_{Rd}^*$ and $SD_N^*$, $SD_P^*$, $SD_K^*$…..,$SD_{Rd}^*$ respectively, were then calculated. The CND indices, denoted as $I_N$, $I_P$, $I_K$, …. $I_{Rd}$ were then calculated from the row-centred log ratios:

$$I_N = \frac{V_N - V_N^*}{SD_N^*},\ I_P = \frac{V_P - V_P^*}{SD_P^*},\ I_K = \frac{V_K - V_K^*}{SD_K^*},\ \ldots\ldots\ I_{Rd} = \frac{V_{Rd} - V_{Rd}^*}{SD_{Rd}^*} \tag{9}$$

The nutrient imbalance index of a diagnosed specimen, which is its CND $r^2$, was computed as:

$$r^2 = I_{\mathrm{N}}^2 + I_{\mathrm{P}}^2 + I_{\mathrm{K}}^2 + \ldots\ldots. + I_{Rd}^2 \tag{10}$$

The mean, variance and coefficient of variation (CV) for each possible nutrient pair ratio were calculated for both low and high bunch weight sub-populations, according to Beaufils (1973). For each nutrient pair, the mean and CV of the ratio that maximized the variance ratio between the low- and high-bunch weight group were selected as norms for that pair of nutrients, as described by Walworth and Sumner (1987) and Letzsch (1985). Increase in variance ratio results in increase in diagnostic sensitivity as it increases chances of discriminating between the two sub-populations (Walworth and Sumner, 1987).

DRIS indices were calculated, for each plot, using two steps. First, for each pair of nutrients, observations were related to norms using standardization and index equations (Beaufils, 1973) as shown in the example below.

$$f(N/P) = \left(\frac{N/P}{n/p} - 1\right)\left(\frac{1000}{CV_{n/p}}\right) \quad \text{if } N/P > n/p \tag{11}$$

$$f(N/P) = \left(1 - \frac{n/p}{N/P}\right)\left(\frac{1000}{CV_{n/p}}\right) \quad \text{if } N/P < n/p \tag{12}$$

where lower case type refers to the reference-population nutrient ratio, upper case type refers to the sample being evaluated, *f* is the functional relationship between the sample and reference-population values, and *CV* is the coefficient of variation of the nutrient ratio in the reference population.

Next, values from the standardization equations were used to calculate indices as shown in the examples below.

$$I_{N1} = \frac{-f(\mathrm{P/N}) + f(\mathrm{N/K}) - f(\mathrm{Ca/N}) - f(\mathrm{Mg/N})}{4} \tag{13}$$

and

$$I_{N2} = \frac{-f(\mathrm{P/N}) + f(\mathrm{N/K}) - f(\mathrm{Ca/N}) - f(\mathrm{Mg/N}) - f(R_5/\mathrm{N})}{5} \tag{14}$$

where $I_{N1}$ and $I_{N2}$ are N indices for DRIS and DRIS where the $R_d$ was included (DRIS-$R_d$), respectively.

Negative indices denoted relative deficiencies while positive indices denoted excesses. For any sample, the nutrient indices sum to zero. The measure of the total nutritional imbalance, the nutrient imbalance index (*NII*), was calculated using the absolute values of the indices generated for the sample as shown in the examples below.

$$NII_1 = |I_{N1}| + |I_{P1}| + |I_{K1}| + |I_{Ca1}| + |I_{Mg1}| \quad (15)$$

for DRIS or

$$NII_2 = |I_{N2}| + |I_{P2}| + |I_{K2}| + |I_{Ca2}| + |I_{Mg2}| + |I_{R_d}| \quad (16)$$

for DRIS-$R_d$. The greater the sum, the more the imbalance among nutrients (Snyder and Kretschmer, 1987).

The relationships between CND and both DRIS and DRIS-$R_d$ were explored using regressions. The coefficient of determination ($R^2$) indicated the goodness of fit. Coefficient confidence intervals (95%) were used to compare all the regressions relating CND and DRIS indices, as well as regressions relating CND and DRIS-$R_d$. Regressions were assumed to be similar if the coefficients did not differ significantly based on confidence intervals (Akram-Ghaderi and Soltani, 2007).

Since CND is more compatible with PCA than DRIS (Parent et al., 1994a), PCA were performed on row-centred log ratio nutrient values for the low and high bunch weight sub-population. The principal components (PCs) were varimax-rotated to obtain maximum relationships among standardized variables (Vandamme et al., 1978). The *PC* loadings having values greater than the selection criteria (*SC*) were given significance. The *SC* was calculated as follows (Ovalles and Collins, 1988):

$$SC = 0.5/(PC \text{ eigenvalue})^{0.5} \quad (17)$$

Selection of high bunch weight population was carried out using Microsoft Office Excel 2003. Calculation of norms and indices, regression and *PC* analyses were carried out using SPSS for Windows, release 11.0.0, standard version (SPSS Inc., 1989-2001).

## 3. Results

The $S^5$, *i.e.*, six-dimensional ($d$ + 1) simplex was comprised of the five nutrients (N, P, K, Ca, and Mg) and the filling value $R_5$. Bunch weight ranged from 5 to 36 kg while foliar N, P, K, Ca, Mg and $R_5$ ranged between 1.35-3.89, 0.10-0.38, 1.54-5.83, 0.23-1.74, 0.25-0.85 and 89.38-94.51%, respectively. The relationship between the concentrations of N, P, K, Ca, Mg, $R_5$ and bunch weight showed triangular patterns (Figure 1). With increasing nutrient concentrations, there was a gradual increase in the maximum observed bunch weights, until a peak was reached. Further increases in nutrient concentrations subsequently led to a gradual decrease in maximum bunch weight.

The relationship between cumulative variance function and bunch weight was cubic (not presented) and the inflection point ($-b/3a$) was highest for $V_{Mg}$ (15.3 kg) and lowest for $V_{R5}$ (9.9 kg) (Table 1). Hence, 15.3 kg bunch weight was used to partition the low bunch weight sub-population from the high bunch weight sub-population. The high bunch weight sub-population included 45.2% of all observations.

Table 1: Cumulative variance function [$F_i^c(V_x)$] for row-centred ratios and bunch weight (kg) at point of inflection.

| | $F_i^c(V_x) = aY^3 + bY^2 + cY + h$ | $R^2$ | Bunch weight at inflection point = $-b/(3a)$ |
|---|---|---|---|
| $V_N$ | $0.007Y^3 - 0.261Y^2 - 1.891Y + 100$ | 0.96 | 12.2 |
| $V_P$ | $0.010Y^3 - 0.440Y^2 + 0.757Y + 100$ | 0.96 | 14.5 |
| $V_K$ | $0.009Y^3 - 0.384Y^2 + 0.129Y + 100$ | 0.98 | 14.4 |
| $V_{Ca}$ | $0.012Y^3 - 0.490Y^2 + 1.546Y + 100$ | 0.98 | 15.1 |
| $V_{Mg}$ | $0.009Y^3 - 0.422Y^2 + 1.061Y + 100$ | 0.98 | 15.3 |
| $V_{R_5}$ | $0.004Y^3 - 0.122Y^2 - 3.245Y + 100$ | 0.97 | 9.9 |

The mean bunch weight in the high bunch weight sub-population was significantly ($P \leq 0.001$) larger than in the low bunch weight sub-population (Table 2). The N, P, K, Ca and Mg concentrations averaged 2.79, 0.21, 3.79, 0.91 and 0.44%, respectively, in the high bunch weight sub-population and 2.66, 0.21, 3.73, 0.99 and 0.45%, in the low bunch weight sub-population. The high bunch weight sub-population had significantly larger N ($P \leq 0.05$) and less Ca ($P \leq 0.01$) than the low bunch weight sub-population. Average concentrations of other nutrients did not differ significantly ($P \leq 0.05$) between the two sub-populations.

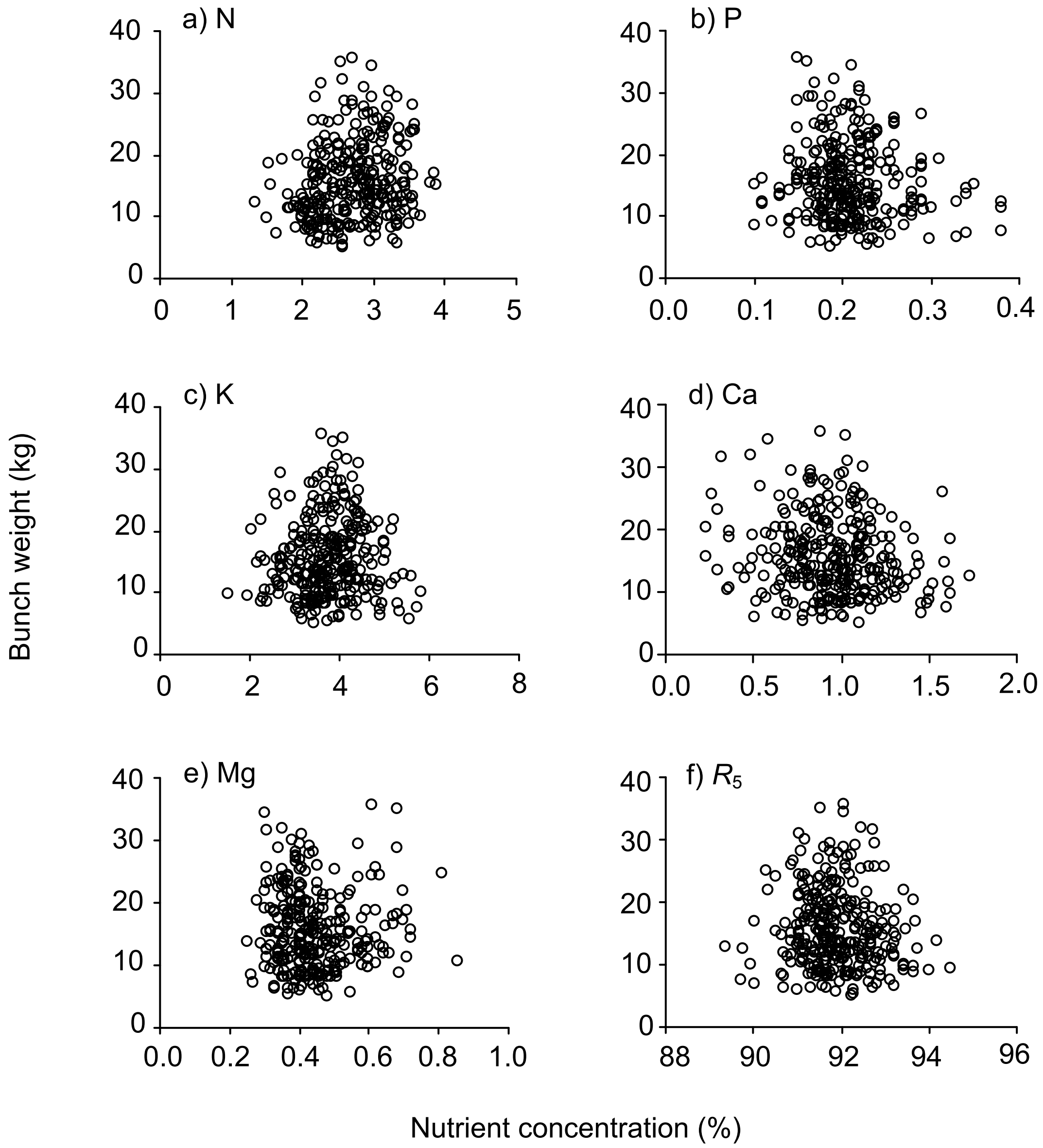


Figure 1: Relationships between foliar nutrient concentrations and bunch weight. $R_5$ denotes the filling value and is the sum of all elements with the exception of N, P, K, Ca and Mg.

The CND norms, i.e. means and standard deviations, of $V_N$, $V_P$, $V_K$, $V_{Ca}$, $V_{Mg}$ and $V_{R5}$, for the high bunch weight sub-population, are presented in Table 3. The variances of the low and high bunch weight sub-populations differed significantly ($P \leq 0.001$) for $V_N$. The variances for other nutrients did not differ significantly ($P \leq 0.05$) between the two sub-populations. These norms were used to estimate nutrient indices for N, P, K, Ca, Mg and $R_5$ and CND $r^2$ values (using equations 9 and 10).

Table 2: Means and standard deviations (SD) of bunch weight (kg) and nutrient concentrations (%) for low and high bunch weight sub-populations

| | Low bunch weight subpopulation | | High bunch weight subpopulation | |
|---|---|---|---|---|
| | Mean | SD | Mean | SD |
| Bunch weight | 11 | 3 | 21*** | 5 |
| N | 2.66 | 0.52 | 2.79* | 0.45 |
| P | 0.21 | 0.05 | 0.21 | 0.04 |
| K | 3.73 | 0.78 | 3.79 | 0.62 |
| Ca | 0.99 | 0.27 | 0.91** | 0.26 |
| Mg | 0.45 | 0.10 | 0.44 | 0.11 |

*, ** and *** denote that means between low and high bunch weight sub-population are significantly different at $P\leq$ 0.05, 0.01 and 0.001, respectively.

Table 3: The means and standard deviations (SD) of row-centred log ratios for low and high bunch weight sub-population.

| | Low bunch weight subpopulation | | High bunch weight subpopulation[a] | |
|---|---|---|---|---|
| | Mean | SD | Mean | SD |
| $V_N$ | 0.237 | 0.195 | 0.302** | 0.153 |
| $V_P$ | -2.294 | 0.208 | -2.312 | 0.176 |
| $V_K$ | 0.574 | 0.211 | 0.607 | 0.168 |
| $V_{Ca}$ | -0.766 | 0.241 | -0.859 | 0.289 |
| $V_{Mg}$ | -1.551 | 0.177 | -1.546 | 0.199 |
| $V_{R_5}$ | 3.801 | 0.102 | 3.809 | 0.087 |

** The variance ratio between low- and high-yielding sub-populations significant at $P\leq0.01$.
[a] The means and SD for high bunch weight sub-population are the Compositional Nutrient Diagnosis (CND) norms for $d$ = 5 nutrients.

The DRIS norms, i.e. means and CVs of the selected nutrient ratios, for high bunch weight sub-populations are presented in Table 4. The variances of the nutrient ratios of the low and high bunch weight sub-population differed significantly ($P \leq 0.05$) for P/N, N/K, P/K, Ca/N, $R_5$/N and P/$R_5$. For all other nutrient ratios, the variances did not vary significantly between the two sub-populations. These norms were used to calculate nutrient indices and nutrient imbalance indices for both conventional (using Eqs 13 and 15) and expanded DRIS (using equations 14 and 16).

Table 4: The mean and coefficient of variation CV (%) of nutrient ratios, for low and high bunch weight populations, for ratios that maximized the variance between the low and high bunch weight sub-population.

| | Low bunch weight sub-population | | High bunch weight sub-population[a] | |
|---|---|---|---|---|
| | Mean | CV (%) | mean | CV (%) |
| P/N | 0.085 | 41.32 | 0.0758*** | 27.49 |
| N/K | 0.755 | 34.41 | 0.755* | 26.18 |
| Ca/N | 0.390 | 36.11 | 0.333* | 33.30 |
| Mg/N | 0.172 | 22.90 | 0.163 | 27.05 |
| P/K | 0.0587 | 26.95 | 0.0548* | 23.36 |
| Ca/P | 4.891 | 32.34 | 4.565 | 32.72 |
| P/Mg | 0.504 | 36.71 | 0.491 | 30.61 |
| Ca/K | 0.281 | 38.21 | 0.249 | 41.27 |
| Mg/K | 0.127 | 39.93 | 0.122 | 37.20 |
| Ca/Mg | 2.281 | 29.20 | 2.101 | 30.34 |
| $R_5$N | 36.086 | 21.67 | 33.864*** | 17.70 |
| P/$R_5$ | 0.00232 | 24.33 | 0.00223* | 18.04 |
| $R_5$/K | 25.871 | 24.46 | 24.792 | 20.63 |
| Ca/$R_5$ | 0.0108 | 27.42 | 0.00989 | 28.39 |
| $R_5$/Mg | 215.842 | 21.39 | 217.107 | 20.67 |

* , ** and *** denote within row significant differences in variances between low and high bunch weight populations at $P \leq$ 0.05, 0.01 and 0.001 respectively.

All regressions relating CND to DRIS or DRIS-$R_d$ were significant ($P \leq 0.001$) (data not presented). The $R^2$ ranged 0.965-0.979 for relationships between CND and DRIS and 0.972-0.991 for relationships between CND and DRIS-$R_d$, for nutrient indices. These regressions differed significantly (95% confidence intervals) with respect to the regression coefficients, for both DRIS and DRIS-*Rd*. When all nutrient indices for DRIS and DRIS-$R_d$ were plotted against the corresponding CND indices in one graph, the distribution of observations for the different nutrients as well as the two DRIS approaches superimposed (as they showed similar trends). Therefore, the relationship for N is presented in this paper to represent all relationships (Figure 2). The regression lines relating nutrient imbalance indices for the two DRIS approaches ($NII_1$ and $NII_2$) to CND $r^2$ and suggested "power" relationships with $R^2$ of 0.767 ($NII_1$) and 0.849 ($NII_2$) (Figure 3).

The two significant PCs identified for each PCA conducted for low and high bunch weight sub-populations had eigen values that summed to 3.641 and 3.3841, explaining 72.81 and 67.66 % of the total variance, respectively (Table 5). The first PC of the low bunch weight sub-population was positively correlated for N and Mg and negatively for P and K while that for the high bunch weight sub-population correlated positively for N and P and negatively for Ca and Mg. For both sub-populations N and Ca had an inverse relationship in the second PC.

Table 5: Loadings or correlations between the row-centred log ratios and the first two principal components for the low and the high bunch weight sub-population, extracted from varimax normalized matrix.

| | Low bunch weight subpopulation | | High bunch weight subpopulation | |
|---|---|---|---|---|
| | PC1 | PC2 | PC1 | PC2 |
| $V_N$ | 0.635* | -0.656* | -0.218 | 0.781* |
| $V_P$ | -0.769* | 0.033 | 0.834* | -0.043 |
| $V_K$ | -0.780* | -0.289 | 0.714* | 0.346 |
| $V_{Ca}$ | 0.272 | 0.903* | -0.437* | -0.795* |
| $V_{Mg}$ | 0.797* | 0.040 | -0.755* | 0.067 |
| Eigen value | 2.310 | 1.330 | 2.015 | 1.368 |
| Selection criteria | 0.329 | 0.434 | 0.352 | 0.427 |
| % variance | 46.21 | 26.61 | 40.30 | 27.36 |

* Significance loading

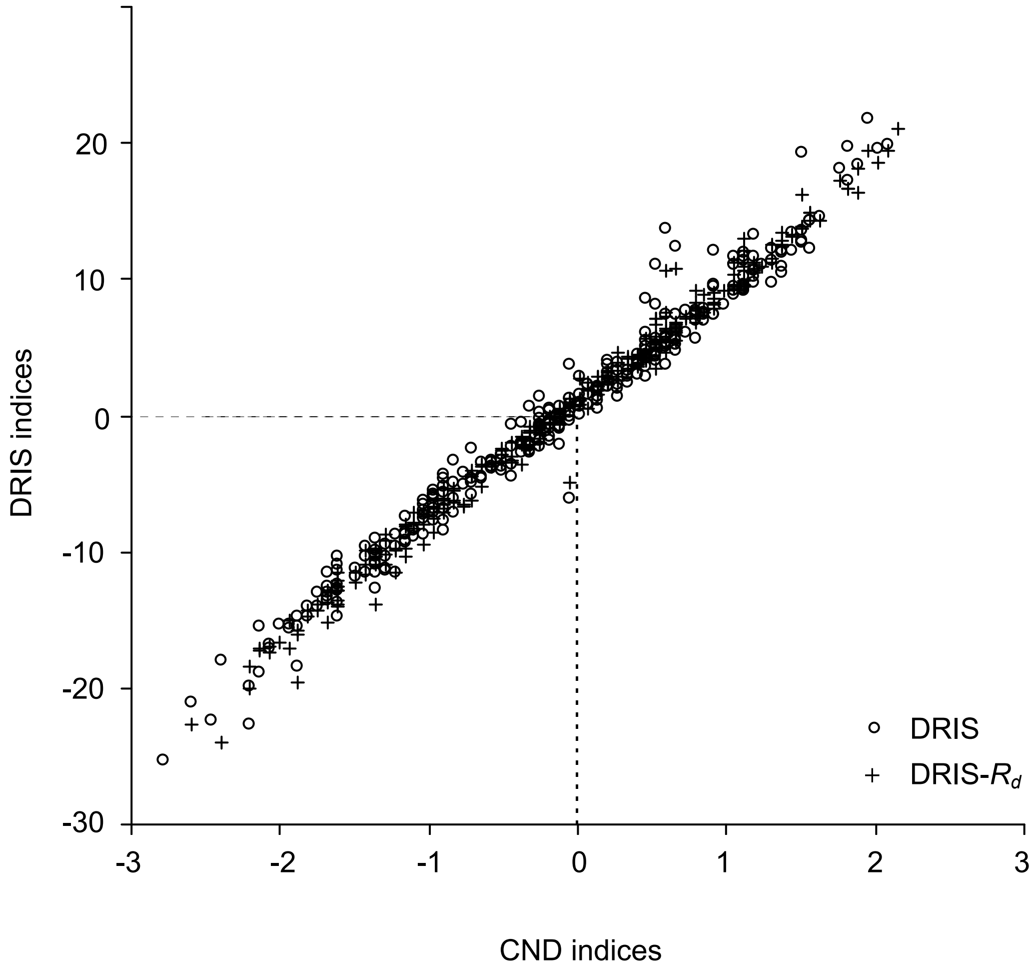


Figure 2: Relationship between CND and Diagnosis and Recommendation Integrated System (DRIS and DRIS-$R_d$) nutrient indices for N. The dotted lines depict the $y$ = 0 and $x$ = 0 relationships.

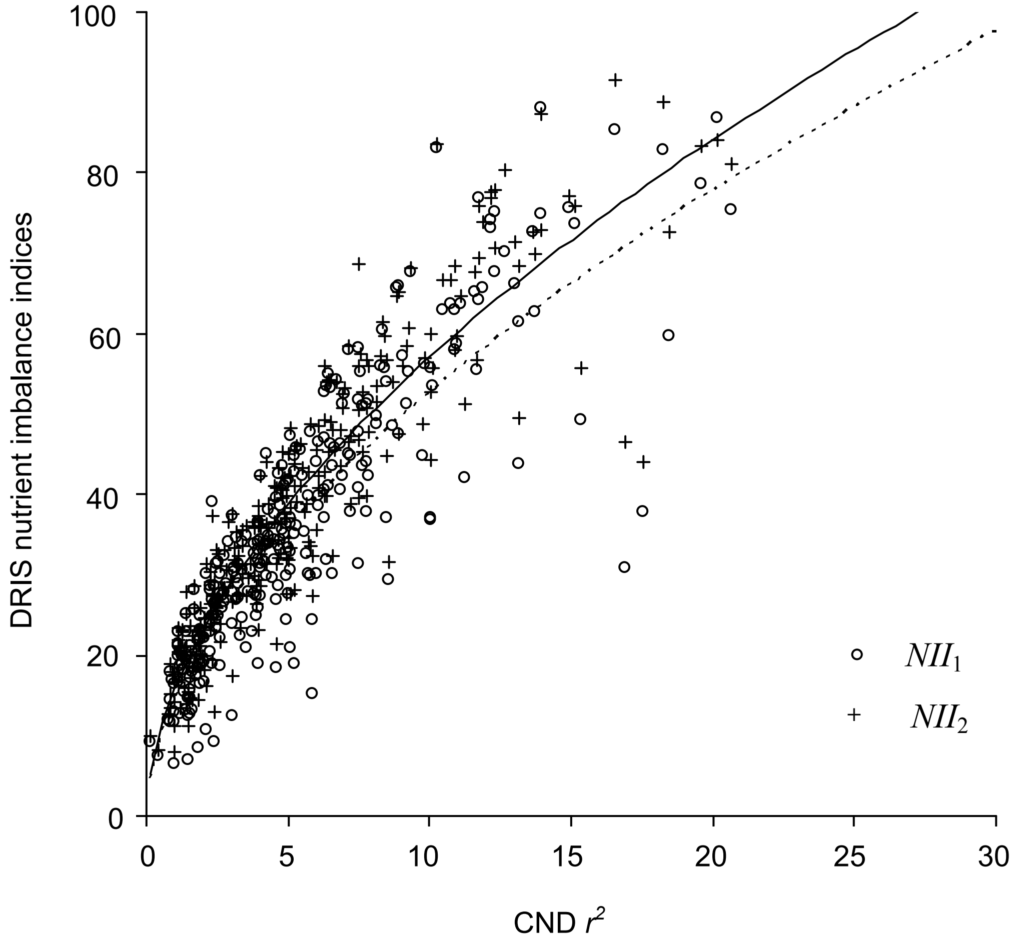


Figure 3: Relationship between CND $r^2$ and Diagnosis and Recommendation Integrated System (DRIS and DRIS-$R_d$) nutrient imbalance indices ($NII_1$ and $NII_2$). $NII_1$ and $NII_2$ are the nutrient imbalance indices for DRIS and DRIS-$R_d$, respectively. The dotted and continuous lines are regression lines for $NII_1$ and $NII_2$ with $R^2$ of 0.767 and 0.849, respectively.

# 4. Discussion

## 4.1 Relationships between nutrient concentrations and bunch weight

The triangular distribution patterns observed between foliar nutrient concentrations and bunch weights (Figure 1) suggest that the latter are influenced by several (interacting) factors and not by single nutrients alone. Similar conclusions were reached by other authors (Quesnel et al., 2006; Walworth and Sumner, 1987; Vizycayno-Soto and Côté, 2004) who observed similar relationships between foliar nutrients and production. The upper boundaries of the data clouds expressing the maximum bunch weight at a given nutrient concentration show a typical positive relationship between yield and nutrient concentration at low nutrient concentrations and a negative relationship at high nutrient concentrations. Increase in concentration of a deficient nutrient leads to increases in yield up to a maximum beyond which yield declines (Havlin et al., 2004). The decline in yield due to excessive nutrient concentration is due to toxicity or reduction in concentrations of other nutrients below their critical requirement (Havlin et al., 2004).

The fact that partitioning data at the highest inflection point of 15.3 kg (Table 1) placed 45.2% of the observations in the high bunch weight population suggested that the Cate-Nelson approach, as used by (Khiari et al., 2001a; Khiari et al., 2001b; Khiari et al., 2001c), was applicable. This approach is not always applicable however: for example, the highest inflection points were beyond the range of observations with *Opuntia ficus-indica* (Magallanes-Quintanar et al., 2004) and *Aloe vera* (García-Hernández et al., 2006).

The significantly higher N concentration of the high bunch weight sub-population ($P \leq 0.05$) (Table 2) is in agreement with observations of Walworth and Sumner (1987) on maize data collected worldwide. They concluded that that low yields are more frequently associated with low N than with high N because farmers are likely to apply inadequate amounts of nutrients. The significantly higher Ca ($P \leq 0.01$) in the low bunch weight sub-population compared with the high bunch weight sub-population may be due to a negative interaction between N and Ca in the plant. Still, these differences in nutrient concentrations, between the two sub-populations, justify use of the high bunch weight sub-population to derive norms instead of using all the observations. Using the high yield sub-population to derive norms assumes that the distribution of observations at low yields is skewed (Walworth and Sumner, 1987).

## 4.2 CND and DRIS norms

The mean nutrient concentrations observed in the high bunch weight sub-population (Table 2) did not fully tally with those observed in other studies. Wortmann et al. (1994) found higher N (3.15 vs. 2.79%), P (0.25 vs. 0.21%) and Ca (1.13 vs. 0.91%), and lower K (3.04 vs. 3.84%) for AAA-EA cultivars, while for Robusta (AAA) and Ney Poovan (AB) dessert bananas, Raghupathi et al. (2002) had lower P (0.17%), and Angeles et al. (1993) had higher K (4.49%). Furthermore, the norms derived by Wortmann et al. (1994), were based on data collected in a single eco-region (i.e. Kagera in Northwest Tanzania) and may not be applicable outside this region. On the other hand, the norms derived in this study are based on data from a wide range of ecological regions and may therefore have a wider application.

Previous studies have suggested that norms may differ between genome groups. For example, DRIS norms derived for Gros Michel (an AAA triploid), Ney Poovan (AB) and a cultivar thought to be Pisang Awak (ABB) seemed to differ (Bosch et al., 1996). Similarly, P.J.A. van Asten and S. Gaidashova (unpublished data, 2009) observed that foliar nutrient concentrations for Pisang Awak (ABB) were consistently smaller for N (15%) and Ca (36%) than with Intuntu (AAA-EA) in 12 sites across Rwanda. Also, K and Ca concentrations differed significantly ($P \leq 0.05$) between Robusta and Ney Poovan (Raghupathi et al., 2002). These differences further highlight the importance of the norms calculated in this study for diagnosing nutrient imbalances in the East African highland banana as they are specific to the genome group AAA.

Although the norm for K derived in this study differs from those calculated by Wortmann et al. (1994) and Angeles et al. (1993), it is in agreement with observations made in other studies on banana in Uganda. Smithson et al. (2001) suggested that the norm for K in banana should be below the 4.49% suggested by Angeles et al. (1993) and higher than the 3.04% suggested by Wortmann et al. (1994). Other studies on banana confirm this suggestion. For example, in a nematode trial in Uganda, in 1997 plots with mulch had had significantly higher K concentrations, averaging 3.7%, compared with plots that were not mulched, which averaged 2.2 and 2.3% (McIntyre et al., 2000). Production was also significantly higher in the mulched plots compared with those without mulch. In another trial where application of K was reported to increase annual yield from 14.4 to 18.9 t $ha^{-1}$ $year^{-1}$, foliar K concentrations in plots where K was applied averaged 3.3% (Smithson et al., 2004). Hence, it is likely that our norm for K could be more appropriate for diagnosing nutrient imbalances in the East African highland banana production systems.

Furthermore, the fact that the low and high bunch weight sub-population differed in variances of CND calculated $V_n$ (Table 3), as well as DRIS calculated P/N, N/K, Ca/N, P/K, $R_5$/N and P/$R_5$ (Table 4) implied that nutrient imbalances contributed to the differences in bunch weight between the two populations. Since Walworth and Sumner (1987) suggested that, for DRIS, discrimination between the two sub-populations is maximized when the ratio of variances between the two sub-populations is maximized, it is likely that this suggestion may also be true for CND. We, therefore conclude that the CND and DRIS norms calculated in this study are reliable for diagnosing nutrient imbalances in the East African highland bananas.

CND and DRIS norms developed in this study were closely related, in line with earlier studies on tomato (Parent et al., 1993), potato (Parent et al., 1994b) and sweet corn (Khiari et al., 2001a). The regressions relating CND to DRIS and DRIS-$R_d$ had high $R^2$ (0.965-0.991) for all nutrients and showed similar trends (Figure 2). Interestingly, the regressions relating CND to DRIS or DRIS-$R_d$ differed significantly (95% confidence intervals) with respect to regression coefficients suggesting that the order of nutrient imbalances calculated for an observation may differ between CND and DRIS (cf. Kumar et al., 2003). For example, the order of imbalances in one plot in Central region was P (-1.24) < K (-0.28) < Ca (0.17) < N (0.33) < Mg (1.31) for CND, P (-13.01) < Ca (-1.32) < K (-0.47) < N (2.80) < Mg (11.99) for DRIS, and P (-12.20) < Ca (-0.45) < K (0.16) < N (4.15) < Mg (14.0) for DRIS-$R_d$ (data not presented). Although the order differed between CND and DRIS or DRIS-$R_d$, all methods identified P as being most deficient, Mg as least deficient and N as the second least deficient. This suggests that the differences between the methods are small. This is further supported by the fact that all three approaches agreed in categorizing of observations as either deficient or excess (Figure 2).

The closeness in relationships between CND to DRIS or DRIS-$R_d$ ($R^2$ = 0.965-0.991) suggests that both DRIS and DRIS-$R_d$ methods give similar diagnosis. On the other hand, the fact that the $R^2$ relationship between DRIS-$R_d$ and CND $r^2$ had a slightly higher adjusted $R^2$ (0.849) compared with the relationship between DRIS and CND $r^2$ (0.767) (Figure 3) suggests that the DRIS-$R_d$ may be superior. Nonetheless, we found no strong evidence to suggest that the inclusion of the filling value in DRIS would be required when identifying nutrient deficiencies with the aim to develop new fertilizer recommendations for East African highland bananas.

### 4.3 Nutrient interactions

The positive relationship between P and K and the negative relationship between these nutrients and Mg as well as the negative relationship between N and Ca in the two sub-populations (Table 5) suggest the positive P-K interaction and negative interactions: N-Ca, P-Mg and K-Mg interaction. In addition, the positive N-Mg interaction and the negative N-P and N-K interactions were specific to the low bunch weight sub-population while the positive Ca-Mg interaction and negative P-Ca and K-Ca interactions were specific to the high bunch weight sub-population. These results partially agree with findings in dessert bananas by Raghupathi et al. (2002) where the first PC of the high yield sub-population was positively correlation for N, P and K and negatively for Ca and Mg. The observation that some nutrient interactions were sub-population specific is in agreement with studies in *Aloe vera* (García-Hernández et al., 2006) and yellow pepper (García-Hernández et al., 2004).

Although the underlying mechanisms of nutrient interactions are not always well understood, some of the interactions have been explored. For example, an increase in the $NH_4^+/NO_3^-$ ratio in the growth solution contributes to decreased foliar $K^+$ and $Ca^{2+}$ concentrations (Grattan and Grieve, 1999). The antagonism between P and Ca has been attributed to the reduction in the activity of P due to ionic strength effects and the weak solubility of the Ca-P minerals (Grattan and Grieve, 1999).

The fact that all nutrients are either positively or negatively correlated to at least one other nutrient suggests that no nutrient influences banana production in isolation. This implies that nutrient uptake and distribution in the East African highland banana are interdependent – in agreement with observations made on dessert bananas (Raghupathi et al., 2002), *Aloe vera* (García-Hernández et al., 2006) yellow pepper (García-Hernández et al., 2006) and other crops. Since in both sub-populations, all nutrients except Ca in the low bunch weight sub-population and N in the high bunch weight were correlated to more than one other nutrient, a multivariate approach (i.e. CND) is expected to be superior to the dual ratio approach (i.e. DRIS). Interestingly, this study showed that the differences in approach between the CND and DRIS did not yield large differences. Nonetheless, CND may still be the preferred approach in practice, since norms and indices proved much easier to compute compared with DRIS.

## 5. Conclusions

Bunch weights are determined by several interacting factors and not by single nutrients alone. Both CND and DRIS norms derived in this study proved to be reliable tools for diagnosing nutrient imbalances in the East African highland bananas. Inclusion of a filling value ($R_d$) in DRIS improved the correlation with the CND approach, but overall differences between the the CND, DRIS and DRIS-$R_d$ methods were small. Comparison with earlier nutrient studies on bananas revealed that norms developed using data from specific eco-regions and cultivars could not be applied to other regions and cultivars. Nutrient interactions showed that the multivariate approaches of CND and DRIS are better in diagnosis of nutrient imbalances in banana production than single nutrient approaches. Given the wide range of agro-ecologies sampled in this study, we believe that the norms presented will provide a good indication for nutrient deficiencies for most of the East African highland region. Identification of nutrient imbalances will help farmers to prioritize investments in nutrient inputs that target the primary nutrient deficiencies. The development of site/region-specific fertilizer recommendations will help farmers to increase farm production and profitability.

# Chapter 4

# Abiotic constraints override biotic constraints in East African highland banana systems

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## Abstract

Banana is the primary food crop in Uganda, but yields are poor due to a complex of abiotic and biotic constraints. However, quantitative information on the importance, interactions, and geographic distribution of yields and constraints is scanty. We monitored yields, biotic and abiotic constraints in 159 plots in Central, South and Southwest Uganda in 2006–2007. About half the plots were on-farm demonstrations that received fertilizer (average 71N, 8P, 32K kg $ha^{-1}$ $year^{-1}$) through a development project, the rest were ordinary farmer fields (i.e. controls). Fresh banana yields in controls were significantly ($P \leq 0.05$) higher in Southwest (20 t $ha^{-1}$ $year^{-1}$) compared with Central (12 t $ha^{-1}$ $year^{-1}$) and South (10 t $ha^{-1}$ $year^{-1}$). Demonstrations yielded 3–10 t $ha^{-1}$ $year^{-1}$ more than controls. Yield losses were calculated using the boundary line approach. In Central, yield losses, expressed as percentage of attainable yield, were mainly attributed to pests (nematodes 10% loss, weevils 6%) and suboptimal crop management (mulch 25%). In South, poor soil quality (pH 21%, SOM 13%, N-total 13%, and Clay 11%) and suboptimal crop management (weeds 20%) were the main constraints. In Southwest, suboptimal crop management (mulch 16%), poor soil quality (K/(Ca + Mg) 11%) and low rainfall (5%) were the primary constraints. The study revealed that biotic stresses (i.e. pests, weeds) are particularly important in Central, whereas abiotic stresses (i.e. nutrient deficiencies, drought) dominate in South and Southwest. This study concludes that (i) technologies currently available allow farmers to double yields and (ii) past research efforts have neglected abiotic constraints mistakenly.


**Keywords:** Boundary line analysis; Yield gap; Production constraints; Soil fertility; Crop management; Pest pressure; Uganda.

# 1. Introduction

Banana is one of the most important food crops in the world (Samson, 1992) and is widely grown in the warm and humid tropics (FAO, 2009). Uganda was the second largest producer of banana in the world, and the most important in Africa in 2007 (FAO, 2009). Although East African highland bananas (*Musa* spp., AAA-EA genome) are a primary food and cash crop in Uganda (Bagamba, 2007), actual production is poor (<30 t $ha^{-1}$ $year^{-1}$) compared with attainable yield (>70 t $ha^{-1}$ $year^{-1}$) (van Asten et al., 2005).

Numerous studies in Uganda have reported on biophysical production constraints such as soil fertility problems (Bekunda and Woomer, 1996), inadequate moisture (Okech et al., 2004a), banana weevil (*Cosmopolites sordidus*) (Gold et al., 1999), parasitic nematodes (*Radolpholus similis, Helicotylenchus multicintus*) (Speijer et al., 1999), and plant diseases (Tushemereirwe, 2006). However, these studies have several shortcomings. Firstly, yield reductions attributed to these constraints were observed in only a few fields, which may not be representative of the region. The few studies that covered a larger geographical area (e.g. Bekunda and Woomer, 1996; Bagamba, 2007) used farmer estimates of production collected during single visit surveys. Furthermore, national statistics for Uganda, for example FAO data, are based on calculated estimates and survey studies, and not on direct measurements and monitoring. Surveys take a snapshot of production and constraints, whereas yields and constraints show large temporal variations (Birabwa et al., 2010). Most studies on pests (e.g. Rukazambuga et al., 1998; Speijer et al., 1999) were conducted on-station under controlled environments, where pest pressure was artificially increased in some plots and eliminated in others. Although several authors suggested that some factors are more limiting than others (e.g. Gold et al., 1999; Smithson et al., 2001), the effects of the different constraints on yield have not been partitioned.

Research on highland bananas has mostly focused on pest constraints (van Asten et al., 2005) probably because farmers rank pests as the most important constraint. For example, farmers ranked pest pressure to be more important in restricting yields than poor soil fertility in Central Uganda (Gold et al., 1999). Subsequently, tolerance to banana weevil was ranked more important than tolerance to marginal soil fertility for germplasm selection in Central, South and Southwest Uganda (Gold et al., 2002b). A major drawback of relying on farmer diagnosis is that farmers cannot assess phenomena that they cannot see (Grossman, 2003), or that are uniformly distributed within their field or village (van Asten et al., 2009).

This study aimed to: (i) identify important factors limiting banana production in Uganda; (ii) quantify the possible yield gap attributed to each of these factors; and (iii) explore potential areas of interactions between these yield loss factors. To avoid geographic or temporal bias, this study reports on data collected in farmer fields across Uganda's major banana production areas during a 12-month period in 2006-2007.

# 2. Materials and methods

## 2.1 Study area

The study was conducted on 159 plots, in mature plantations (from 5 to over 100 years old), in Central, South and Southwest regions of Uganda. The area lies approximately between latitudes 0º45'N and 0º 49'S and longitude 29º 54' and 32º 49'E at an altitude of 1120-1700 m above sea level (masl). The soils are mainly Acrisols and Ferralsols according to the FAO classification. The parent rocks underlying the soils sampled in this study have been described as Archaean Gneissic-Granulitic-Complex, Proterozoic metamorphic rocks and Proterozoic sediments (Schlüter, 2008). The East African Meteorological Department (1963) generalized the rainfall pattern as bimodal with highest rainfall from March to May, and from September to November.

Of the study plots, 86 were demonstration plots (28, 24 and 34 of the plots in Central, South and Southwest regions, respectively) established in 2004 by the Agricultural Productivity Enhancement Program (APEP). Control plots were selected in 2006 within the farms hosting demonstrations or on nearby farms. Although at the start of the study control and demonstration plots were paired, the data presented is not based on paired plots as 13% of the farmers dropped out before the end of the study period. APEP only picked plots for demonstration practices if the farm included an area of at least 0.4 ha under banana, and the owners were willing to host demonstrations and share information with neighbouring farmers. Each demonstration plot was 'owned' by learning groups of on average 10 farmers. Control plots were picked from the same farm as demonstration plots or from neighbouring farms showing similar 'average' management practices. On average 71, 8, 32 kg ha$^{-1}$ year$^{-1}$, of N, P, K, respectively, from a compound fertilizer (22.0% N, 2.6% P, and 10.0% K) were applied to demonstration plots. The rate of fertilizer applied (*Fertilizer,* kg of compound fertilizer ha$^{-1}$ year$^{-1}$) varied among demonstration plots because all farmers applied equal fertilizer rates (66, 8 and 30g year$^{-1}$ of N, P and K, respectively), to individual mats, but plant population densities (mats ha$^{-1}$) varied. The fertilizer was applied at the beginning, in the middle and towards the end of each of the two rainy seasons in a year. The fertilizer was applied in a shallow circular furrow and covered with soil at a distance between 0.3 and 0.6 m from the mat. External mulch was applied in 21% and 67% of the control and demonstration plots, respectively. Mulch thickness averaged 1 and 2 cm in control and demonstration plots, respectively. Banana production in all plots was rain-fed.

### 2.2 Data collection

Data were collected over a 12- month period during 2006-2007; i.e. more than two years after the establishment of the demonstration plots, so that any anticipated yield improvements would already be fully visible. Within each plot, 30 mats of AAA-EA cooking varieties were randomly selected and marked for monitoring. Data on yield related parameters, major management practices (i.e. mulching and weeding) and crop damage by pests were recorded during farm visits made at 3-5 months intervals during the study period. Farmers received weighing balances to record bunch weights of marked mats. Data on girth of stem at base and 1 m, number of hands, number of fingers in the bottom row of the second lowest hand were collected from fruiting plants and used to estimate bunch weights where data on bunch weights were missing, using the general allometric regression derived by Wairegi et al. (2009). Banana mats were defined as a single family of banana plants with interconnected living corms; i.e. single mother plants and their connected suckers. Banana mat spacing was determined by measuring the distances from a randomly selected mother plant to the nearest four mother plants that did not belong to the same mat. At each farm 10-20 mother plants were selected to determine average mat spacing per plot. Average population densities (*Population*) in terms of mats per hectare were then estimated from average mat spacing. Yield (t $ha^{-1}$ $year^{-1}$) was then calculated based on total weight of bunches harvested from the monitored mats in the year and population density. Root necrosis percentage (*Nematodes*) caused by root lesion nematodes was assessed on roots of flowering plants according to Speijer and Gold (1996). Percentage of banana weevil damage in the corm (*Weevils*) was estimated at harvest using the methods described by Gold et al. (1994). The presence of sigatoka leaf fungal diseases was not monitored after initial field visits showed that there was little disease pressure; i.e. the youngest leaf showing at least 10 spots with a necrotic dry centre (Vakili, 1968) was ≥5. The presence and intensity of other plant diseases, such as banana bunchy top disease and banana *Xanthomonas* wilt (BXW), were recorded when visual symptoms were observed. Mulch thickness (*Mulch*; cm) was the average of mulch measurements taken in 40 randomly selected points in each plot. These measurements did not distinguish between self-mulch and external mulch. The product of estimated weed canopy surface cover (%) and average maximum weed height (cm) as measured at 20 points in the plot was calculated. The weed pressure indicator (*Weeds*) was the square root of this product.

Composite soil samples per plot were collected in the dry season at 0-30 cm from points not too close (> 1 m) to banana mats to avoid possible fertilizer contamination in demonstration plots. Analytical methods used are described by Okalebo et al. (1993). Soil pH was measured in 1:2.5 sediment-water suspension. Soil organic matter (*SOM*) was determined using Walkley-Black procedure (Nelson and Sommers, 1982). Total N (*N-Total*) was determined using Kjeldahl digestion with sulphuric acid and selenium as a catalyst, and measured colorimetrically. Available P and extractable cations (K, Ca and Mg) were extracted using Mehlich-3 extraction solution (Mehlich, 1984), Available P was measured colorimetrically using the molybdenum blue method, K was measured using a flame photometer, while the other cations were determined using an atomic absorption spectrophotometer. Texture analysis (for *Sand*, *Silt* and *Clay*) was performed using the hydrometer method (Gee and Bauder, 1986).

Annual rainfall (mm year$^{-1}$) at the study sites was based on mean monthly rainfall simulated using *LocClim* (FAO, 2006). The software estimates mean monthly rainfall for a location based on past rainfall records of nearby meteorological stations, and altitude, latitude, and longitude of the study location. *LocClim* rainfall estimates were assumed to be reliable because the mean annual rainfall predicted by *LocClim* for specific sites in Central and Southwest was not significantly different ($P \leq 0.05$) from actual observations reported for these sites in previous studies (e.g. Smithson et al., 2004; Okech et al., 2004a). In addition, farmers and local agricultural staff observed that there were no anomalies in rainfall amount and distribution during the study period. *LocClim* was found to be reliable in estimating rainfall observations in areas where mean annual rainfall was <5000 mm year$^{-1}$ (Mokany et al., 2006) and has been used in other studies to estimate rainfall (e.g. Heaton et al., 2004; Mokany et al., 2006).

### 2.3 Analytical approach

Means for yield and biophysical factors, including cation ratios, were compared among regions using analysis of variance and means comparisons. Then, Spearman's test for non-parametric data was used to explore correlations between continuous biophysical factors and yield.

We developed functional relationships between yield and those biophysical factors that correlated significantly ($P \leq 0.05$) with yield in Spearman's test, or for those variables for which the upper boundary points in the scatter plot with yield suggested a functional relationship. For each data set of biophysical factor ($x$-axis) and ($y$-axis) yield, upper boundary points were built from scatter plots using the boundary line development system (BOLIDES) developed by Schnug et al. (1996) and applied in several studies to derive functional relationships between yield and biophysical factors (e.g. Fermont et al., 2009; Shatar and McBratney, 2004). For data sets where positive correlations between yield and boundary points were observed (i.e. increase in the biophysical factor corresponded to increase in yield), boundary lines were fitted through the upper boundary points of the data cloud using the model adapted by Fermont et al. (2009):

$$Y_l = \frac{Y_{att}}{1 + (K \exp(-Rx))} \quad (1)$$

where $Y_{att}$ is the highest yield attained during this study in a region, $x$ is the independent variable and $K$ and $R$ are constants. For data sets with negative correlations between yield and boundary points (i.e. increase in the biophysical factor corresponded to a decrease in yield), quadratic or linear regression lines were fitted through the boundary points to achieve the highest coefficient of determination ($R^2$). Each boundary line function was then used to predict the maximum yield possible ($Yx_i$) for each biophysical factor ($i = 1, 2, \ldots n$) in each plot. The highest yield observed in each region was assumed to be the attainable yield in farmers' fields in that region.

For each biophysical factor, the gap between $Y_{att}$ and $Yx_i$ *was* calculated, for each plot. The yield gap was then expressed as percentage of $Y_{att}$ to allow for comparison among regions.

For each plot, assuming responses according to von Liebig's law of the minimum (Shatar and McBratney, 2004), the minimum predicted yield ($Y_{min}$) described as

$$Y_{min} = \text{Min}\ (Yx_1,\ Yx_2,\ \ldots\ldots, Yx_n) \quad (2)$$

was identified. The explainable yield gap was defined as the difference between $Y_{att}$ and $Y_{min}$, and the unexplained yield gap was defined as the difference between $Y_{min}$ and observed yield ($Y_{obs}$). This approach to quantify yield gaps has not only been successfully used with cereals (e.g. Casanova et al., 1999; Shatar and McBratney, 2004), but also with cassava (Fermont et al., 2009).

Finally, for each biophysical factor, the number of plots in which it was identified as the most limiting was calculated for each region. This allowed the ranking of most limiting factors per region, with the most important biophysical constraint being the factor that was most often identified as corresponding to $Y_{min}$.

Statistical analyses were performed with SPSS for Windows, release 11.0, standard version (SPSS Inc., 1989-2001) and Microsoft Office Excel 2003.

## 3. Results

Banana yields ranged from 1.9 to 31.1 t ha$^{-1}$ year$^{-1}$ in Central, 3.8 to 36.2 t ha$^{-1}$ year$^{-1}$ in South, and 4.6 to 37.0 t ha$^{-1}$ year$^{-1}$ in Southwest (Table 1). When averaged across all plot types, yields were significantly ($P\leq0.05$) higher in Southwest (22.2 t ha$^{-1}$ year$^{-1}$) compared with Central and South (both 15.7 t ha$^{-1}$ year$^{-1}$) (Table 1). In all regions, yields (t ha$^{-1}$ year$^{-1}$) were significantly ($P\leq0.05$) increased in demonstration plots compared with control plots (20.4 vs 12.4 in Central, 19.7 vs 9.7 in South, 22.8 vs 20.0 in Southwest). Control plots in Southwest had significantly ($P\leq0.05$) larger yields than control plots in Central and South. Average corm damage caused by weevils was significantly ($P\leq0.05$) more severe in Central (5%) compared with South and Southwest (both 3%) (Table 1). Other factors presented in Table 1 did not differ significantly ($P\leq0.05$) among regions. Altitude in Central, South and Southwest averaged 1186, 1238 and 1485 masl, respectively.

No visual symptoms of banana bunchy top disease were observed. Symptoms of BXW were present only in five plots. In one of these plots, approximately 30% of the mats had symptoms and all the mats in that plot were uprooted. In the other four plots, the disease was observed in approximately 1-2% of the mats and was controlled by uprooting the mats with symptoms. The disease appeared to have been controlled successfully in the four plots because no new incidences were observed during subsequent visits. We therefore did not explore the relationship between disease intensity and yield.

Table 1: Descriptive statistics of yield and biophysical factors in Central, South and Southwest regions of Uganda.

| Factors[a] | Central ($n$ = 52) | | | South ($n$ = 43) | | | Southwest ($n$ = 64) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min. | Max. | Mean | Min. | Max. | Mean | Min. | Max. | Mean |
| Yield (t $ha^{-1}year^{-1}$) | 1.9 | 31.1 | 15.2 | 3.8 | 36.2 | 15.2 | 4.6 | 37.0 | 22.2 |
| Nematodes (% root necrosis) | 0 | 38 | 11 | 0 | 42 | 8 | 0 | 15 | 4 |
| Weevils (% corm damage) | 0 | 18 | 5 | 0 | 13 | 3 | 0 | 20 | 3 |
| Soil pH | 5.6 | 7.1 | 6.4 | 5.8 | 7.9 | 6.8 | 3.8 | 7.3 | 5.6 |
| Soil organic matter (%) | 2.32 | 5.82 | 3.58 | 2.23 | 6.06 | 3.73 | 1.40 | 5.60 | 3.08 |
| Total soil N (%) | 0.08 | 0.28 | 0.18 | 0.10 | 0.35 | 0.22 | 0.08 | 0.27 | 0.16 |
| K/(Ca+Mg) ratio | 0.03 | 0.39 | 0.18 | 0.07 | 0.35 | 0.18 | 0.05 | 0.52 | 0.17 |
| Clay (%) | 18.9 | 45.8 | 29.1 | 15.7 | 43.7 | 30.5 | 11.0 | 42.5 | 24.9 |
| Rainfall (mm $year^{-1}$) | 1157 | 1391 | 1285 | 892 | 1188 | 1029 | 782 | 1416 | 1083 |
| Mulch depth (cm) | 0 | 7 | 1 | 0 | 8 | 2 | 0 | 5 | 1 |
| Weeds[b] | 0 | 17.60 | 9.39 | 0 | 16.17 | 6.27 | 0 | 15.79 | 5.67 |
| Population (mats $ha^{-1}$) | 400 | 2500 | 1396 | 730 | 2066 | 1276 | 692 | 2066 | 1107 |

[a] Factors for which boundary lines were not drawn (e.g. soil P concentration, sand and silt content) are not presented.
[b] Weeds is the cube root of the product of weed canopy (%) and height (cm).

Yield was correlated positively with *Fertilizer* ($r$ = 0.29-0.69, $P$≤0.05) and *Mulch* ($r$ = 0.42-0.57, $P$≤0.01) in all regions. Yield was correlated positively with plant *Population* in the Central region ($r$ = 0.30, $P$≤0.05) and *Rainfall* in the Southwest ($r$ = 0.51, $P$≤0.001).

Boundary regression lines were determined for the factors: *Nematodes*, *Weevils*, *N-total*, K/(Ca+Mg), *Mulch*, *Weeds* and *Population* in Central, *Nematodes*, *pH*, *SOM*, *N-total*, K/(Ca+Mg), *Clay*, *Fertilizer*, *Weeds* and *Rainfall* in South, and *Nematodes*, *Weevil*, *pH*, *SOM*, *N-total*, K/(Ca+Mg), *Fertilizer*, *Mulch* and *Rainfall* in Southwest. Yields declined with increase in *Nematodes* (Figure 1a), *Weevils* (Figure 1b) and *Weeds* (Figure 1h). For other factors, yields increased until the attainable yield was reached (e.g., *pH*, Figure 1c; *SOM*, Figure d) in the observed range. Separate boundary lines were plotted for each factor and region.

Average yield gaps (expressed as percentage of $Y_{att}$, where $Y_{att}$ was 31.1, 36.2 and 37.0 t ha$^{-1}$ year$^{-1}$ in Central, South and Southwest, respectively) corresponding to each factor by region combination, did not differ significantly ($P$≤0.05) between control and demonstration plots for all factors except *Fertilizer* (control and demonstration plots averaged 53.1% and 7.4%, respectively, in South, and 31.0% and 4.8%, respectively, in Southwest), *Weeds* (control and demonstration plots averaged 19.9% and 4.6%, respectively, in Central, and 36.1% and 17.2%, respectively, in South), and *Mulch* (control and demonstration plots averaged 20.0% and 10.4%, respectively, in Central, 28.0% and 11.7%, respectively, in Southwest) (the rest of the data is not presented). The distribution of yield gaps varied among factors and regions (Figure 2). Since the figure illustrated that the distribution of the yield gaps was not normal for all factors, medians instead of means were used to describe the data, to show the expected yield gap in a typical plot. In Central, the largest yield gap median was for *Mulch* (25.3%), followed by *Nematodes* (10.3%), *Weevils* (5.5%), *N-total* (3.0%), *Population* (2.3%), *Weeds* (1.6%) while K/(Ca+Mg) had the least (0.4%). In South, the largest median was for *pH* (20.6%), followed by *Weeds* (19.9%), *SOM* and *N-total* (both 13.0%), *Fertilizer* (12.5%), *Clay* (11.3%), and *Nematodes* (7.9%), *Rainfall* (3.2%) while K/(Ca+Mg) had the least (2.7%). In Southwest, *Mulch* had the largest median (16.3%), followed by K/(Ca+Mg) (11.3%), *Fertilizer* (7.0%), *Rainfall* (4.5%), *Weevils* (3.8%), *SOM* and *N-total* (both 2.2%), *Nematodes* (1.9%) while *pH* caused the smallest yield gap (1.0%).

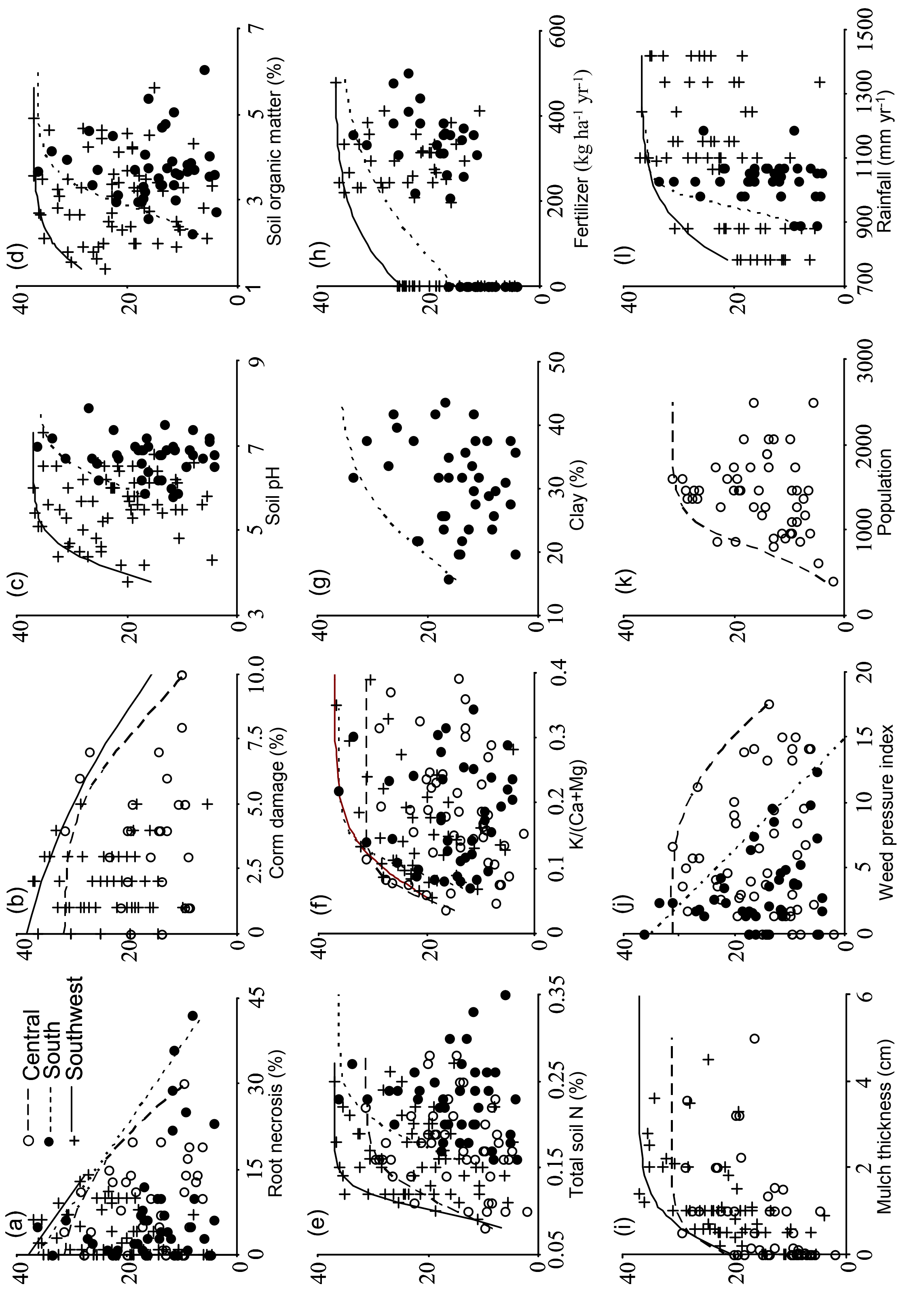


Figure 1: relationship between highland banana yield and biophysical factors in Central, South and Southwest regions of Uganda. The lines represent the boundary lines

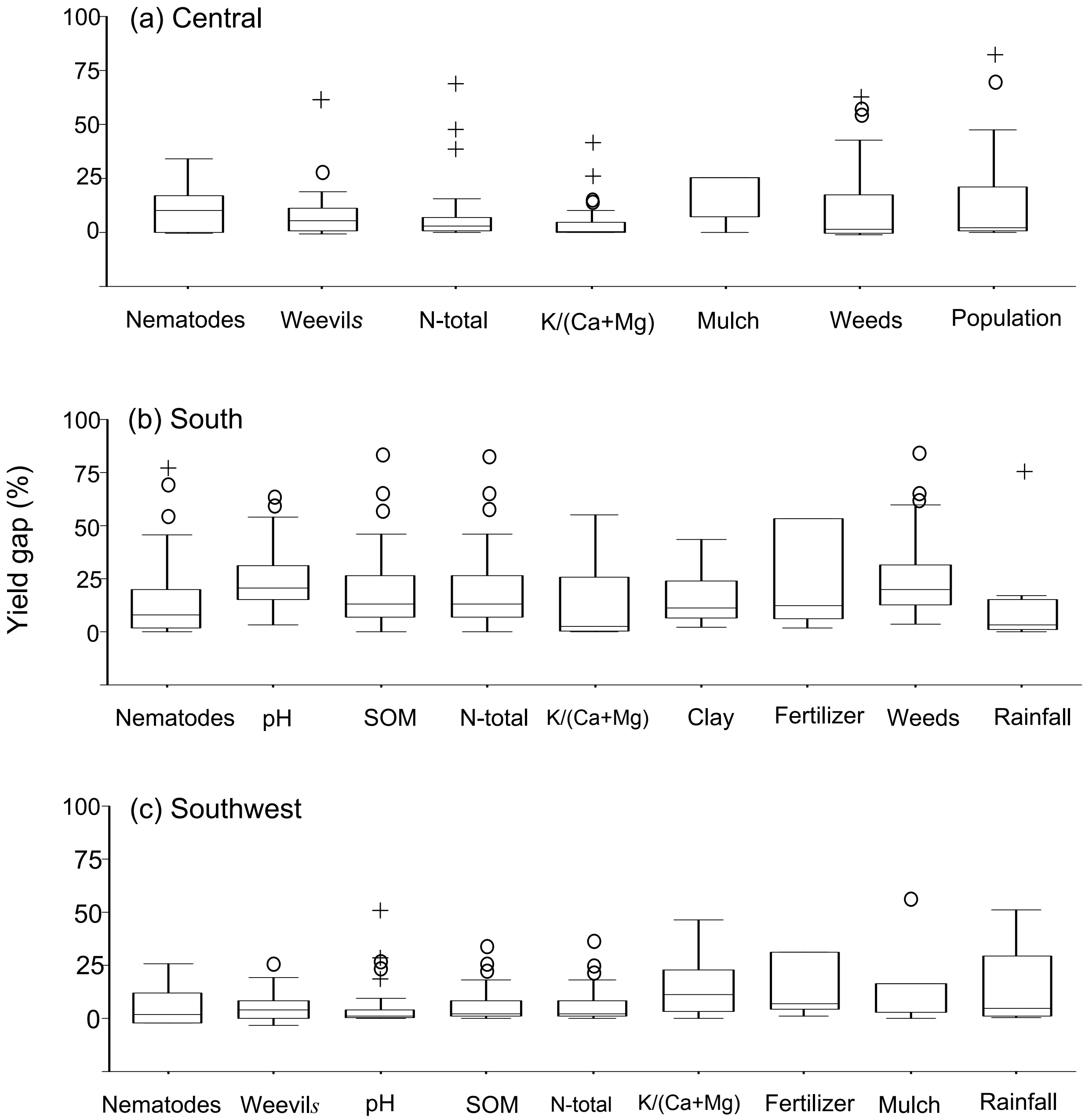


Figure 2: The yield gap explained by biophysical factors, expressed as percentage of maximum yield attained, for (a) Central, (b) South and (c) Southwest regions of Uganda. The solid lines across boxes are medians. The boxes represent the interquartile range (25–75$^{th}$ percentile), circles represent outliers outside the central box by between 1.5 and 3 times the interquartile range, crosses represent outliers outside the central box by above 3 times the interquartile range, while bars represent the smallest and largest observations which are not outliers. For mulch, both median and upper bar are close to the top line of the box.

In Central, South and Southwest, the explained average yield gap was 10.9, 18.4 and 13.3 t ha$^{-1}$ year$^{-1}$, respectively and the unexplained yield gap averaged 5.0, 2.2 and 1.9 t ha$^{-1}$ year$^{-1}$, respectively (Figure 3). The $R^2$ of the relationship between $Y_{obs}$ and $Y_{min}$ was 0.38, 0.66 and 0.64 for Central, South and Southwest, respectively.

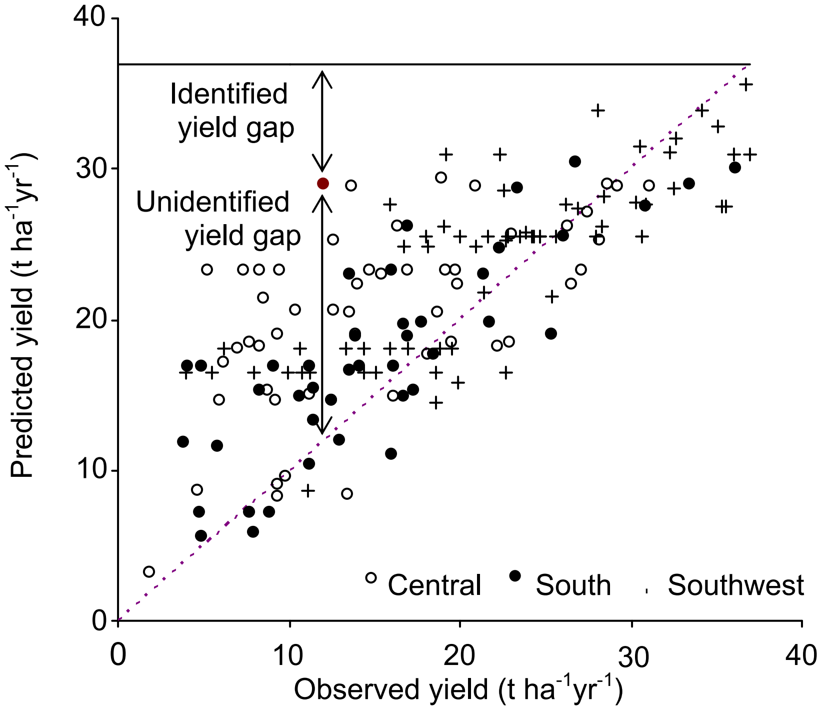


Figure 3: Observed and predicted yield from the boundary line approach for Central, South and Southwest regions of Uganda. The predicted yield was the minimum prediction based on biophysical factors. The continuous line $y$ = 37 t ha$^{-1}$ year$^{-1}$ represents the maximum observed yield in the Southwest region while maximum yields for Central (31.1t ha$^{-1}$ year$^{-1}$) and South (36.2 t ha$^{-1}$ year$^{-1}$) are not shown. The dotted diagonal line depicts the relationship $y = x$.

In Central, *Mulch* was the most limiting factor in 20.9% of the plots, followed by *Weevils* (18.6%), *N-total* (15.4%), *Nematodes* (12.2%), *Weeds* (11.5%), *Population* (11.3%) and K/(Ca+Mg) (10.2%) (Figure 4). In South, *Weeds* was the most limiting factor in 20.8% of the plots, followed by, *pH* and *Fertilizer* (both 14.2%), *N-total* (13.6%), K/(Ca+Mg) and *Rainfall* (both 9.3%), *SOM* (7.1%), *Nematodes* (6.8%) and *Clay* (4.7%). In Southwest, *Mulch* was the most limiting factor in 19.4% of the plots, followed by *Fertilizer* (17.9%), *Rainfall* (14.4%), K/(Ca+Mg) (11.6%), *Weevils* (11.1%), *N-total* (9.1%) and *pH* (7.2%), *Nematodes* (4.9%) and *SOM* (4.3%).

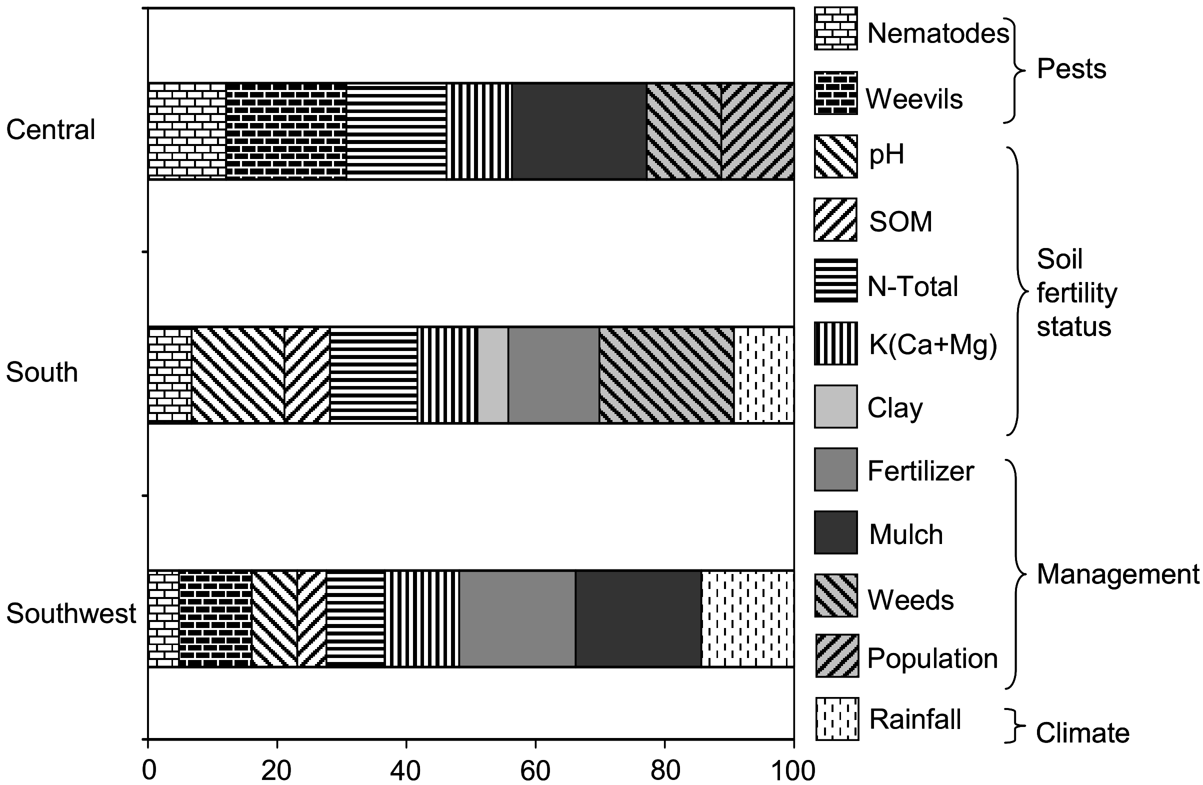


Figure 4: The most limiting biophysical factors identified using the boundary line approach and the corresponding proportion of plots (%) in which these factors were most limiting, in Central, South and Southwest regions of Uganda.

# 4. Discussion

## 4.1 Banana yields

The poorer yields observed in control plots in Central (12.4 t ha$^{-1}$ year$^{-1}$) and the South (9.7 t ha$^{-1}$ year$^{-1}$) compared with Southwest (20.0 t ha$^{-1}$ year$^{-1}$) is partially in agreement with previous studies. Although yields in the Central, South and Southwest regions were estimated as 7.3, 8.0 and 18.9 t ha$^{-1}$ year$^{-1}$, respectively, in a survey by Bagamba (2007) and 5, 7 and 19 t ha$^{-1}$ year$^{-1}$, respectively, in another survey by Kalyebara et al. (2006), both surveys seemed to underestimate yields in the Central region. Furthermore, the yields observed in control plots in our study, and those reported in the surveys, suggest that the estimated national average of 5.5 t ha$^{-1}$ year$^{-1}$ for Uganda in 2007 (FAO, 2009) is unrealistically small. The large difference between the average yields and the maximum yields we observed (Table 1) suggests that banana yields in Uganda can be doubled using management technologies currently available to farmers. On the other hand, achieving the suggested attainable yield of >70 t ha$^{-1}$ year$^{-1}$ (van

Asten et al., 2005) may be constrained by factors that cannot be addressed using management practices currently available.

## 4.2 Limiting factors

### *4.2.1 Boundary line functions*

The separate boundary lines identified for regions (Figure 1) suggest that the boundary line approach is more appropriate for data confined to a single agro-ecological zone and less appropriate for data covering a wide geographical region. For example, the relationship between minimum predicted yields and observed yields for all data was much better for boundary lines specific to regions ($R^2$ = 0.58) than for boundary lines that were based on pooled data ($R^2$ = 0.04) (data not presented). The lines also suggested that management decisions should not be only based on visual assessment of single constraints, but based on a comprehensive understanding of yield reduction causes. For example, although weed density in the Central region was 29% higher than in the South (Table 1), the median yield reduction attributed to weed pressure was 1.6 and 19.9% in the Central and the South, respectively.

### *4.2.2 Important constraints to banana production*

Poor soil fertility was an important constraint in all regions, which was illustrated by the featuring of soil parameters (i.e. SOM, N-total, K/(Ca+Mg) amongst the most limiting factors, with pH, SOM being particularly important in the South and the Southwest, and N-total and K/(Ca+Mg) playing an important role in all regions (Figure 2 and Figure 4). The importance of soil fertility in banana production was further emphasized by the stronger yield reductions associated with its related parameters (i.e. Mulch in the Central region and the Southwest, pH in the South, fertilizer in the South and Southwest) compared with other factors in all regions (Figure 2). Pest constraints (Nematodes, Weevils) were particularly important in Central Uganda, but not in the South and Southwest (Figure 4). Other key constraints were soil moisture in the Southwest (Figure 4) and weed pressure in the South (Figure 2 and Figure 4). The importance of factors in respect to the yield reductions they caused and the number of plots in which they were most limiting implied that that poor banana production in Uganda is to a greater extent due to abiotic constraints (soil fertility and moisture) than to biotic constraints (pests and diseases). Although we did not discriminate between control and demonstration plots, the proportion of plots in which factors related to management were most liming was most likely higher for control plots compared with demonstration plots because yield gaps attributed to fertilizer use, mulch thickness and weed pressure were higher in control than in demonstration plots.

Although values of yield loss factors were similar for many plots, there were few plots that were uniquely different from the rest (Figure 2). For example, although yield gaps attributed to root necrosis had a median of 7.9% in the South, the outliers suggested that in some farms, yield loss attributed to nematodes could be as high as 80%. These outliers may partially be due to spatial variability in constraints within regions. For example, since the South region comprised of two districts, further exploration of data (data not presented) showed that yield gaps attributed to root necrosis, cation ratios and clay differed significantly ($P \leq 0.05$) between the two districts. This suggests the need to target units smaller than regions when diagnosing constraints and subsequently developing recommendations.

Although we did not quantify the yield gap attributed to diseases, we believe that diseases deserve mention because they have often been cited as important constraints to banana production in several studies (e.g. Gold et al., 1999; Tushemereirwe, 2006). Sigatoka leaf fungal diseases, which were assessed during initial field visits, did not seem to be a major problem in the plots studied i.e. the position of the youngest leaf spotted was ≥5, indicating low disease pressure. Although BXW, which causes yield losses of up to 100% (Tushemereirwe, 2006), was reported to be spreading in Uganda (Smith et al., 2008), the disease did not seem important in the plots studied as symptoms were observed in <3% of the plots. This can be partially attributed to the training of participating farmers on appropriate management practices for controlling the disease by the APEP project, so our BXW incidence findings may be slightly biased. Adoption of BXW management strategies has been reported to reduce disease incidence to less than 10% (Tripathi et al., 2009). Although diseases did not seem important in this study, we believe that there is a need to monitor banana systems continuously to prevent potentially devastating outbreaks.

*4.2.3 Comparison of our findings with past research*

Our suggestion that poor soil fertility is a constraint in Central, South and Southwest Uganda is in agreement with previous studies. Soils under which bananas are grown in Uganda are often Ferralsols and Acrisols, which have been reported to have poor inherent fertility (Sanchez et al., 1989). Also, the significant increases yields reported in the Central and Southwest regions on fertilizer application (Smithson et al., 2004) support this suggestion.

The importance of pests in the Central region, compared with other regions has also been documented in previous studies. Smithson et al. (2001) reported high root necrosis in experiments in the Central region (12% and 24%) compared with the Southwest (0.5%). In the same study, corm damage was higher in the Central (5.3-18.6%) compared with the Southwest (1%). Studies have related the geographic distribution patterns of pests in Uganda to altitude. For example, corm damage by banana weevils was severe up to 1400 masl while no weevils were present above 1700 masl in Uganda (Speijer et al., 1993) and yield losses could apparently be attributed to nematodes at low altitude sites (<1300 m altitude) but not at high altitude sites (≥1500 m) in Rwanda (Gaidashova et al., 2009). This seems to agree with our study as average altitude was 1186 m in the Central region compared with 1238 m in the South and 1485 m in the Southwest. Although few studies have quantified yield reductions due to moisture stress, yield losses of 40-50% have been estimated when rainfall is 1100 instead of 1500 mm year$^{-1}$ (Godfrey Taulya, personal communication) and Okech et al. (2004a) reported a yield reduction of 50% in the Southwest. Since the standard deviation of the mean for rainfall in the Southwest was more than double that for other regions (data not presented) and other constraints were less important, our results support the conclusion of earlier studies that low rainfall is a particularly important constraint in the Southwest.

*4.2.4 Comparison of our findings with farmer perceptions*

Our findings that poor soil fertility was an important constraint to production in Central, South and Southwest Uganda, nematodes and weevils were important constraints in the Central region, and low rainfall was important in the Southwest partially agree with farmer perceptions. In the survey conducted by Gold et al. (1999) farmers in the Central region ranked pests as the major cause of decline in banana production while both soil fertility decline and climatic change (increased drought and unreliability of rainfall) ranked second. Interestingly, the pests they actually referred to were weevils as they could not recognize nematode damage. Farmers in an erosion prone area in the South ranked constraints to production in order of importance as changes in rainfall pattern, soil exhaustion, soil erosion, and pests and diseases (Tenywa et al., 1999). In the Southwest, the higher ranking given to pests and diseases compared with poor soil fertility by farmers (Okech et al., 2004b) and the higher ranking given to resistance to banana weevil compared with tolerance to poor soil fertility in germplasm selection (Gold et al., 2002b) disagrees with our findings. The suggestion by van Asten et al. (2009) that farmers find it difficult to detect constraints that show little spatial or temporal variation at plot, farm or village level may explain the differences between our findings and farmer perceptions.

*4.2.5 The "Unexplained" yield gap*

The higher $R^2$ for the relationship between observed yield and the yield predicted by the most limiting factor in the South (0.66) and the Southwest (0.64), compared with the Central region (0.38) (Figure 3) and the higher average explained yield gap in the South (94% of the total yield gap) and the Southwest (93%) compared with the Central region (68%) suggests that the study may have excluded some important limiting factors in Central. For example soil physical factors (e.g. porosity, compaction, aeration, water-holding capacity) and soil temperature are important factors in banana production (Robinson, 1996). It could also be attributed to interactions among factors influencing yield (Fermont et al., 2009). Nutrient and water uptake is impaired when plant roots are infested by nematodes or corms are damaged by weevils (Robinson, 1996). Furthermore, higher damage by banana weevil has been reported in plants infested by nematodes compared with non-infested plants (Speijer et al., 1999. We therefore believe that the low $R^2$ in Central may have been partially due to the interaction between pests and soil related factors as the boundary line approach does not take account of such interactions. This agrees with the suggestion by Smithson et al. (2001) that banana production in Central is influenced by a complex of pests, diseases and soil status rather than any one cause in isolation. Therefore, our study indicates that the boundary line approach can help rank constraints and give a semi-quantitative estimation of the problems. On the other hand, in areas where biotic constraints are particularly important, the method then predicts yields less accurately due to the higher order interactions between constraints. Under such conditions, the situation is further removed from Liebig's law and in closer agreement with Liebscher's Law of the Optimum. Also, since the method uses covariates which at times can be closely related, results can sometimes be difficult to interpret. For example, soil organic matter was correlated positively with total soil nitrogen in all regions ($r$ = 0.78, 0.76 and 0.86, in Central, south and Southwest, respectively; $P \leq 0.05$) (data not presented) but soil organic matter was not a limiting factor in Central while N limited production in all regions (Figure 4).

## 5. Conclusions

In this study, the yields quantified by monitoring production in farmer control fields during a 12-month period were almost double the official national statistics for Uganda. Earlier studies reporting on banana yields in Uganda often had the weakness that data were collected during single point surveys or through farmer estimates, and not by actually quantifying yields over time. Our finding suggests that highland banana production and consumption may be much more important than previously estimated, but careful mapping of banana acreage is required to verify this accurately. Despite these relatively higher yields, the actual average farmer yield remains poor (10-20 t $ha^{-1}$ $year^{-1}$) compared with the estimated potential (>70 t $ha^{-1}$ $year^{-1}$) and the largest yield attained in the best plot (37 t $ha^{-1}$ $year^{-1}$). This shows that there is considerable scope for yield improvement. This is the first study to quantify the strong spatial variation in highland banana yield constraints. Biotic constraints were important in Central, but not in South and Southwest Uganda. The higher pest pressure in the Central region may be due to the lower altitude, which is more favourable for nematodes (*R. similis* and *H. multicintus*) and weevils, and poorer crop management. Poor soil fertility proved to be an important constraint in all regions. The yield gap in banana production in Uganda can be best addressed by region-specific management interventions that address the spatial variation in crop constraints. Despite the importance of soil fertility and drought, little research has been conducted on these constraints in highland bananas. Considering past publication records and current research staff investments, we estimate that over 80% of the research resources on highland bananas focused primarily on overcoming pest and disease constraints through development of biocontrol options and resistant germplasm. Pest and disease constraints and outbreaks (e.g. the outbreak of BXW in 2001) remain a threat to these systems that deserves continuous attention, but current research investments are imbalanced. Not addressing abiotic constraints will prevent farmers from substantially and sustainably improving banana yields in one of Africa's most densely populated regions where agricultural intensification is increasingly considered a necessity, not a luxury.

Chapter 5

# The agronomic and economic benefits of fertilizer and mulch use in highland banana systems in Uganda

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Abstract

Banana is the most important food crop in Uganda. However, there has been a decline in productivity, attributed to declining soil fertility, drought, pests and diseases and crop management factors. This study aimed to explore the possibility of increasing yields through the use of fertilizer and mulch, and to evaluate the benefits of these inputs across the major banana producing regions in Uganda. This study was carried out in 179 smallholder plots in Central, South, Southwest and East Uganda in 2006-2007. Half of the plots were 'demonstration plots' of an agricultural development project, while the other half were neighbouring farmer plots that acted as 'control'. Demonstration plots received mineral fertilizer (100% of plots), averaging 71 N, 8 P, 32 K kg $ha^{-1}year^{-1}$ and external mulch from grass and crop residues (64% of plots), whereas control plots received no mineral fertilizer and little external mulch (26 % of plots). Demonstration plots had significantly ($P \leq 0.05$) higher yields than control plot in the Central, South and Southwest regions, but average yield increases varied from 4.8 t $ha^{-1}year^{-1}$ (Southwest) to 8.0 (Central), and 10.0 (South). There was little weevil corm damage (average 3%) and nematode-induced root necrosis (7%), so yield increases could only be explained by the use of fertilizer and mulch. The largest demonstration plot yield increases were observed where fertilizer addressed key nutrient deficiencies identified using the Compositional Nutrient Diagnosis approach. Farm gate bunch prices declined from 0.17 (Central Uganda) to 0.07 US$ $kg^{-1}$ (Southwest Uganda). Consequently, average marginal rate of return (MRR) of fertilizer and mulch use ranged from 0.1 (Southwest) to 5.8 (Central). The technologies were likely to be acceptable to farmers (MRR≥1.00) up to 160 km away from the capital. Fertilizer use is likely to be acceptable in all regions (MRR= 0.7 to 9.4) if local fertilizer prices of 2006-2007 (average US$ 0.56 $kg^{-1}$ of fertilizer) were reduced by 50%. Doubling of fertilizer prices is likely to make fertilizer use unacceptable beyond 100 km away from the capital. The study concludes that there is scope for increased input use in banana systems in Uganda, but that regional variations in crop response, input/output prices, and price fluctuations must be taken into account.

**Keywords:** Distance to market; Farm gate prices; Fertilizer; Mulch; Nutrient deficiencies; Price fluctuations; Profitability.

# 1. Introduction

The East African highlands is one of the most densely populated and intensively cultivated agricultural zones in Africa (Voortman et al., 2003) but suffers from chronic food and nutrition insecurity, according to FAO statistics (FAO, 2010). This trend tallies with poor crop productivity as most staple crops have yields of less than 30% of what is attainable (FAO, 2010). For example, although banana was estimated to meet more than 10% of the dietary energy requirements in Uganda, Rwanda and Burundi between 2003 and 2005 (FAO, 2010), actual yields are less than 40 t $ha^{-1}$ $year^{-1}$ (Wairegi et al., 2010 – Chapter 4), while the potential is greater than 70 t $ha^{-1}$ $year^{-1}$ (van Asten et al., 2005). The poor productivity has been attributed to declining soil fertility, drought, pests and diseases and socio-economic factors (Gold et al., 1999).

There is evidence that poor soil fertility is an increasing constraint to productivity in the region (Nandwa and Bekunda, 1998). The rapidly growing population has resulted in increase in land pressure (e.g. Fermont et al., 2008) and hence traditional methods of shifting cultivation and fallow are no longer feasible. In addition, use of nutrient inputs is inadequate (e.g. Bekunda and Woomer, 1996). Traditional livestock systems where cattle transferred nutrients from communal grazing land to farms have almost collapsed due to decrease in communal grazing land (e.g. Baijukya et al., 2005) and overgrazing. Most of the soils are highly weathered tropical soils (Acrisols, Ferralsols) that contain small nutrient stocks (Jaetzold and Schmidt, 1982). Hence, continuous production without use of adequate soil inputs has led to high nutrient depletion (Stoorvogel et al., 1993).

Addressing crop nutrient requirements using fertilizer has resulted in enormous increases in agricultural productivity in the developed world for close to 50 years (Cassman, 1999) and more recently in Asia where the Green Revolution succeeded (Voortman et al., 2003). Despite the indication in several studies in the East African region that traditional soil management practices should be complemented with fertilizer use (e.g. Palm et al., 1997; Sanchez et al., 1997), fertilizer use by farmers remains restricted. Literature reviewed by Mwangi (1997) identified high prices of fertilizer, low availability of fertilizer, the heterogeneity of the production environments leading to differences in nutrient requirements, differences in farmer resource endowments and market access among the challenges to profitable and sustainable use of fertilizers in the region. This paper addresses some of the constraints to fertilizer use in banana production by evaluating both agronomically and economically the benefits of fertilizer and mulch use in banana plantations and analysing how recommendations should be tailored to take into account variability in socio-economic and biophysical conditions.

# 2. Materials and methods

## 2.1 Study area

The study was conducted in 179 plots, in mature plantations (5-50 years old), in Central (Wakiso, Mukono, Luwero and Mpigi districts, denoted as $Central_1$, $Central_2$, $Central_3$ and $Central_4$, respectively), South (Masaka and Rakai districts, denoted as $South_1$ and $South_2$, respectively), Southwest (Mbarara and Bushenyi districts, denoted as $SWest_1$ and $SWest_2$, respectively) and East (the former Mbale district) regions of Uganda. The area lies approximately between latitudes 1º30' N and 1º00' S and longitude 29º52' and 34º 30' E at an altitude of 1120-1700 m above sea level. The soils are predominantly Acrisols and Ferralsols according to the FAO classification. The parent rocks underlying the soils sampled in this study have been described as predominantly Archaean Gneissic-Granulitic-Complex ($Central_{1-4}$ and $South_1$), Proterozoic metamorphic rocks ($SWest_1$, $SWest_2$), Proterozoic sedimentary rocks ($South_2$) and Cenozoic volcanic outcrops (East) (Schlüter, 2008). The East African Meteorological department (1963) generalized the rainfall pattern as bimodal with rains occurring in March-May and September-November. Annual rainfall at the study sites was estimated using *LocClim* (FAO, 2006) and ranged 782-1797mm $year^{-1}$. *LocClim* rainfall estimates were assumed to be reliable because the mean annual rainfall predicted by *LocClim* for specific sites in Central and Southwest was not significantly ($P \leq 0.05$) different from actual observations reported for these sites in previous studies (e.g. Smithson et al., 2004; Okech et al., 2004a). The *LocClim* has been used in other studies to estimate rainfall (e.g. Heaton et al., 2004; Mokany et al., 2006). The distance, by road, from the farms to the capital, Kampala, which is the major market, ranged from 16 to 344 km. The average distance in increasing order was 17 ($Central_1$), 43 ($Central_2$), 46 ($Central_3$), 80 ($Central_4$), 138 ($South_1$), 216 ($South_2$), 285 (East), 290 ($SWest_1$) and 322 ($SWest_2$) km.

Of the study plots, 95 were banana demonstration plots established in 2004 by the Agricultural Productivity Enhancement Program (APEP) while the rest were control plots. Although at the start of the study control and demonstration plots were paired, the data presented are not based on paired plots as 13% of the farmers dropped out before the end of the study period. Selection of demonstration plots was based on: i) the banana plantation area (i.e. at least 0.4 ha), and ii) the willingness of the owners to host demonstrations and to share information with neighbouring farmers. Each demonstration plot was ‘owned’ by learning groups of on average 10 farmers. Farmers were supplied with free fertilizer to apply on demonstration plots and were encouraged to use mulch through an incentive of US$ 20. The control plots depicted farmer management practices. Demonstration plots were applied a compound N, P, K fertilizer averaging (± standard deviation) 71±20, 8±2, 32±9 kg ha$^{-1}$ year$^{-1}$, respectively. The variability in the rate of fertilizer applied per hectare was because all farmers applied equal fertilizer rates to individual mats, but plant population densities (mats ha$^{-1}$) varied. The fertilizer was applied at the beginning, in the middle and towards the end of each of the two rainy seasons in a year. Banana production in all plots was rain-fed.

## 2.2 Data collection

Data were collected over a one year period (2006-2007). Within each plot, 30 mats of AAA-EA cooking varieties were randomly selected for monitoring. Data on yield related parameters, major management practices (i.e. mulching, manure application, and weeding) and crop damage by pests were recorded every three to five months during farm visits. Farmers were trained to record the fresh weight of bunches harvested from any of the 30 monitored mats. Data on girth of stem at base and 1 m above the ground, number of hands, and number of fingers in the bottom row of the second lowest hand were collected from fruiting plants. These data were used to estimate bunch weights using the general allometric regression derived by Wairegi et al. (2009) where farmers failed to properly record bunch weight data. Yield (t ha$^{-1}$ year$^{-1}$) was then calculated based on the harvested bunches, bunch mass, and plant population density. Root necrosis percentage (*Nematodes*) caused by root lesion nematodes was assessed on roots of flowering plants (Speijer and Gold, 1996). Banana weevil damage percentage in the corm (*Weevils*) was estimated at harvest using the methods described by Gold et al. (1994). The presence of sigatoka leaf fungal diseases was not monitored after initial field visits showed that there was little disease pressure (i.e. youngest leaf spotted >5). The presence and intensity of other plant diseases, such as banana bunchy top disease and banana *Xanthomonas* wilt (BXW), was recorded when visual symptoms were present. Mulch thickness (*Mulch*, cm) was the average of mulch measurements taken at 20 randomly selected points in each plot. These measurements did not distinguish between self-mulch and external mulch. Farmers provided information on whether manure was applied. The product of estimated weed canopy surface cover (%) and average maximum weed height (cm) as measured at 20 points in the plot was calculated. The weed pressure indicator (*Weeds*) was the cube root of this product. Banana mats were defined as a single family of banana plants with interconnected living corms; i.e. single mother plants and their connected suckers.

Plant population density (*Population*) was derived from the average spacing between mats. Mat spacing was determined at each plot by measuring the distances from 10-20 randomly selected mother plants to the nearest four mother plants that did not belong to the same mat.

Farmers were trained to record data on farm gate prices (USh bunch$^{-1}$) at harvesting. The costs related to fertilizer and mulch, which were the major technologies promoted by APEP, were recorded. Since farmers were supplied with fertilizer free of charge, fertilizer prices were obtained from the nearest stockists. Data on costs related to mulch were obtained from farmers and extension agents. For both fertilizer and mulch, local transport and labour costs for application were recorded. Although farmers were requested for information on costs related to manure application, many farmers were unable to provide reliable information on quantities and costs of the applied manure.

Foliar sub-samples of 10 by 20 cm were collected from both sides of the midrib in the midpoint of the lamina from the third most fully expanded leaf of a flowering plant (Lahav, 1995) and bulked for each plot. The sample size ranged from 3 to 7 per plot. Since plots were not uniform in size, efforts were made to collect more sub-samples in larger plots than in smaller plots. Total N was determined using Kjeldahl digestion with sulphuric acid and selenium as a catalyst, and measured colorimetrically. Available P and extractable cations (K, Ca and Mg) were extracted using Mehlich-3 extraction solution (Mehlich, 1984), Available P was measured colorimetrically using the molybdenum blue method, K was measured using a flame photometer, while the other cations were determined using an atomic absorption spectrophotometer (Okalebo et al., 1993). The foliar samples were analysed for nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) using standard methods (Okalebo et al., 1993).

## 2.3 Analytical approach

### *2.3.1 Analysis of agronomic data*

The t-test for independent samples was used to compare yield, *Nematodes*, *Weevils*, *Weeds*, *Population*, and *Mulch* between demonstration and control plots. Nutrient imbalances were explored using Compositional Nutrient Diagnosis (CND) approach outlined by Parent and Dafir (1992) and using the computation steps of Khiari et al. (2001b). The CND indices for N, P, K, Ca and Mg were calculated using norms published by Wairegi and van Asten (2010a) which were based on the same data set. Negative indices denoted relative deficiencies while positive indices denoted excesses.

The calculated indices were averaged separately for control and demonstration plots for each region. We first compared control and demonstration plots using the t-test for independent samples. Then we explored the distribution using a box plot.

Statistical analyses were performed with SPSS for Windows, release 11.0, standard version (SPSS Inc., 1989-2001).

*2.3.2 Economic analysis*

The profitability of demonstration plots compared with control plots was evaluated using partial budget analysis as described by CIMMYT (1988). Instead of analysing the data at regional level, we carried out partial budget analysis at district level, since we assumed that distance from farm to market was a major factor influencing farm gate bunch prices, thereby affecting profitability and subsequently adoption of the tested technologies. Given that the control and demonstration plots were not always paired, we used means of control and demonstration plots in the cost-benefit calculations. Monetary values were converted from the local currency (USh) at a rate of 1800 USh/US$, which was the average exchange rate during the study period. Farm gate prices were used to calculate the value of yield. Total variable costs were summed using costs of purchase, transport, and labour for application for fertilizer and mulch. The labour associated with change in yield was not taken into consideration because banana for sale was often harvested by the traders, bananas for other purposes was harvested piece meal during daily movements in the farm and harvests are not done in single labour intensive periods. Hence, estimating time invested in harvesting is difficult. The change in benefits of the additional inputs used in the demonstration plots compared with control plots was calculated as the change in the value of the yield less the change in the total variable costs (TVC) associated with fertilizer and mulch application. This change in benefits over change in TVC gave the marginal rate of return (MRR). Since the minimum rate of return acceptable to farmers documented by CIMMYT (1988) and used in fertilizer studies (e.g. Donovan et al., 1999; Alimi et al., 2006) is 0.50-1.0, the combination of fertilizer and mulch used in demonstration plots was considered economically worthwhile if MRR lay within or above 0.5-1.0.

Sensitivity analysis was performed to evaluate how change in fertilizer prices affected fertilizer profitability as a function of distance to the Kampala market using the approach described by Alimi and Manyong (2000). MRR were calculated based on 50% and 200% of the fertilizer prices in 2006/7. Other costs and benefits related to fertilizer and mulch use remained unchanged from those reported in 2006/7. These calculations were done for all regions except East, because bananas produced in East are consumed within the surrounding region and do not reach Kampala market. Banana bunch prices in all other districts depend on the Kampala urban market, which is the main market for their surplus produce. The calculated MRR based on prices 50%, 100% and 200% of the fertilizer prices for 2006/7 were then plotted against distance to market for evaluation.

Statistical analyses were performed with SPSS for Windows, release 11.0, standard version (SPSS Inc., 1989-2001) and Microsoft Office Excel 2003.

# 3. Results

## 3.1 Production

Regional averages for cycles ranged from 0.73 to 1.26 bunches mat$^{-1}$ year$^{-1}$, for bunch weight from 10 to 25 kg, and for yields from 9.7 to 32.6 t ha$^{-1}$ year$^{-1}$, (Table 1). In all regions, except for the East, demonstration plots had significantly ($P \leq 0.05$) more cycles, larger bunch weights and greater yields than control plots.

## 3.2 Biophysical factors

Root necrosis by nematodes did not differ significantly ($P \leq 0.05$) between demonstration and control plots. In the South, control plots had significantly ($P \leq 0.05$) higher corm damage than demonstration plots, but corm damage remained low (<5%). In other regions, corm damage did not differ significantly between the two plot types. Disease pressure was low in both plot types. Since pests and diseases could not be used to explain differences between the two plot types, we do not present data on these two factors in this paper.

Weed density in Central and South was significantly ($P \leq 0.01$) higher in control plots (28.9 and 15.9, respectively) compared with demonstration plots (11.6 and 3.6, respectively) (Table 1). In Southwest and East, *Weeds* did not differ significantly ($P \leq 0.05$) between the two plots. Weed density declined with increase in mulch thickness (Figure 1). In Central and Southwest, *Population* was significantly ($P \leq 0.05$) higher in control plots compared with demonstration plots (Table 1). *Population* in South and East did not differ significantly ($P \leq 0.05$) between the two plots.

Table 1: Means of production and biophysical factors in control and demonstration plots in the four regions in Uganda

| Parameter | Central | | South | | Southwest | | East | |
|---|---|---|---|---|---|---|---|---|
| | Controls (*n* = 27) | Demos (*n* = 28) | Controls (*n* = 19) | Demos (*n* = 24) | Controls (*n* = 30) | Demos (*n* = 34) | Controls (*n* = 8) | Demos (*n* = 8) |
| Cycles (no. of bunches harvested $mat^{-1}$ $year^{-1}$) | 0.76 | 1.08*** | 0.73 | 1.17*** | 1.05 | 1.26*** | 1.08 | 1.23 |
| Bunch weight (kg) | 11 | 15*** | 10 | 14*** | 16 | 20** | 20 | 25 |
| Yield (t $ha^{-1}$ $year^{-1}$) | 12.4 | 20.4*** | 9.7 | 19.7*** | 20.0 | 24.8* | 25.5 | 32.6 |
| Weeds[a] | 28.9 | 11.6** | 15.9 | 3.6*** | 9.2 | 4.4 | 10.4 | 10.9 |
| Population (mats $ha^{-1}$) | 1518 | 1279* | 1338 | 1227 | 1222 | 1006** | 1090 | 1099 |
| Mulch (mulch thickness, cm) | 0.5 | 1.4** | 1.0 | 2.8** | 0.5 | 1.5*** | 0.0 | 0.5 |

[a]Weeds is the cube root of the product of weed canopy (%) and height (cm).

*, ** and *** denote significant differences at $P \leq 0.05$, 0.01 and 0.001, respectively, between Control and Demo (Demonstration) plots within a region.

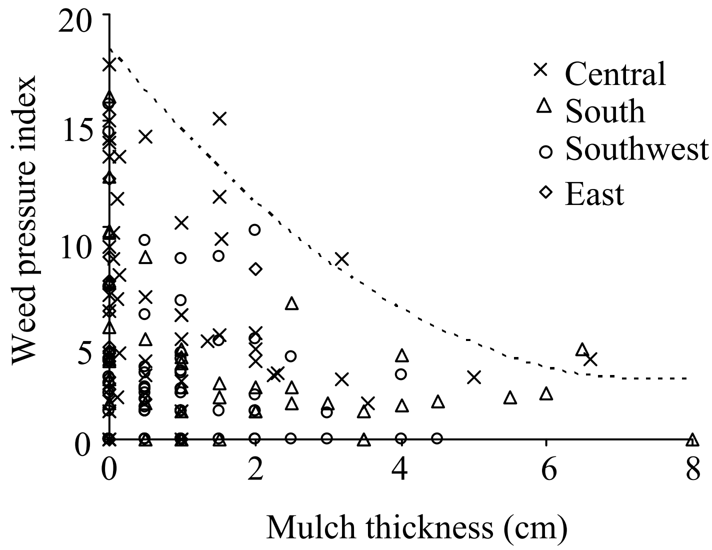


Figure 1: Relationship between mulch thickness (cm) and weed pressure in highland banana systems in Central, South, Southwest and East regions of Uganda. Weed pressure is the cube root of the product of weed canopy (%) and height (cm). The dotted line represents the boundary line.

### 3.3 Soil management technologies

The major soil management practices observed in banana fields were application of fertilizer, grass mulch, and cattle manure. Fertilizer (N, P, K averaging 71, 8, 32 kg $ha^{-1}$ $year^{-1}$, respectively) was applied in all demonstration plots. Manure and mulch were applied in some controls and demonstration plots at different frequencies; 38% of the control plots and 46% of the demonstration plots received manure, whereas 13% of the control plots and 53 % of the demonstration plots received external mulch. Although methods of application for mulch and manure varied among farms, in most plots where these inputs were used mulch was spread evenly while manure was applied around the mat. Mulch thickness was significantly greater ($P\leq0.05$) in demonstration plots compared with control plots in all regions except the East (Table 1). Yields in plots with and without manure did not differ significantly ($P\leq0.05$) and the proportion of plots with and without manure did not differ significantly ($P\leq0.05$) between control and demonstration plots.

### 3.4 Foliar nutrient imbalance

Foliar nutrient concentrations and imbalances did not differ significantly ($P \leq 0.05$) between control and demonstration plots. Hence, only data on nutrient imbalances indices found in the control plots are presented (Figure 2) because the data reflect the existing nutrient deficiencies in farmers' fields and could help to explain crop response to fertilizer. Indices for Ca are not presented because Ca did not appear to be a constraint in any region. In Central, P and K were significantly ($P \leq 0.05$) more deficient than N. Compared with other nutrients, N was significantly ($P \leq 0.05$) more deficient in the South. Although K was relatively more deficient compared with other nutrients in the Southwest, the difference was only significant ($P \leq 0.05$) for Mg. This region had the lowest minimum value for K compared with other regions. For East, Mg indices were significantly ($P \leq 0.05$) lower than for other nutrients.

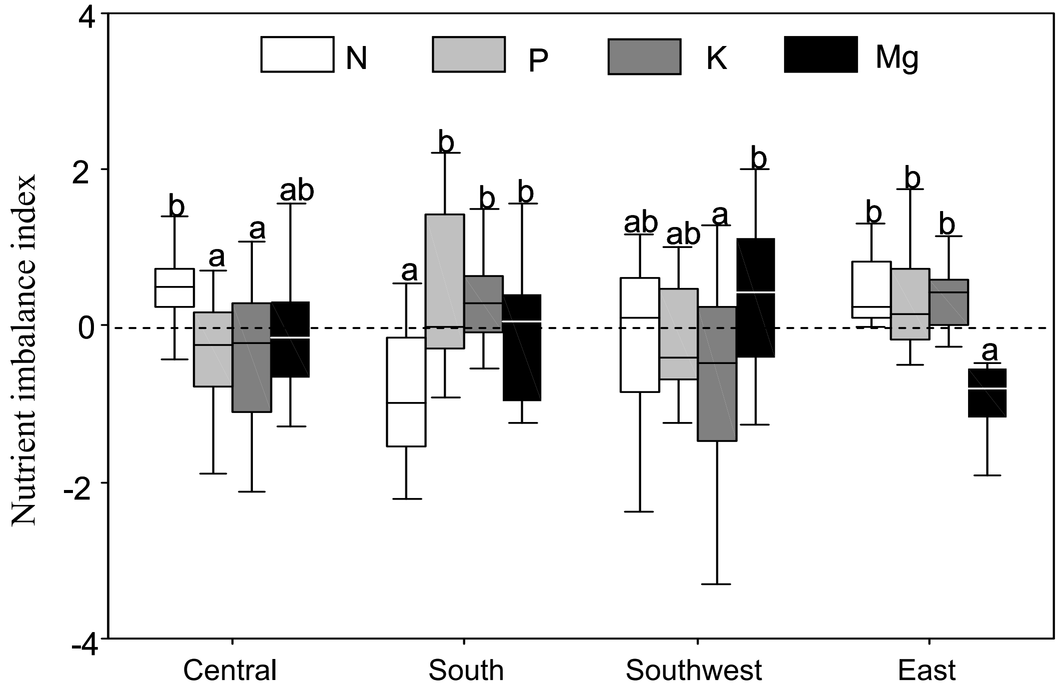


Figure 2: N, P, K and Mg nutrient imbalance indices for bananas in control plots in Central, South, Southwest and East regions of Uganda. The boxes represent the inter quartile range ($25^{th}$-$75^{th}$ percentile), the bars indicate the 5/95% values, and the solid lines across boxes are medians. The dotted line depicts indices that are equal to zero. Indices below and above the dotted line show deficiencies and excesses, respectively. Different letters within a region, signify significant differences at $P \leq 0.05$.

## 3.5 Partial budget

Farm gate prices of bananas ranged from 0.17 (near the capital) to 0.07 US$ kg$^{-1}$ (370 km Southwest of the capital). The relationship between farm gate prices in the Central, South and Southwest regions, and distance from these regions to the main market (the capital, Kampala), was best represented by a negative “power” relationship ($R^2$ = 0.92) (Figure 3). Average farm gate price in the East (0.10 US$ kg$^{-1}$) was not included in Figure 3 because bananas produced in the region are mostly consumed in the surrounding areas and not Kampala.

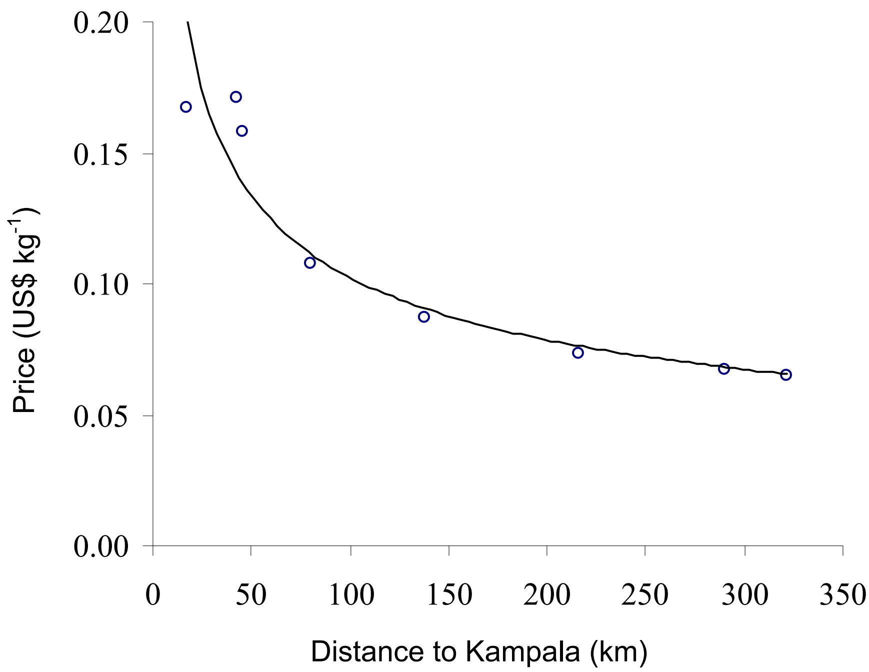


Figure 3: Relationship between average distance for farms at district level to the main market (the capital, Kampala) and farm gate prices of bananas, for Central, South and Southwest regions of Uganda. The regression line equation was $Y$ =0.60$x^{-0.38}$ and $R^2$ = 0.92.

Average values of yield in control and demonstration plots ranged between US$ 692-2,990 and US$ 1,150- 4,780, respectively (Table 2). Demonstration plots had larger yields than control plots but these differences were only significant ($P \leq 0.05$) in $\text{Central}_4$, $\text{South}_1$ and $\text{South}_2$. The difference between the two plots was greatest in $\text{Central}_1$ (US$ 1,790) and least in $\text{SWest}_2$ (US$ 299).

The costs related to application of manure were not included in the economic analysis because yields in plots with and without manure did not differ significantly ($P\leq 0.05$), the proportion of plots with and without manure did not differ significantly ($P\leq 0.05$) between control and demonstrations, and many farmers were unable to provide information on quantities and costs of the applied manure. Fertilizer prices averaged US$ 0.56 $kg^{-1}$ of fertilizer in 2006-2007. The mean differences costs of external inputs (fertilizer and mulch), in terms of purchase, transport and labour for application, between the two plot types, ranged from US$ 205 (East) to 344 (Central$_4$) (Table 2). This difference was to a greater extent due to fertilizer costs, and to a lesser extent to mulch costs, as fertilizer costs averaged US$ 226 while differences in mulch costs between control and demonstration plots averaged US$ 53. Fertilizer costs ranged between US$ 187 in East and US$ 265 while the differences in mulch costs between control and demonstration plots ranged between US$ -14 and 105.

The district-level differences in net benefits between the two plots ranged between US$ 27 (SWest$_2$) and 1525 (Central$_1$) (Table 2). The MRR for the soil management technologies promoted in the demonstration plots subsequently ranged from 0.10 (SWest$_2$) to 5.75 (Central$_1$) in the year 2006-2007 (Table 2). The MRR in the South$_2$, SWest$_1$ and SWest$_2$ regions was below 0.50 while other districts had values above 1.00. MRR calculated using the prices of 2007-2008 ranged from 2.98 to -0.34 while MRR calculated using half the prices of 2006-2007 ranged between 9.40 and 0.65 (Figure 4). The relationships between distance from farms to the capital and MRR were quadratic (Figure 4).

Table 2: Partial budget of the benefits and costs of demonstration plots over control plots in the four regions in Uganda

| Parameter | | Central | | | | South | | Southwest | | East |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $Central_1$ | $Central_2$ | $Central_3$ | $Central_4$ | $South_1$ | $South_2$ | $SWest_1$ | $SWest_2$ | East |
| Value of yield | Controls | 2990 | 1233 | 2081 | 1256 | 864 | 692 | 1129 | 1510 | 2560 |
| | Demonstrations | 4780 | 2428 | 2642 | 2415 | 2009 | 1150 | 1480 | 1809 | 3280 |
| [a]Fertilizer costs | Demonstrations | 241 | 232 | 265 | 239 | 233 | 239 | 196 | 203 | 187 |
| [a]Mulch costs | Controls | 37 | 0 | 19 | 7 | 37 | 48 | 3 | 23 | 0 |
| | Demonstrations | 61 | 22 | 5 | 112 | 127 | 149 | 65 | 92 | 18 |
| [b]Net benefits | Controls | 2953 | 1233 | 2062 | 1249 | 828 | 645 | 1126 | 1487 | 2560 |
| | Demonstrations | 4478 | 2174 | 2371 | 2064 | 1650 | 762 | 1219 | 1514 | 3075 |
| [c]Difference | Net benefits | 1525 | 941 | 309 | 815 | 822 | 118 | 93 | 27 | 517 |
| | Costs | 264 | 254 | 252 | 344 | 323 | 340 | 259 | 272 | 205 |
| [d]MRR | | 5.75 | 3.70 | 1.23 | 2.37 | 2.54 | 0.35 | 0.36 | 0.10 | 2.52 |

[a] Combined costs of purchase, transport, and labour for application.
[b] Value of yield minus costs. The costs were for mulch in control plots, and fertilizer and mulch in demonstration plots.
[c]Difference calculated by subtracting values in control plots from values in demonstration plots.
[d]Marginal rate of return of investment of demonstration plots compared with control plots.
Value of yield and costs are in US$ $ha^{-1}$ $year^{-1}$.

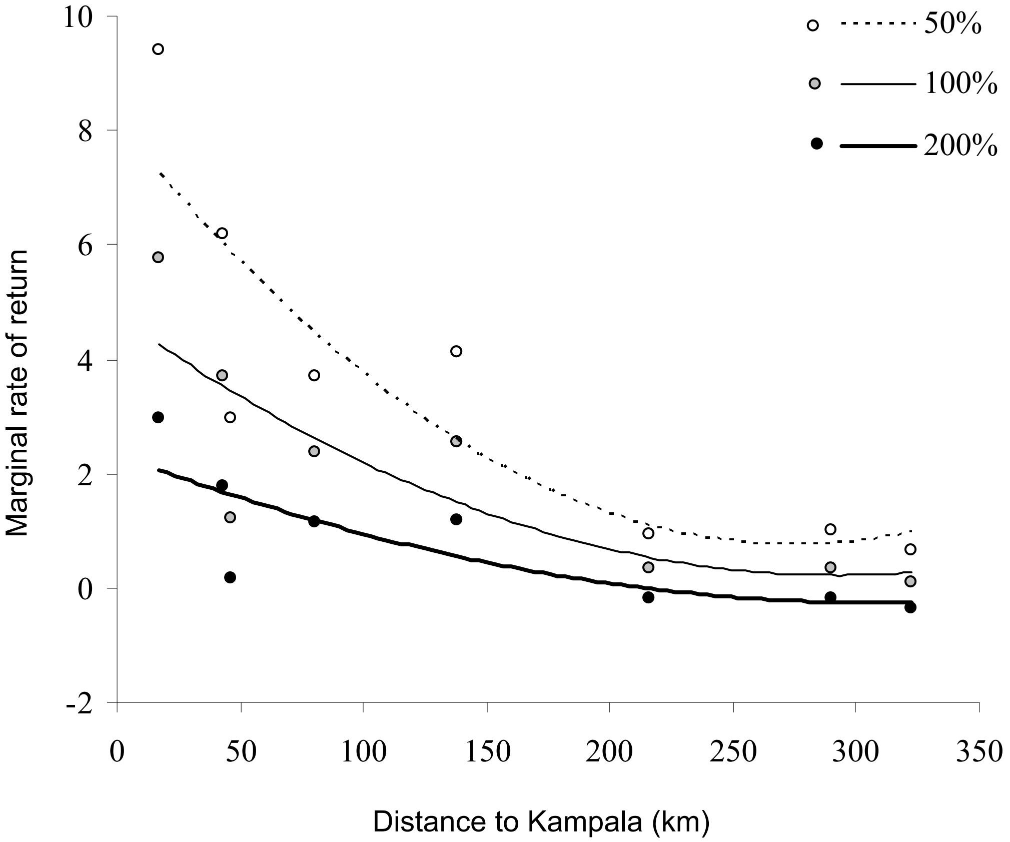


Figure 4: Relationship between marginal rate of return (MRR) and average distance from farms at district level, to the main market (the capital, Kampala), for Central, South and Southwest regions of Uganda. MRR are based on 50%, 100% and 200% of local fertilizer and banana farm gate prices in 2006-2007. Fertilizer prices in 2006-2007 averaged 0.56 US$ $kg^{-1}$ of fertilizer. The regression lines based on 50%, 100% and 200% of the fertilizer prices in 2006-2007, had the equations $Y = 0.00010x^2 - 0.0537x + 8.1353$, $Y = 0.00005x^2 - 0.0311x + 4.7710$, and $Y = 0.00003x^2 - 0.0166x + 2.3430$, respectively and $R^2$ of 0.74, 0.69 and 0.65, respectively.

# 4. Discussion

## 4.1 Relationship between yield and biophysical factors

Yield differences, caused by higher bunch weights and larger number of bunches harvested per mat per year (Table 1) between demonstration and control plots, could mainly be attributed to differences in fertilizer and mulch applications. In addition, reduced weed densities in demonstration plots when compared with control plots, in the Central and South regions, could have also contributed to the yield differences between the two plot types. The reduced weed pressure in demonstration plots compared with control plots could be partially explained by the fact that demonstration plots had significantly more mulch (Table 1) and weed pressure declined with increase in mulch thickness (Figure 1).

Mulch from crop residues has been reported to increase productivity in bananas (McIntyre et al., 2000; Bananuka et al., 2000) and plantains (Salau et al., 1992; Coyne et al., 2005) and to suppress weeds in other crops (e.g. Ramakrishna et al., 2006; Singh et al., 2007). In addition, the improved plant growth in the demonstration plots most likely increased light interception by the banana canopy, thereby further reducing weed pressure. Application of fertilizer promoted leaf area production and light interception but reduced weed pressure in a study by Olasantan et al. (2001).

The fact that control plots had slightly higher plant population densities in the Central and Southwest regions when compared with demonstration plots (Table 1) could not have contributed to poorer yields in the controls at the current plant density levels. These densities were generally very low compared with the common plant densities (>2500 plants $ha^{-1}$) found and recommended for commercial banana plantations elsewhere in the world (Robinson, 1996). Since pest pressure did not differ between plot types and disease pressure was low, it is unlikely that pest and disease pressure created significant yield differences between plot types across Uganda. We conclude from the above that the observed yield differences between demonstration and control plots were largely due to the use of external mulch and fertilizer inputs. Although it was not possible to separate the effects of fertilizer and mulch, the reported importance of fertilizer in the South and Southwest and mulch in the Central and Southwest (Wairegi et al., 2010) suggests that the combination of mulch and fertilizer was more important in the Southwest compared with Central and South regions. Addressing other limiting factors in demonstration plots, for example pest pressure and weed pressure (Wairegi et al., 2010), can increase yields further.

The variability in nutrient imbalances (Figure 2) among regions clearly showed that nutrient deficiencies differed among regions. The fact that the most deficient nutrients were P and K in the Central region, N in the South, K in the Southwest and Mg in the East, suggests that the applied fertilizer included the most limiting nutrients in all regions except the East. This is confirmed by the observation that yield increases in all regions except the East were significant ($P \leq 0.05$) (Table 1). Furthermore, the relatively higher yield increase in the South (103%) compared with other regions (Central 65%, Southwest 23%, East 28%) was probably because N was the most limiting nutrient in the South (Figure 1) and the fertilizer had a relatively large proportion of N (71 kg $ha^{-1}$) compared with P (8 kg $ha^{-1}$) and K (32 kg $ha^{-1}$). These findings indicate that banana fertilizer recommendations in Uganda should best be site specific and should address nutrient deficiencies that can currently be measured in ordinary farmers' fields (i.e. control plots).

Our observations that fertilizer addressed the most liming nutrients in the Central, South and Southwest regions and that Mg was the most limiting nutrient in the East are partially in agreement with findings in previous studies. Application of K increased banana yields in the Central (Smithson et al., 2004) and the Southwest regions (Smithson et al., 2004; Okech et al., 2004a), combining K and Mg did not increase the yield further in both regions (Smithson et al 2004) and available P was below critical concentration in poorly managed plantations in the South (Rubaihayo et al., 1994) and at a research farm in the Central region (Murekezi, 2005). In addition, the N and Mg deficiencies observed in banana production systems in the South and East, respectively, were also reported in coffee production systems (van Asten et al., 2008).

**4.2 Profitability of fertilizer and mulch application**

The low MRR of the demonstrated technology in the Southwest districts compared with other regions (Table 2) was mainly due to low farm gate prices and poor crop response compared with other regions. This is confirmed by the fact that the costs associated with fertilizer and mulch application only showed small variation (≤US$ 137) when compared with the variation in yield value (≤ US$ 1491 among districts (Table 3).  The increase in farm gate banana prices with increase in distance to the capital (Figure 3) and the strong relationship between MRR and distance to the capital (Figure 4) evidently show the strong relationship between farm gate prices, economic benefits and distance to market. Furthermore, the high MRR calculated for $Central_3$ which is 46 km from the capital (MRR = 1.2), despite the district having the smallest increase in yield (3.6 t $ha^{-1}$ $year^{-1}$), suggests that use of the demonstrated technology is economically attractive in areas near the capital even when crop response is moderate.

Farmers were likely to adopt use of fertilizer (MRR≥1.0) if their farms were situated up to a distance of 160 km away from the capital, in 2006/7, but only up to 90 km when prices doubled (Figure 4), as happened in 2007-2008 when the costs of the raw materials for the production and transport of fertilizer reached their peaks on the world market. However, calculations based on half the prices of 2006-2007 suggested that distance would no longer be a constraint to adoption of the demonstrated technologies, even in the most remote regions (Figure 4). The large fluctuations in profitability of fertilizer suggest that research and development actors should be very careful with promoting fertilizer use, and that they should take into consideration temporal and spatial variation in crop response and in input and output prices.

Some of our findings are in agreement with other studies. In a survey in the Central, South and Southwest regions, Bagamba (2007) concluded that banana price were highest and lowest in the Central and Southwest, respectively. The initial rapid decline in banana prices which lessened as distance to market increased (Figure 3) is similar to the trend reported for the relationship between milk prices and distance to market in Kenya by Staal et al. (2003). This is further supported by the fact that banana and milk are both perishable commodities that can only be sold fresh. The low profitability of fertilizer use in the Southwest has also been documented. The average benefit cost ratio for a six year trial in the Southwest Uganda was 0.7 (Okech et al., 2004a). Although profitability of fertilizer use in banana systems has not been documented in other regions, a benefit cost ratio of 0.8 was calculated for fertilizer use in crop production in Uganda by Nkonya et al. (2005). The reported increase in fertilizer use in production of food and cash crop as transport costs to market decreased (Omamo, 2003) implied that the profitability increased as distance to market increased. Distance to market influences adoption of modern technologies in crop production in Africa (Mwangi, 1997).

### 4.3 Improving the efficiency of fertilizer use

We concluded in the previous paragraph that the purchase of external nutrient inputs may not be very profitable in the areas far from the market, such as Southwest Uganda. Unfortunately, the current banana production and export realized in the Southwest seem unsustainable due to massive soil mining. Lopez (1999) estimated from literature that a highly productive plantation (70 t $ha^{-1}$ $year^{-1}$) exports 126, 15 and 399 kg $ha^{-1}year^{-1}$ of N, P and K, respectively. Bazira et al. (1997) reported net removal of 52.6, 9.3 and 58.0 kg $ha^{-1}year^{-1}$ of N, P and K, respectively, in banana farms in Central Uganda. Decline in productivity, particularly in the South and Southwest regions, would cause a serious food shortage in the country because the Southwest is the major source of banana destined for Kampala and these two regions together produce approximately 61% of the total banana output in the country (Silsbury et al., 2002).

Profitability, and subsequently adoption of fertilizer use can be improved by adjusting fertilizer recommendation to address existing nutrient deficiencies. For example, increasing K application in the Southwest where K seemed to be most limiting (Figure 2), and including Mg in the fertilizer applied in the East where Mg was limiting

(Figure 2), would be expected to give much higher crop response than what we observed in the demonstration plots. In addition, profitability of fertilizer use can be further improved by using single- or double-nutrient fertilizers that often cost less than the current NPK fertilizer blends. For example, since N seems to be the most limiting nutrient in the South (Figure 2) and the demonstrated fertilizer did not seem to be always profitable (MRR 2.5 and 0.4 in $South_1$ and $South_2$, respectively) (Table 3), we estimated higher MRR of 4.2 and 1.0 in $South_1$ and $South_2$, respectively, by replacing the demonstrated fertilizer with urea as the former had 22% N and latter has 46% N. Similarly, in another example based on the observation that K seemed to be the most limiting nutrient in the Southwest (Figure 2) and MRR of the demonstrated fertilizer were below 0.5 (Table 2), we estimated higher MRR of 1.9 and 1.4 in $SWest_1$ and $SWest_2$, respectively, if muriate of potash was used instead of the demonstrated fertilizer as the former has 52% K and the latter had 10% K. In both calculations, we assumed that labour costs and fertilizer prices remained unchanged from those of the NPK fertilizer used in the demonstration plots.

Although our study was based on data collected in Uganda, the findings suggest that fine-tuning fertilizer recommendations in the East African highlands can increase profitability of fertilizer use in the region. For example, in a study in Rwanda by Rutunga and Neel (2006) where crop response to compound NPK fertilizer was evaluated, yields could most likely have been higher if the fertilizer applied had targeted the suspected P deficiency. Obviously, fine-tuning fertilizer recommendations is crucial in replenishing soil nutrients and increasing productivity in sub-Saharan Africa.

## 5. Conclusions

The combined application of fertilizer and mulch in highland banana systems can be highly profitable, but recommendations should not be generalized into “blankets” that apply for an entire country like Uganda. The profitability of the tested fertilizer + mulch technology is highly variable due to regional differences in crop response, costs of inputs, and particularly banana farm gate prices. Application of external nutrient inputs is very profitable in areas with good farm gate prices (e.g. close to Kampala) and good crop response (e.g. $South_1$), but may not always be profitable in areas far away (e.g. parts of Southwest Uganda) or in areas with relatively poor fertilizer response (e.g. East). Our study shows that fertilizer response was much higher in areas where the tested blanket fertilizer application corresponded largely with the existing plant nutrient deficiencies. Hence, profitability and adoption of fertilizer use can be substantially improved if fertilizer recommendations are tailored to the primary plant nutrient deficiencies currently observed in farmers' fields. Besides large spatial variation in banana bunch prices and crop response, there are large temporal variations in fertilizer prices on the local and global markets. Research and development actors should be wary of these large temporal and spatial variations in input and output prices before launching campaigns to increase fertilizer adoption by smallholder farmers. At present, recommending use of fertilizer in areas close (<100 km) to the large urban market of Kampala seems the only safe bet. Like other African countries, Uganda is challenged with a rapidly increasing demand for food, an increasing pressure on its limited arable land, and a global market that is characterized by violent changes in food, fertilizer, and fuel prices. Intensification towards more productive and sustainable agricultural systems in Africa is not an option but a requirement. This has been recognized by many, as illustrated by the large donor efforts to launch a 'Green Revolution for Africa'. Like elsewhere in the world, perishable and bulky (i.e. expensive to transport) staple food products are generally produced close to the market, whereas dry, dense, and storable or expensive food products are often produced far from the market where production costs are lower. The Ugandan tradition of producing most of its primary staple crop (i.e. banana) far (>200km) from its urban consumers may need to be revised if the predominantly risk-averse smallholder farmers are to be encouraged to sustainably intensify. Intensification of banana production should occur close to the large urban markets, but it does not seem to make much sense for Uganda's current prime supplying area (i.e. Southwest) to intensify given the current dynamics in local and global input and output prices. Fine-tuning fertilizer recommendations to provide farmers with the best advice on input use will be required. This would not only be applicable in Uganda, but also in other East African countries (i.e. Tanzania, Kenya, Rwanda, Burundi and the Democratic Republic of Congo) where similar production systems for highland banana are found.

# Factors driving fertilizer adoption in banana systems in Uganda

This article is adapted from:
van Asten, P.J.A., Wairegi, L.W.I, Bagamba, F., Drew, C., 2010. Factors driving fertilizer adoption in banana systems in Uganda. Acta Horticulturae (in press)

## Abstract

Poor soil fertility is among the important factors limiting highland banana (*Musa* spp., AAA-EA genome) yields in Uganda. We demonstrated fertilizer use in 95 plots in Central, South, Southwest, and East Uganda to identify constraints and opportunities to fertilizer adoption in banana systems. Demonstration plots received on average of 71 N, 8 P and 32 K kg $ha^{-1}year^{-1}$. The demonstration plots were used for learning by nearby collaborating farmers. Structured interviews were conducted to understand farmers' perceptions of demonstrated technologies. Farmers observed that demonstration plots had consistently higher yields than plots without fertilizer due to bigger bunches of better quality. Farmers perceived fertilizer prices as the most important constraint to adoption, despite limited knowledge of actual prices. Other important constraints perceived by farmers were poor supply, labour required for fertilizer application and the belief that fertilizer negatively affected soil quality. The demonstration plot approach simultaneously allowed participatory evaluation, fine-tuning, and adoption and adaptation of fertilizer recommendations. This approach shortens and strengthens the adoption pathway, provided the process is supported by proper agronomic and economic evaluation of the technologies tested.

**Keywords:** Demonstrations; Farmer perceptions; Fertilizer use; Yield constraints.

# 1. Introduction

Banana is the most important food crop in Uganda and is produced by millions of smallholder farmers. Yields of banana in Uganda are small (5-30 t $ha^{-1}$ $year^{-1}$) compared with potential yield (70 t $ha^{-1}$ $year^{-1}$) (van Asten et al., 2005).

Poor soil fertility has been reported to be one of the major yield constraints (Gold et al., 1999). The most common soil management practice used is application of organic amendments such as compost, livestock manure and mulch (Bekunda and Woomer, 1996; Bekunda 1999; Goldman and Heldenbrand, 2002). Although the National Agricultural Research Organization (NARO) banana handbook gives several blanket recommendations, for example application of 54 and 138 g of N $mat^{-1}$ $year^{-1}$ as diammonium phosphate and urea fertilizer, respectively (NARO, 2003), few Ugandan farmers use mineral fertilizers (Bekunda, 1999; Sseguya et al., 1999; Goldman and Heldenbrand, 2002). In 2003, a USAID-funded Agricultural Productivity Enhancement Program (APEP) initiated a fertilizer extension programme in major banana producing areas which recommended a blanket recommendation of 11 g of N fertilizer $mat^{-1}$ $month^{-1}$, 1 g of P and 5 g of K during the wet season. Before this programme was started, the blanket NPK fertilizer recommendations were not tested across a large selection of farmers' fields in Uganda. The recommendations may not correspond well with actual plant nutrient requirements and hence may not be efficacious nor profitable. Furthermore, low adoption of fertilizer use in Uganda has been attributed to high fertilizer prices (Omamo, 2003), poor availability and lack of knowledge on their use (Dramadri et al., 2005).

The sparse use of external inputs by Ugandan banana farmers results in substantial nutrient mining (van Asten et al., 2005), particularly of N and K (Lahav, 1995; Bazira et al., 1997). This will eventually impact negatively on yields. Increasing land pressure leads to a reduction in farm size and/or fallow land (Fermont et al., 2008). Therefore, a sustainable maintenance or increase of national banana production will increasingly depend on improvement of yield per unit area, which requires fertilizer use.

Testing of the existing fertilizer recommendations in farmers' fields ensures that farmer evaluation, adoption and adaptation of the technology can be take place simultaneously. On-farm testing of fertilizer also allows researchers to determine the biophysical and economic efficiency of the applications.

The aim of this joint study between the APEP extension officers and agricultural researchers based in Uganda was: i) to demonstrate fertilizer use on bananas in farmers' fields across Uganda; ii) to identify farmer perceptions and the associated potential constraints to adoption of fertilizer use; in order to iii) provide advice that would help further adaptation and adoption of fertilizer use in Ugandan banana systems.

## 2. Materials and methods

The study was conducted in the Central (Wakiso, Mukono, Luwero and Mpigi districts, denoted as $Central_1$, $Central_2$, $Central_3$ and $Central_4$, respectively), South (Masaka and Rakai districts, denoted as $South_1$ and $South_2$, respectively), Southwest (Mbarara and Bushenyi districts, denoted as $SWest_1$ and $SWest_2$, respectively) and East Regions (the former Mbale district) (Table 1). The overall study area lies between latitudes 1º30'N and 1º00'S and longitudes 29º52'E and 34º30'E at an altitude of 1120-1700 m above sea level. The rainfall pattern is bimodal with most rains occurring in March-May and September-November (East African Meteorological Department, 1963).

Table 1: Monitored plots and surveyed households in Central, South, Southwest and East Uganda.

| Region | District | Demo plots | Surveyed households | |
|---|---|---|---|---|
| | | | Demo | Control |
| Central | $Central_1$ | 5 | 4 | 44 |
| | $Central_2$ | 5 | 2 | 47 |
| | $Central_3$ | 8 | 6 | 42 |
| | $Central_4$ | 10 | 5 | 42 |
| South | $South_1$ | 13 | 11 | 35 |
| | $South_2$ | 11 | 5 | 37 |
| Southwest | $Swest_1$ | 16 | 11 | 26 |
| | $Swest_2$ | 18 | 13 | 29 |
| East | East | 9 | 9 | 39 |

Demo plots denotes demonstration plots. Demo and Control households denote households with and without demonstration plots, respectively.

Each of the 95 demonstration plots (Table 1) was owned by learning groups of c. ten farmers. Fertilizer (averaging 71N, 8P, 32K kg $ha^{-1}year^{-1}$) was the applied in all demonstration plots and 53% of the plots received external mulch.

Farmer meetings were held between late 2007 and early 2008. In each district, an average of 50 households was selected for interviewing from farmer lists compiled at the sub-county level. Efforts were made to also include demonstration plot holders among those selected. Structured interviews were carried out in 407 households in the four regions (Table 1). Farmers were asked to identify and rank the perceived benefits of and constraints to fertilizer adoption. Group meetings were held later in each district and in each meeting, two focus groups (one for male farmers and one for female farmers) each with 5-10 members, were selected. These were farmers who either had demonstration plots on their farms or did not have a demonstration plot on their farm but belonged to a learning group. These focus groups were asked to identify and rank perceived constraints to banana production, as well as benefits of fertilizer use and factors that may interfere with its use.

The number of times a benefit or constraint was mentioned was assumed to indicate its overall importance. Differences in the order of importance of benefits and constraints for different regions and for farmers with and without demonstration plots were explored using Pearson's chi-square tests. All data analysis was done using SPSS Version 11.0 (SPSS Inc., 1989-2001).

For benefits and constraints identified and ranked by focus groups, the total number ($n$) of benefits and constraints across districts were identified. For each district, ranks of one, two, three … were given scores of $n$, $n$-1, $n$-2 … respectively.

# 3. Results

### 3.1 Farmer perception of banana production constraints

There were slight differences in ranking between male and female focus groups (Table 2). Male focus groups in five districts ($Central_4$, $South_1$, $South_2$, $Swest_1$ and East) identified insect pests as the most important constraint. Female focus groups in $Central_4$ and $South_2$ also identified insect pests as the most important constraint while for those in $South_1$, $Swest_1$ and $Swest_2$ it was poor soil fertility. Overall, the order of ranking from most to least important, for both male and female focus groups was pests, poor soil fertility, diseases, drought and lack of suitable cultivars.

### 3.2 Farmer perceptions of fertilizer benefits and constraints

In the household interviews, there were no significant differences in perceived benefits among regions or between demonstration and control plot holders (*P*≤0.05). Overall, the perceived benefits were increased yields (39% of respondents), increased harvest frequency (33%), and improved banana quality (29%).

All the focus groups ranked increased production as the most important benefit of fertilizer application (Table 3). Other important benefits were that fertilizer use was less labour-intensive when compared with inputs like mulch, manure and compost, fertilizer improved the looks of the bunch and improved taste and texture of cooked banana.

Although all interviewed farmers were asked to rank constraints to fertilizer use, enumerators got very few responses in the East region. So, only responses from the Central, South and Southwest regions are presented (Figure 1). The importance of constraints differed significantly (*P*≤0.05) among these regions. In the three regions, the most important constraint was the high fertilizer prices mentioned by some 25% of the farmers. Not having the fertilizer available in nearby shops was the second most important constraint in the Central and Southwest but was less perceived as a problem in the South. Around 20% of all farmers believed fertilizer spoiled the soil. Although responses from demonstration plot holders did not significantly differ from other farmers (data not presented), higher percentage of demonstration plot holders (17.1%) felt that fertilizer application was labour-demanding than other farmers (9.8%).

All the focus groups (Table 4) ranked high fertilizer prices as either the most important or the second most important constraint. Other important constraints were non-availability in nearby shops, farmers were unsure of fertilizer quality in nearby shops especially if repackaged and the perception that fertilizer spoils the soil.

Table 2: Scores and overall ranking of banana production constraints ranked by farmer focus groups in Central, South, Southwest and East Uganda.

| Constraints | Central | | South | | | | Southwest | | | | East | | Overall | | Overall | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Central_4$ | | $South_1$ | | $South_2$ | | $Swest_1$ | | $Swest_2$ | | East | | score | | ranking | |
| | M | F | M | F | M | F | M | F | M | F | M | F | M | F | M | F |
| 1. Pests | 5 | 5 | 5 | 4 | 5 | 5 | 3 | 4 | 5 | 3 | 5 | 4 | 28 | 25 | 1 | 1 |
| 2. Low soil fertility | 4 | 4 | 4 | 5 | 4 | - | 5 | 5 | 3 | 5 | 3 | 3 | 23 | 22 | 2 | 2 |
| 3. Diseases | - | 3 | 2 | 2 | 3 | 3 | 4 | 2 | 4 | 4 | 4 | 5 | 17 | 19 | 3 | 3 |
| 4. Drought | 3 | - | 3 | 3 | 2 | - | 2 | 3 | 2 | 2 | 2 | 1 | 14 | 9 | 4 | 4 |
| 5. Lack of good cultivars | - | - | 1 | - | - | - | - | - | - | - | 1 | 2 | 2 | 2 | 5 | 5 |

Constraints were rated by giving a score of 5 to the most important and 1 to the least important constraint.
M and F denote male and female focus groups, respectively.

Table 3: Scores and overall ranking of advantages of using fertilizer ranked by farmer focus groups in Central, South, Southwest and East Uganda.

| Advantages of fertilizers | Central | | South | | | | Southwest | | | | East | | Overall | | Overall | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Central_4$ | | $South_1$ | | $South_2$ | | $Swest_1$ | | $Swest_2$ | | East | | score | | ranking | |
| | M | F | M | F | M | F | M | F | M | F | M | F | M | F | M | F |
| 1. Increased production | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 54 | 54 | 1 | 1 |
| 2. Application not labor intensive | 8 | 8 | 6 | - | 3 | - | - | - | 8 | 8 | - | - | 25 | 16 | 2 | 2 |
| 3. Improved bunch appearance | - | - | 8 | 8 | 8 | - | - | - | - | - | - | 8 | 16 | 16 | 3 | 2 |
| 4. Improved taste, food soft | - | 7 | 7 | - | 7 | - | - | - | - | - | - | - | 14 | 7 | 4 | 5 |
| 5. Less corm damage by weevils | - | - | - | - | 6 | 8 | - | - | - | - | - | - | 6 | 8 | 6 | 4 |
| 6. More material for mulching produced | - | - | - | - | 5 | - | - | - | 7 | - | - | - | 5 | 7 | 6 | 5 |
| 7. Small quantities required[1] | - | - | - | - | 4 | - | - | - | - | - | - | - | 4 | 0 | 7 | - |
| 8. Weeds easier to pull out | - | - | - | - | - | - | - | - | 6 | - | - | - | 0 | 6 | - | 7 |
| 9. Intercropped beans benefit | - | - | - | - | - | - | - | - | 5 | - | - | - | 0 | 5 | - | 8 |

Advantages were rated by giving a score of 9 to the most important and 1 to the least important advantage.
M and F denote male and female focus groups, respectively.
[1]Compared with manure, smaller quantities of fertilizer required.

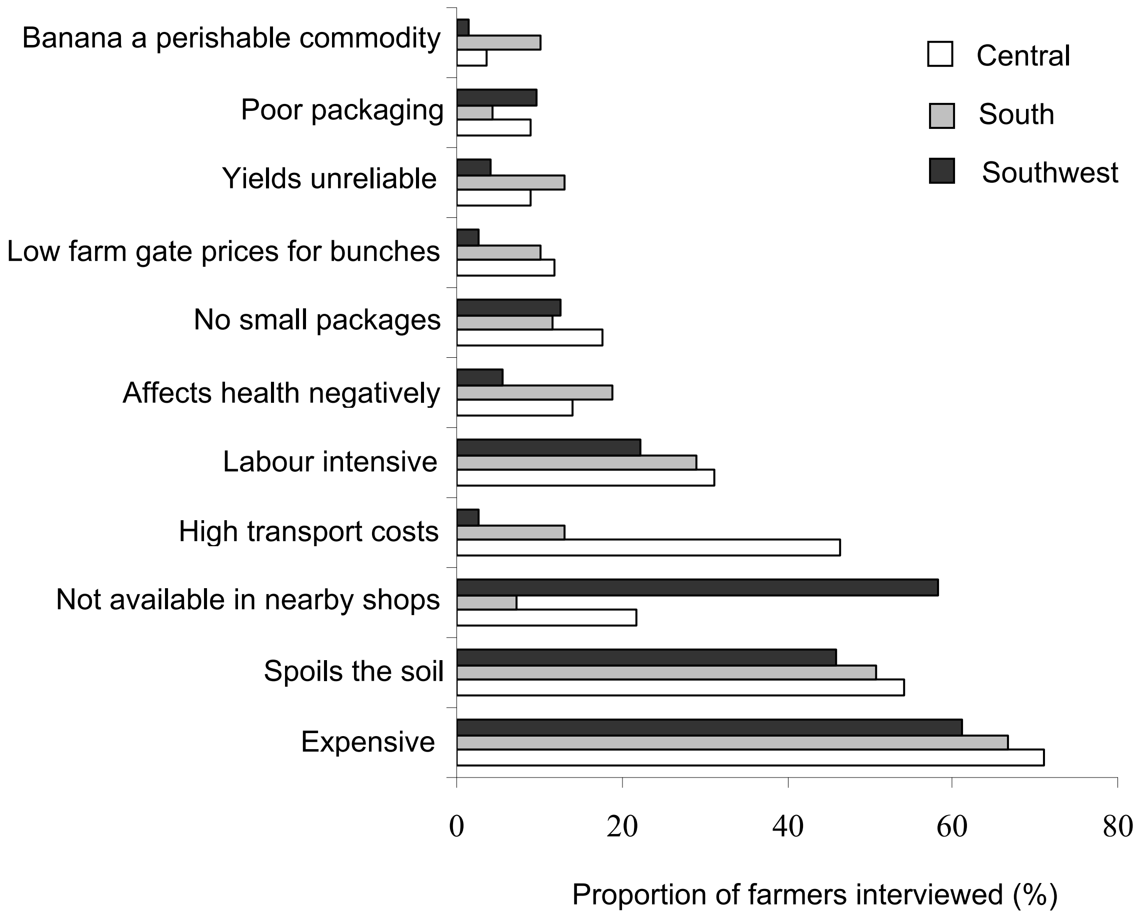


Figure 1: Perceived constraints to fertilizer use by farmers in Central, South and Southwest Uganda.

Table 4: Derived scores of constraints to fertilizer use ranked by farmer focus groups in Central, South, Southwest and East Uganda.

| Constraints | Central | | South | | | | Southwest | | | | East | | Overall | | Overall | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Central_4$ | | $South_1$ | | $South_2$ | | $Swest_1$ | | $Swest_2$ | | East | | score | | ranking | |
| | M | F | M | F | M | F | M | F | M | F | M | F | M | F | M | F |
| 1. Expensive | 10 | 10 | 10 | 9 | 10 | 9 | 10 | 9 | 9 | 10 | 10 | 10 | 59 | 57 | 1 | 1 |
| 2. Fertilizer not available in nearby shops | 9 | 9 | 9 | 10 | - | - | - | 7 | 10 | 9 | 8 | 7 | 36 | 42 | 2 | 2 |
| 3. Unsure of quality of fertilizer in shops | - | - | 7 | 8 | - | - | - | - | - | - | 9 | 9 | 16 | 17 | 3 | 4 |
| 4. Spoils the soil | - | - | 8 | - | 8 | 10 | - | - | - | - | - | - | 16 | 10 | 3 | 6 |
| 5. Application depends on soil moisture | - | - | 6 | - | - | - | - | 10 | - | - | - | 8 | 6 | 18 | 8 | 3 |
| 6. Application needs gloves | - | 8 | - | - | - | - | - | 6 | - | - | - | - | 0 | 14 | - | 5 |
| 7. Labor intensive | - | - | - | - | 7 | - | - | - | 8 | - | - | - | 15 | 0 | 6 | - |
| 8. Packed in big volumes | - | - | - | - | - | - | 9 | - | - | - | 7 | - | 16 | 0 | 3 | - |
| 9. Has no residual effect | - | - | - | - | 9 | - | - | - | - | - | - | - | 9 | 0 | 7 | - |
| 10. Resulting big bunches require staking[1] | - | - | - | - | - | - | - | 8 | - | - | - | - | 0 | 8 | - | 7 |

Constraints were rated by giving a score of 10 to the most important and 1 to the least important constraint.
M and F denote male and female focus groups, respectively.
[1]Staking material for the resulting big bunches scarce or unavailable.

## 4. Discussion

The perception that pests, poor soil fertility, diseases and drought limit production agrees with findings of a previous study by Gold et al. (1999). The perception that pests ranked higher than poor soil fertility was surprising, because fertilizer application correlated strongly, positively with yield while the correlation of yield with pest damage was weaker (Wairegi et al., 2010 – Chapter 4), suggesting that poor soil fertility is a greater constraint to production than pest damage. Still, the high ranking given to these two constraints agrees with studies carried out in Uganda by Sserunkuuma (2001) and Tenywa et al. (1999). The perception that pests such as the banana weevil (*Cosmopolites sordidus*) are important may be related to the fact that this constraint is easily visible to farmers and may help to explain local plant performance variations within a plot (van Asten et al., 2009).

The degree of importance farmers attach to a constraint influences the decision to invest and adopt technologies addressing the constraint (Semgalawe, 1998). Since pests, in most cases, were given higher ranking than poor soil fertility, it is possible that farmers may prefer to invest in pest management technologies instead of soil fertility improvement technologies. There is need to quantify the profitability of these technologies in farmers' fields.

Farmers' perception that fertilizer application improved production agreed with the findings in the demonstration plots (Wairegi and van Asten, 2010b – Chapter 5). Mulch application may nonetheless have been very beneficial, particularly in low rainfall areas, due to improved soil moisture retention (Wairegi et al., 2010 – Chapter 4). Taulya et al. (2006) estimated yield losses due to drought stress at 40-50% when rainfall is 1100 mm year$^{-1}$ instead of 1500 mm year$^{-1}$. Where drought is a constraint, the combined package of fertilizer and mulch would most likely encourage adoption as McCown et al. (1992) reported that low rainfall contributed towards low adoption of fertilizer.

The perception that fertilized bananas tasted better than those grown without fertilizer agrees with other studies. In a farmer sensory evaluation study by the International Institute of Tropical Agriculture (IITA), fertilized bananas were ranked higher than unfertilized bananas when the fruit was steamed and mashed to make 'matooke' (G. Taulya, pers. commun.). In another study by Kumar and Kumar (2007), bananas fertilized using foliar sprays of K had higher sugar concentration and lower acidity compared with unfertilized bananas.

Despite the benefits of fertilizer, adoption may primarily be limited by high prices. In sub-Saharan Africa, fertilizer prices are very high, partly because most fertilizer is imported (Mwangi, 1997). Fertilizer costs and farm-gate prices influence fertilizer use (Byerlee et al., 1994) as they affect profitability. Due to the high fertilizer prices, adoption of the demonstrated technology (fertilizer use and mulch application) is more likely in areas close to Kampala than in far away areas. The profitability of these technologies tended to be good in the former areas compared with the latter (Wairegi and van Asten, 2010b – Chapter 5). Since spatial variability in nutrient imbalances and crop response suggested that the fertilizer used in demonstration plots did not always address nutrient imbalances (Wairegi and van Asten, 2010b – Chapter 5), targeting fertilizer applications to actual plant nutrient deficiencies would enhance plant response and therefore returns to investment.

Lack of access to inputs is a major constraint for technology adoption in Africa (Mwangi, 1997). Although farmers felt that unavailability of fertilizer was a constraint to its use, it is not possible to tell whether this unavailability is due to lack of demand from farmers or due to lack of supply. Farmers may have the feeling that they can still produce enough by using traditional soil management practices. A relationship between farm size, cattle ownership, soil fertility management and banana yield has been suggested. Bekunda (1999) observed that where farms were large, farmers had cattle, used cattle manure, banana and crop residues for soil fertility management, banana bunches were bigger than on smaller holdings where cattle manure was not used.

Farmer decisions can also be influenced by labour availability (Barnett et al, 1995). Although some farmers considered fertilizer application to be labour-demanding, it's labour demands are much less than those required for organic inputs like manure and compost. Hence, fertilizer adoption is more likely where labour is a constraint. Although there were no clear differences in perceptions between males and females, it is still possible that gender can influence fertilizer use. Nkonya et al. (2005) reported that male-headed households were more likely to use organic inputs and less likely to use fertilizers than female-headed households. They suggested that this was due to female farmers facing more sever labour constraints although they did not find differences in farm labour intensity between the two household types. Differences in adoption between genders have been suggested to be due to differences in access to inputs (Doss and Morris, 2001).

Although there was no strong perception that fertilizer spoils the soil, it should not be ignored and it needs to be mentioned that farmers disagreed amongst each other on this subject. Those who had no experience with fertilizer were more likely to have this negative perception. Apparently organic farming proponents told farmers that discontinuation of fertilizer use would lead to sharp decline in production to levels lower than those attained before fertilizer application.

## 5. Conclusions

Farmers relate poor yields to poor soil fertility, but generally perceive pests as a more important constraint to banana production. Farmers are aware that fertilizer increases production and bunch quality. However, fertilizer adoption seems particularly hampered by i) high prices, ii) a perceived lack of availability of high quality fertilizer in nearby shops, and c) the idea that fertilizer spoils the soil. Adoption can be increased by addressing these constraints where possible.

Blanket fertilizer recommendations do not take into account large regional differences in nutrient deficiencies. Hence, site-specific recommendations would probably make fertilizer use more profitable. Fertilizer demonstration plots in farmers' fields help farmers to better understand the effects of fertilizers and compare this effect with traditional soil management practices. More research would be required to better understand the potentially positive interactions between fertilizer use, mulch, and manure applications.

The increasing population pressure, land pressure, and nutrient mining will eventually have to lead to a further adoption of external nutrient inputs. Fertilizer will play an increasingly important role. The development of site-specific recommendations that are locally available in small high quality packs remains a challenge. Establishing sufficient demand and supply flows may require some external support to kick-start this process. The use of on-farm demonstrations or experimentation (e.g. through farmer field schools) can help to overcome farmers' suspicion that the fertilizers are not cost-effective or of poor quality.

Chapter 7

# General discussion

# 1. Introduction

In this final chapter, the main findings of the thesis and their implications for sustainable improvement of banana-based farming systems are discussed. Further, suggestions are made for future research. I return to the overall objective of this thesis which is to generate technologies and information that researchers and farmers can use to improve the productivity, profitability, and sustainability of banana-based systems. In addition to discussing the main findings of the study, I propose how the study could be followed up to arrive at site-specific recommendations for enhancing banana production through improved nutrient management.

# 2. Opportunities for increasing banana production

## 2.1 Banana yields and the yield gap

Although past research efforts aimed at addressing the problem of poor banana production have generated substantial information, production remains poor according to existing statistics (e.g. FAO, 2009). We found that the average yields in typical farmers' fields in the four regions were more than double the official national statistics for Uganda. Average yields ranged between 9.7 and 25.5 t ha$^{-1}$ year$^{-1}$ in typical farmer plots, while FAO (2009) estimated the national average to be only 5.5 t ha year$^{-1}$. Our results suggest that banana production and consumption in Uganda is far greater than previously thought. It would be useful to quantify banana production area more accurately in order to get a better insight into Uganda's overall annual banana production and consumption, and its importance for food security and farmer incomes. Earlier studies that reported banana yields in Uganda had the weakness that yield data were collected during single-point surveys or farmer estimates, and did not quantify actual yields over time as done in our study. It is essential that the methods employed by FAO to estimate yield of banana are revised if their statistics are to be used for developing national policy on food production and food security.

Comparison of average farmer yields with the largest yields attained in the best plots within regions (Figure 1) suggested that there still is much room for improvement of banana yields in Uganda; i.e. yield can be doubled using the management technologies currently available to farmers. On the other hand, attaining the likely yield potential for banana of >70 t ha$^{-1}$ year$^{-1}$ (van Asten et al., 2005) may be constrained by factors that cannot be addressed using the management practices currently available. For example, as rainfall is well below the 1500-2500 mm considered as ideal by

Purseglove (1985) in most of the banana growing regions suggests that improved water conservation and irrigation could further reduce the yield gap. Unfortunately, irrigation in not likely to be economically feasible for the majority of farmers who produce banana in Uganda, or elsewhere in the region.

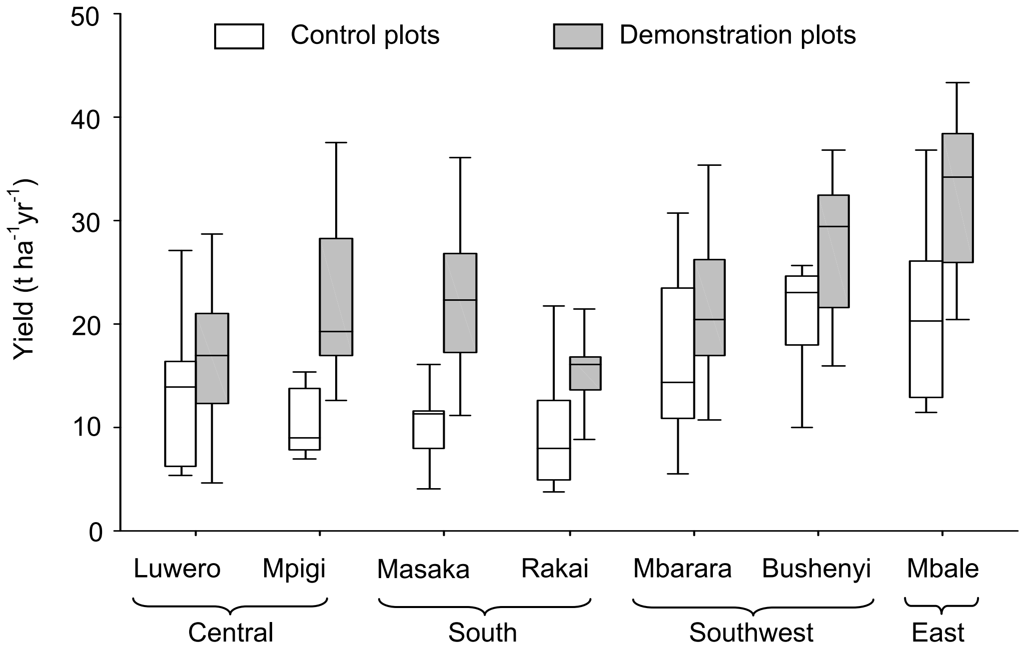


Figure 1: Banana yields in control and demonstration plots in Central, South, Southwest and East Uganda

## 2.2 Constraints to production

The importance of biotic and abiotic constraints differed strongly between regions (Chapter 4). Although poor soil fertility and drought proved to be important constraints in all regions, research investment has primarily focused on addressing pest and disease constraints in the past. Since nutrient deficiencies and drought are severe yield constraints that are likely to gain in importance due to nutrient mining and climate change, more research should be focused on these constraints to improve the productivity of banana in the East African highlands.

The Agricultural Productivity Enhancement Programme (APEP) demonstration plot approach revealed that fertilizer response was much stronger where the tested blanket fertilizer application largely corresponded with the existing plant nutrient deficiencies. The relatively larger yield increase in the South (103%) compared with other regions

(Central 65%, Southwest 23, East 28%) was probably because N was the most limiting nutrient in South and the fertilizer applied contained a relatively large proportion of N (71 kg $ha^{-1}$) compared with P (8 kg $ha^{-1}$) and K (32 kg $ha^{-1}$). These results indicate that addressing nutrient deficiencies using single- or double-nutrient fertilizers, which often cost less per unit nutrient mass than the current NPK fertilizer blends, can double the profitability of fertilizer use (Chapter 5). Fine-tuning of fertilizer recommendations to address existing nutrient deficiencies would make fertilizer use much more profitable.

Intensification of banana production through application of external inputs (fertilizer and mulch) proved to be profitable near the urban market (Chapter 5). Based on the fertilizer and banana farm gate prices at the time of the survey (2006-2007), farmers could find fertilizer use attractive (i.e. MRR≥1.0) if their farms were situated up to a distance of 160 km away from the capital. The distance could be further reduced as fuel costs are likely to increase in future as fossil fuel becomes scarcer. Subsequently, the area of land required to meet per capita food requirements will continue to grow as soils become poorer. In the long run, banana production in peri-urban areas may turn out to be more sustainable than production in distant rural areas as input and transport costs are less. The Ugandan tradition of producing most of its favourite bulky and perishable commodity far more than 200 km from the main urban consumers in Kampala needs to be revisited for smallholder farmers – who are predominantly risk-averse – are to be encouraged to intensify their production systems sustainably. Therefore, Uganda’s agricultural policy should perhaps focus on intensification of banana production close to the large urban markets (e.g. the Central region), whereas areas far from the urban market (e.g. Southwest) are better suited for production of storable commodities (e.g. coffee) that can be transported at a relatively low price. Banana production in the remote Southwest region will always remain important for local food supply, but its role as the dominant supply line to Central Uganda’s urban markets is certain to come under increasing pressure. The situation could change if bananas are processed (e.g. peeled and dried, or peeled and vacuum packed) locally and transported to urban areas.

Demonstrations of fertilizer use in farmers’ fields helped farmers to better understand the effects of fertilizers and how this compares with traditional soil management practices (Chapter 6). Farmers were aware that fertilizer increases production and bunch quality. The major constraints to fertilizer use were high fertilizer prices, a perceived lack of availability of high quality fertilizer in nearby shops, and the perception that fertilizer spoils the soil (not uncommon in Africa – Vanlauwe and Giller, 2006). The latter constraint was more important for farmers who had no experience in fertilizer use than with those who had experience. These findings showed that the adoption pathway can be shortened and strengthened by simultaneous demonstration and testing of technologies.

### 2.3 Conclusions

This study showed that recommendations to address banana yield-limiting factors must consider the strong spatial variation in biophysical and socio-economic settings. The major importance of nutrient deficiencies and drought stress shows there is need to focus more research efforts towards addressing these constraints. Recommendations addressing these abiotic constraints should be coupled with improved crop management and effective control of biotic constraints. From the greater importance attached to some of the constraints (e.g. the perceptions that fertilizer use spoils the soil and is a labour intensive activity) by farmers who had no experience with fertilizer use compared with farmers with experience, it is clear that there is need for close collaboration between researchers and farmers in technology development and adaptation. These findings confirm the key hypothesis of this thesis that biophysical constraints and interventions addressing these constraints differ in importance among major banana growing regions in Uganda while successful adoption/adaptation of interventions aimed at closing the yield gap is highly influenced by regional variations in their profitability and farmer-perceived opportunities and constraints. We therefore conclude that there is need to intensify research in development of site-specific recommendations in collaboration with farmers.

## 3. Directions for future research

### 3.1 Deriving fertilizer recommendations

In my opinion, future research aimed at improving banana production in Uganda should give priority to development of site-specific recommendations. This is based on the assumption that banana will continue to be the major food crop in Uganda, demand for banana will continue to outstrip supply as the population triples in the next thirty years, and competition for resources between banana production and other farm activities will continue. The findings presented in this thesis may serve as a reference for such a study.

In recent years, the need to base fertilizer recommendations on large numbers of trials has been reduced through the use of crop simulation models which match crop requirements to biophysical characteristics. Of the existing models, I suggest the

QUantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model (Janssen et al., 1990) should be used to formulate fertilizer recommendations for bananas in Uganda. QUEFTS is a relatively simple tool and takes into consideration the three major nutrients in banana production (N, P and K). The model, which was initially developed for maize and has also been used for crops such as rice (e.g. Haefele et al., 2003) and wheat (Khurana et al., 2008) and more recently for highland bananas (Nyombi et al., 2010). In addition to deriving a relationship between fertilizer rates and yield as was done by Nyombi et al. (2010), the recommendations should go further and include marginal returns in the calculation (Haefele et al., 2003). QUEFTS parameters presented in Nyombi et al. (2010) were based on a single highland banana cultivar using data from two trial sites in Uganda. Further calibration and validation will be needed to make the model applicable to multi-cultivar highland banana systems and to expand its geographic scope. Nyombi et al. (2010) observed relatively poor recovery rates of added nutrients in their trials, suggesting that fertilizer use would not be profitable in many cases. However, we observed (Chapters 4 and 5) that relatively modest fertilizer doses gave a good crop response and were profitable. The good fertilizer response observed in our on-farm plots may be related to denser plant stands and integrated management of organic and inorganic nutrient inputs, compared with solely mineral fertilizer inputs in the trials reported by Nyombi et al. (2010). The causes for differences in response between the farmer-managed trials presented in this thesis, and the researcher-managed trials presented by Nyombi et al. (2010) should be further explored.

Fertilizer recommendations are also required for bananas intercrop systems (e.g. coffee-banana, banana-beans) which are common in Uganda. The increased coffee yields when fertilizer N is applied to coffee intercropped with banana (van Asten et al., 2008), supports this. As with pure stand of banana, formulation of fertilizer recommendations for intercrops requires exploration of potential additional benefits in terms of recovery efficiencies, profitability, and subsequent returns to investment (i.e. land, labour, inputs).

### 3.2 Constraints to adoption of recommendations

Deriving recommendations does not necessarily lead to adoption by farmers. Poor availability of inputs, lack of immediate benefits (Esilaba et al., 2005), high prices (Nandwa and Bekunda, 1998), lack of information on technologies, risks associated with use of technologies, and increased labour requirements (Delve and Ramisch, 2006) are some of the constraints associated with use of soil management technologies. The preferential application of organic manures near homesteads commonly seen in African smallholder farms (Giller et al., 2006), which is also observed in Uganda, suggests that distance from the homestead to the banana plantation could be a constraint to use of manure. Although it is obvious from the data presented in this thesis and other studies that mineral fertilizers should be coupled with use of organic inputs, the misconceptions of farmers that organic inputs are sufficient for banana production and mineral fertilizer is not necessary (Nyombi et al., 2006) suggests that farmers may be unwilling to use both nutrient sources in combination. There are other factors that contribute towards preferential use of inputs. For example, inorganic fertilizers have higher concentrations of nutrients and are therefore required in smaller quantities than organic inputs. Hence, inorganic inputs require less labour.

Use of nutrient inputs in smallholder farming systems in Uganda is influenced by the intense competition among enterprises for limited resources. In mixed farming systems, there is competition for land for production of crops or livestock feed. Although self mulching is a common practice, removal of banana stalks from plantations for use as mulch in other crops and livestock feed has also been observed (Bekunda and Woomer, 1996). In addition, crop residues can be utilized as livestock feed and mulching material (Powell et al., 2004). There is also competition from outside farms for the limited resources. For example, in East Uganda where energy sources are low (Pender et al., 2004), farmers reported that mulch and leaves from banana plants were stolen from banana plantations to be burnt for cooking or for thatching houses. We observed that there was less mulch in the East compared with other regions. Although we did not collect data on this, mulch availability seemed to be least close to locations where local beer was sold as the mulch was used as a source of heat in beer preparation. This means that when developing recommendations, factors within the farm and from outside the farm, which may interfere with adoption should be taken account of.

### 3.3 Addressing constraints to adoption of recommendations

Whether farmers can access nutrient inputs in the required quantities and at the 'right' prices is another question. Obviously, supply, demand and prices are interrelated and subsequently determine use of fertilizer. Mwaura and Woomer (1999) suggested that competitive marketing can reduce fertilizer prices. This may be especially true for Uganda as the expense of fertilizer has been attributed partially to presence of few fertilizer importers and wholesalers (Woelcke et al., 2006). In addition, fertilizer subsidies could be an option for stimulating fertilizer use in Uganda, as has been recently introduced in some African countries. For example, maize production in

Malawi has been stimulated by provision of subsidized fertilizer (Denning et al., 2009). Whether fertilizer importers and retailers in Uganda are willing to invest in fertilizer types that address the nutrient requirements of banana (e.g. K-rich fertilizers) is another question. For example, major fertilizer importers informed us that the demand for specific fertilizer formulations that address existing deficiencies is likely to be too small to be profitable for the companies. Fertilizer prices in Uganda could be decreased if fertilizer was imported directly from overseas manufactures and suppliers instead of from Kenyan importers, but the requirement by overseas suppliers that the consignment should be at least 300 MT makes direct importation difficult (Omamo, 2003). Although availing fertilizer and lowering fertilizer prices should increase adoption, for poor farmers caught in the 'poverty trap' who would still be unable to purchase fertilizer, free fertilizer may be the only option.

Unlike with mineral fertilizers, farmers have greater control over availability of organic inputs such as animal manure. Since animal manure used within the farms where it is produced and not purchased, availability and not price is the major constraint to use. Obviously, several factors determine the number of and type of animals kept, for example capacity to invest, farm size, availability of grazing lands and feeds. But in zero-grazed systems farm size is not a constraint as feed and fodder can be grown on other farms or purchased.

Dairy cattle, the most commonly kept livestock, provide milk which is consumed by the family and excess sold, as well as manure which is used within the farm. Milk production in Uganda increased by 5.2% per annum between 2000 and 2008 (FAO, 2010) stimulated by the government and non-governmental organisations (Baltenweck et al., 2007). Still, the gap between demand and supply seems large as the per capita milk production is much less in Uganda (24 kg year$^{-1}$) than Kenya (76 kg year$^{-1}$) (FAO, 2010). Since there is stronger demand for milk in urban areas and unprocessed milk is highly perishable, the intensity of management of dairy cattle is high in peri-urban areas. For example, zero-grazing is more common near Kampala and grazing in paddocks is more common further from Kampala (Baltenweck et al., 2007).

To improve both milk production and the quality of manure, zero-grazed animals could be fed on high quality fodder/feeds preferably produced on the farm (Delve et al., 2001). For example farmers can establish leguminous, deep-rooted, perennial trees (e.g. *Calliandra calothyrsus, Leucaena trichandra*), that provide fodder, firewood and mulch. Some farmers, especially in the Central region, already grow leguminous trees in banana plantations. The amount of manure collected can be improved by confining animals in zero-grazing units instead of allowing them to graze in pastures. The common practice of storing manure without covering it (Briggs and Twomlow, 2002), which results in loss of nutrients, could be replaced by use of polythene covers. Rufino et al. (2007) reported less reduction in biomass and nitrogen in covered manure compared with uncovered manure. In addition, the floor should be waterproof or hard to prevent nutrient losses by leaching. Tittonell et al. (2010) reported greater N concentration in soil beneath heaps of manure compared with adjacent soils and leaching losses of P averaging 19%, from manure, in laboratory tests.

The high demand for labour in zero-grazing systems, and the strong competition for labour between farm and non-farm activities in peri-urban areas, means that farmers very close to urban centres may be unable to invest heavily in zero-grazing. For example, farmers in the Central region, where there was much more weed pressure than in other regions (Chapter 5), complained that labour was scarce and expensive. In another example, low use of organic inputs in farms close to urban centres was attributed to high wage rates (Nkonya et al., 2004). Since the returns to labour increase with increase in number of animals and labour costs increase with proximity to urban centres, Ndambi et al. (2008) suggested that zero-grazing systems in the peri-urban fringe can only be worthwhile if the farmer owns several animals. When farmers have only few or single animals the authors suggested that milk production should shift to more rural farms.

Although dairy farming is by far the most important income-generating livestock production system, other livestock should not be ignored. For example, the per capita production of meat from pigs of 3.41 and 0.33 kg year$^{-1}$ in Uganda and Kenya, respectively, in 2005 (FAO, 2010) shows that pig keeping is an important enterprise in Uganda. In addition, the presence of pigs in the Central and South regions (Figure 2) and the fact that the manure from pigs contains approximately five times the concentration of N, P and K nutrients found in manure from sheep and goats (e.g. Wortmann and Kaizzi, 1998), suggests that pigs are an important source of manure in farms near Kampala. Attention should be given to other livestock as well as cattle when considering possible sources of nutrients for crop production.

Use of mulch, the other important organic input for banana production, is limited by availability and costs associated as it is sourced both from within and outside the farm. There is need to ensure that available mulch is utilized to give the best returns. For example, instead of applying as much mulch as possible, farmers should ensure that they maintain a mulch thickness of 2 cm (Chapter 4). In addition to the common practice of using of grass and crop residues as mulching material, farmers could use other organic resources such as cuttings of *Tithonia diversifolia*, a plant common in hedgerows and roads in east Uganda which accumulates high concentrations of P and K, where available (Delve and Ramisch, 2004).

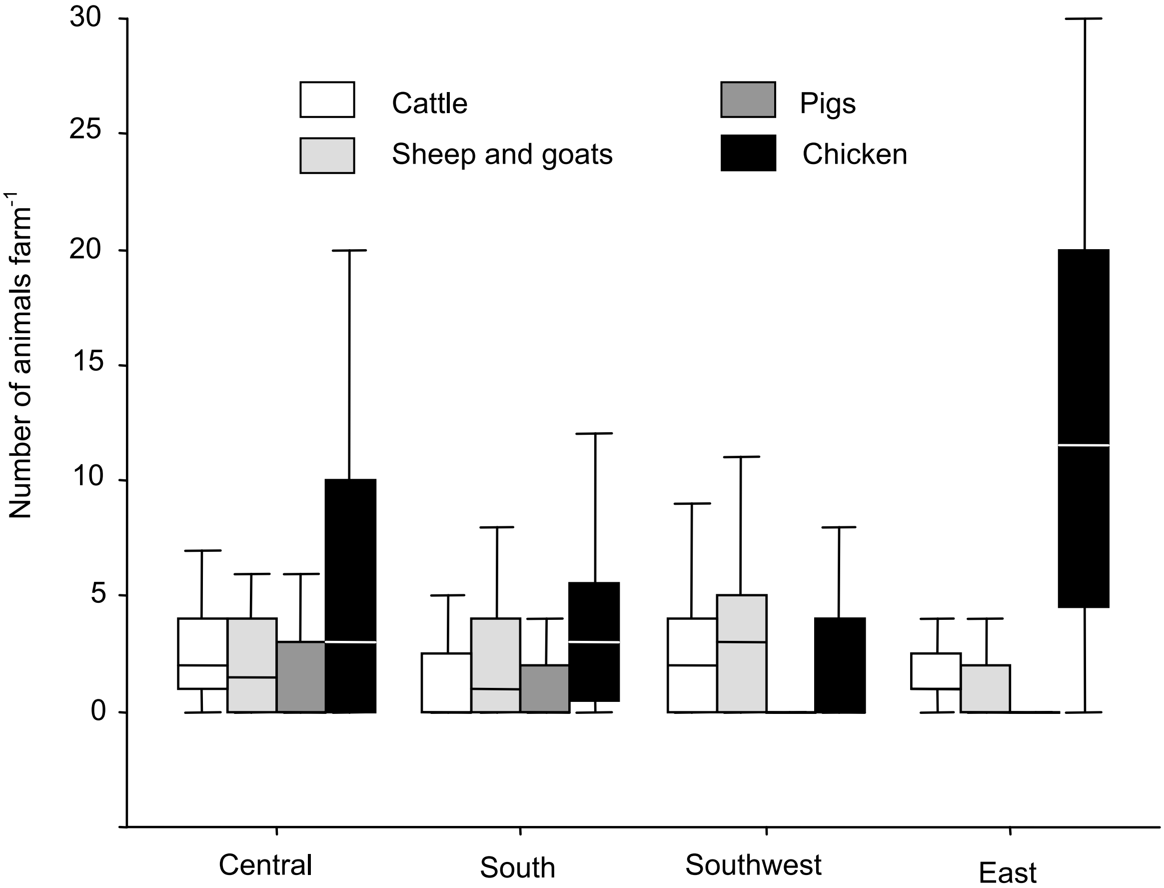


Figure 2: Average number of animals farm$^{-1}$ in Central, South, Southwest and East Uganda. Two farms in the Central region, one with 20 pigs and the other with 3000 chicken, were not included in the figure.

## 4. Concluding remarks

Intensification is required in banana production particularly close to the urban markets, but the intensification pathways and technologies can be diverse. Fertilizer use in banana systems in such areas is certainly one important component that requires further exploration. Introduction of leguminous forage to banana systems would improve N balance of the farm, provide additional mulch, and allow the integration of livestock in these systems. However, although livestock are a good complementary component of the system, they cannot provide the overall solution for densely populated areas where sufficient fodder may not be available. In areas far from urban markets, bananas should still provide an important buffering function for the farming system (e.g. source of food and income, control soil erosion, provide shade to intercrops), but may not be the primary crop to drive intensification. In such areas, intensification should be focused on crops that have low transport costs and good value such as coffee.

I hope that the findings presented in this thesis will be a useful framework for further research to improve food production and farm incomes in the East African region. I believe that there is a strong body of evidence that supports the conclusion that research geared towards addressing poor soil fertility should be given priority. Such research efforts will complement the efforts of African governments aimed at increasing production through increased funding to agriculture and rural development (AU/Maputo, 2003) and to increase fertilizer use to at least 50 kg $ha^{-1}$ by 2015 (NEPAD/Abuja, 2006).

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# Summary

In sub-Saharan Africa (SSA), food production has continued to be below demand as population growth has continued to outstrip increase in food production. The situation has been further aggravated by climate change due to non-regular weather patterns that impact on available water for crops. Although growth in overall agricultural production in SSA in the past was achieved through increase in cropped land, this is no longer feasible in many SSA countries due to increasing land pressure. Still, increase in production can be achieved through agricultural intensification as yields in for most crops are below potential. Banana, a major food crop in Africa, is a primary food and cash crop for over 30 million people in East Africa. In Uganda, the East African highland banana (*Musa* spp. AAA-EA) is the primary staple crop and is particularly important in southern half of the country where a bimodal rainfall pattern dominates.

Despite its importance, estimated average yields are low (<10 t $ha^{-1}$ $year^{-1}$) compared with potential (>70 t $ha^{-1}$ $year^{-1}$). The low production has been attributed to declining soil fertility, drought, pests and diseases and socio-economic factors. However, information is scanty on the importance, interactions, and geographic distribution of yields and constraints is scanty. Furthermore, fertilizer recommendations are "blanket" and do not necessarily address existing deficiencies. Development of site specific recommendations requires tools for identification of plant nutrient imbalances. In addition, on-farm studies require a tool for estimating bunch weight since quantification of production is very difficult as plants are at different stages of production at any given time. Therefore, the overall objective of this thesis was to generate technologies and information that researchers and farmers can use to improve the productivity, profitability, and sustainability of their banana-based systems.

This study is based on data collected through monitoring of farmer plots, household surveys and group interviews in the banana growing belt of Uganda (Central, South, Southwest and East regions) in 2006-2008. Data on production, constraints and management was collected in 300 plots, in mature plantations (5-50 years old). Of these 179 plots were monitored over a period of 12 months in 2006-2007 while the rest were surveyed. In 2008, data on farmer perceptions of the benefits of and constraints to fertilizer adoption were collected using structured interviews in 407 households. Thereafter, farmer perceptions were explored further through focus group discussions.

In Chapter 2, a functional relationship was derived for predicting bunch weights using girth of pseudostem at base and 1 m, number of hands, and number of fingers in the

lower row of the second lowest hand. The number of hands and fingers relate to the potential sink size (i.e. bunch), and the girth at base and 1m were used as a proxy for pseudostem volume, which relates to the potential of the plant to fill the sink. The same regression was applicable for different cultivars (i.e. Enyeru, Kibuzi, Nakabululu and Nakitembe), developmental stages (flowering, early fruiting, late fruiting and full maturity), regions (Central, South, Southwest and East) foliar and soil N, P, K, Ca and Mg concentrations. Although on validation the bias (-9.97%) and modeling efficiency statistic (0.64), suggested that predictions were not always accurate, the total predicted bunch weights were higher than the observed bunch weight by only 2%. We therefore concluded that the regression was suitable for on-farm prediction of bunch weight, for the East African highland cooking banana, regardless of genotypic, developmental and spatial variation. This relationship was then used in the calculation of yield data, where data is missing.

We derived and compared norms for diagnosing nutrient imbalance in AAA-EA bananas, using Compositional Nutrient Diagnosis (CND), Diagnosis and Recommendation Integrated System (DRIS), and a DRIS that includes a filling value (DRIS-Rd) in Chapter 3. The different norms developed in this study are closely related and can all be used to determine nutrient imbalances in AAA-EA bananas. However, we recommend CND for ease of use and its integrated approach. Nutrient interactions require that diagnosis of nutrient deficiencies in AAA-EA bananas should not be based on single nutrient analysis, but on methods that identify plant nutritional imbalances.

Actual yields in farmers' fields were quantified in Chapter 4 and 5. Average yields ranged between 9.7 and 25.5 t ha$^{-1}$ year$^{-1}$ in typical farmer plots, while FAO estimated the national average to be 5.5 t ha year$^{-1}$. These results suggested that the importance of banana in Uganda may be greater than previously thought. Comparison of average yields farmer yields with the highest yields attained in the best plots within regions suggested that there is a lot of room for improvement of banana yields in Uganda; i.e. yield can be doubled using the management technologies currently available to farmers.

The yield gap was quantified, and important factors limiting banana production were identified and their effect on the yield gap explored in Chapter 4. Yield losses were calculated using the boundary line approach. In the Central region, yield losses were mainly attributed to pests (nematodes 10% loss, weevils 6%) and suboptimal crop management (mulch 25%). In the South region, poor soil quality (pH 21%, soil organic matter and total soil nitrogen - both 13%, and Clay 11%) and suboptimal crop management (weeds 20%) were the main constraints. In Southwest, suboptimal crop management (mulch 16%), poor soil quality (K/(Ca + Mg) 11%) and low rainfall (5%) were the primary constraints. The study revealed that biotic stresses (i.e. pests, weeds) are particularly important in the Central region, whereas abiotic stresses (i.e. nutrient deficiencies, drought) dominate in the South and Southwest regions. Although low soil fertility and drought proved to be important constraints, past research efforts have primarily focused on addressing pest and disease constraints and mistakenly neglected abiotic constraints.

The possibility of closing the yield gap through use of the demonstrated technology (fertilizer and mulch) was explored (Chapters 5 and 6). Demonstration plots received mineral fertilizer (100% of plots), averaging 71 N, 8 P, 32 K (kg $ha^{-1}year^{-1}$) and external mulch (64%), whereas control plots received no mineral fertilizer and little external mulch (26 %). The demonstrated technology increased yields but highest increases were observed where fertilizer addressed key nutrient deficiencies identified using the Compositional Nutrient diagnosis approach. Use of the demonstrated technology was very profitable in areas with good farm gate prices (e.g. Central Uganda) and good crop response (e.g. Central, South), but was not profitable in areas far away (e.g. parts of Southwest Uganda) and in areas with poor fertilizer response. The technologies were likely to be acceptable to farmers (MRR≥1.00) up to 160 km away from the capital. Fertilizer use was likely to be acceptable in all regions if local fertilizer prices of 2006-2007 (average US\$ 0.56 $kg^{-1}$ of fertilizer) declined by 50%. Doubling of fertilizer prices, as happened in 2008, is likely to make fertilizer use unacceptable beyond 100 km away from the capital. Hence, given the current dynamics in local and global input and output prices, intensification of banana production should occur close to the large urban markets, but not in the current prime supplying area (i.e. Southwest). Farmers reported that high fertilizer prices were the most important constraint to adoption of fertilizer use by farmers. Other important constraints were poor availability, labour required for fertilizer application, and the belief that fertilizer negatively affected soil quality. It was evident that the demonstration plot approach simultaneously allowed participative evaluation, fine-tuning, adoption and adaptation of fertilizer recommendations. We concluded that there is scope for increased input use in banana systems in Uganda, but that regional variations in crop response, input/output prices, and price fluctuations have to be taken into account. We also concluded that the demonstration approach shortens and strengthens the adoption pathway, provided the process is supported by proper agronomic and economic evaluation of the technologies tested.

# Samenvatting

In Afrika ten zuiden van de Sahara (SSA) voldoet de voedselproductie nog altijd niet aan de vraag door de snelle bevolkingsgroei. Deze situatie wordt verder verslechterd door onregelmatige weerspatronen verooorzaakt door klimaatsverandering. De toenname in voeldselproductie in het verleden werd bereikt door de ingebruikname van nieuwe landbouwgrond. Door de toennemende landdruk blijft dit niet langer mogelijk. Een toenname in landbouwproduktie kan echter worden bereikt door intensificatie, aangezien opbrengsten voor de meeste gewassen nog ver beneden het potentieel zijn. Bananen zijn een belangrijk voedselgewas in Africa en zijn erg belangrijk voor de voedselzekerheid en het inkomen van kleinschalige boeren in de Oost Afrikaanse hooglanden. In Oeganda zijn de Oost Afrikaanse hooglandbananen (*Musa* spp. AAA-EA) het primaire voedselgewas, met name in de zuidelijke helft van het land dat wordt gekenmerkt door een bimodaal regenvalpatroon.

Ondanks het belang van de hooglandbananen zijn de geschatte gemiddelde opbrengsten erg laag (<10 t $ha^{-1}$ $jaar^{-1}$) laag vergeleken met het potentieel (>70 t $ha^{-1}$ $jaar^{-1}$). De lage produktie wordt toegeschreven aan een afnemende bodemvruchtbaarheid, droogte, ziektes en plagen, en sociaal-economische faktoren. Gegevens over de opbrengstniveaus, de produktiebeperkende factoren, de relaties tussen deze parameters, en de geografische verdeling ervan is echter schaars. Er is verder een uniform kunstmestadvies dat geen rekening houdt met bestaanden nutrientengebreken. De ontwikkeling van gebiedspecifieke kunstmestadviezen vereisen gereedschappen om nutrientengebreken te kunnen identificeren. Voor het utivoeren van studies op boerenbedrijven is het verder nodig om trosgewichten te kunnen kwantificeren. Dit laatste is vaak moeilijk omdat op ieder punt in tijd verschillende planten in verschillende stadia van ontwikkeling zijn. De algemene doelstelling van dit proefschrift was om technologien en informatie te genereren die zowel onderzoekers als boeren kunnen helpen om de productie, rentabiliteit, en duurzaamheid van banansystemen te verbeteren.

De data in deze studie is verzameld door het monitoren van boerenvelden en via interviews met individuele huishoudens en met boeren groepen in de periode 2006-2008.. Het studiegebied richtte zich op de belangrijke produktiegebieden van bananen in centraal, zuid, zuidwest, en oostelijk Oeganda. Gegevens over de behaalde produktie, gewasgroeifactoren, en gewasbeheer werden verzameld in 300 velden van langdurige plantages (5-50 jaar oud). Zo’n 179 velden werden gedurende 12 maanden tijd gevolgd, terwijl de resterende velden eenmalig werden bezocht. De percepties van 407 boeren over de voor- en nadelen van het gebruik van kunstmest werden via gestruktureerde interviews verzameld in 2008. Dit werd aangevuld met focus-groep discussies.

In hoofdstuk 2 werd een functionele relatie ontwikkeld om trosgewichten te voorspellen door metingen aan (i) de omtrek van de pseudostam aan de basis en op 1m hoogte, (ii) het aantal handen aan de tros en (iii) het aantal vingers van de onderste rij van de op een na laatste hand van de tros. Het aantal handen en vingers is een indicatie voor de potentiele grootte van de tros, terwijl de omtrek aan de basis en op 1m gebruikt werd als een indicator voor het pseudostam volume welke kan worden gezien als een maat voor de capaciteit van de plant om de tros te vullen. Dezelfde regressie relatie kon worden gebruikt voor (i) verschillende varieteiten (i.e. Enyeru, Kibuzi, Nakabululu and Nakitembe), (ii) voor planten in verschillende ontwikkelingsstadia van de tros (bloei, vroege vruchtvulling, late vruchtvulling, volledig gevulde vrucht), (iii) voor verschillende regios (i.e., Centraal, Zuid, Zuidwest, en Oost Oeganda), en (iv) voor verschillende nutrientenconcentraties in blad en bodem (i.e., N, P, K, Ca, Mg). Validatie van de bias (-9.97%) en de statistische modeleer efficientie (EF = 0.64) suggereerde dat voorspellingen niet altijd nauwkeurig waren, maar het voorspelde trosgewicht was gemiddeld slechts 2% hoger dan wat in het veld was geobserveerd. We concluderen dat voorgestelde regressiemodel geschikt is voor studies naar Oost-Afrikaanse hooglandbananen in boerenvelden waarbij het trosgewicht moet worden bepaald voordat het wordt geoogst, onafhankelijk van variatie in genotype, trosontwikkeling, en agro-ecologische karakteristieken. Het voorgestelde regressiemodel werd in deze studie gebruikt voor planten waarvan het trogsgewicht niet kon worden gemeten.

In hoofdstuk 3 werden voor de diagnose van nutrienten onbalansen normen voor AAA-EA bananen afgeleid en vergeleken met literatuurwaarden. Hierbij werd gebruik gemaakt van ‘Compositional Nutrient Diagnosis’ (CND), ‘Diagnosis and Recommendation Integrated System’ (DRIS), en een DRIS waarbij een vulwaarde wordt geintegreerd (DRIS-$R_d$) om eventueel ontbrekende nutrienten mee te nemen in de analyse. De verschillende normen die werden afgeleid waren sterk aan elkaar gerelateerd en kunnen ieder worden gebruikt om nutrientengebreken in AAA-EA bananen te ontdekken, maar de CND methode is aan te bevelen vanwege zijn gebruiksgemak en zijn geintegreerde benadering. Nutrienten-interacties vereisen dat de diagnose van nutrientengebreken niet moet geschieden op basis van individuele nutrientenconcentraties, maar op basis van methodes die mogelijke nutrienten-inbalansen identificeren.

Aktuele opbrengsten in boerenvelden werden gekwantificeerd in hoofdstuk 4 en 5. De gemiddelde opbrengsten liepen uiteen van 9.7 tot 25.5 t $ha^{-1}$ $jaar^{-1}$, terwijl FAO statistieken suggereren dat het nationale gemiddelde slechts 5.5 t $ha^{-1}$ $jaar^{-1}$ is. Onze reusltaten suggereren dat bananen van groter belang zijn voor Oeganda dan eerder werd aangenomen. De verschillen tussen de gemiddelde opbrengsten en de opbrengsten gemeten bij de beste boeren suggereren dat de opbrengsten nog flink kunnen stijgen in Oeganda; i.e., de opbrengst kan worden verdubbeld wanneer gebruik wordt gemaakt van gewasbeheerstechnieken die reeds bekend zijn bij de boeren.

In hoofdstuk 4 werd de verschillen tussen werkelijke en mogelijke opbrengsten gekwantificeerd, alsmede de factoren die de opbrengsten limiteerden. Opbrengstverliezen werden berekend met behulp van de 'boundary line approach'. In Centraal Oeganda werden opbrengstverliezen voornamelijk toegeschreven aan plagen (nematoden 10% opbrengstverlies, snuitkevers 6%) en suboptimaal gewas beheer (bodembedekking 25%). In Zuid Oeganda waren bodemkwaliteit (pH - 21%, bodem organische stof en total stikstof in de bodem – beide 13%, en kleigehalte 11%) en suboptimaal gewasbeheer (onkruid 20%) de grootste problemen. In Zuidwest Oeganda waren gewasbeheer (bodembedekking 16%), bodemkwaliteit (K/[Ca + Mg] 11%) en lage regenval (5%) de primaire problemen. Onze studie toonde aan dat biotische stress factoren (i.e. ziektes en plagen) voornamelijk belangrijk zijn in Centraal Oeganda, maar dat abiotische stress factoren (i.e. nutrientengebreken, droogte) overheerdsen in Zuid en Zuidwest Oeganda. Alhoewel bodemvruchtbaarheids- en droogteproblemen belangrijke problemen zijn, heeft het onderzoek in de regio zich in het verleden voornamelijk beperkt tot ziektes en plagen en hebben abiotische stressfactoren onterecht weinig aandacht gekregen.

Mogelijkheden om het verschil tussen aktuele en mogelijke opbrengsten te verkleinen door middel van beter bodembeheer (i.e. kunstmest en bodembedekking) werden onderzocht in hoofdstukken 5 en 6. Demostratievelden ontvingen kunstmest (gemiddeld 71 N, 8 P, 32 K kg $ha^{-1}$ $jaar^{-1}$) en externe bodembedeking (64% van de velden). Controlevelden ontvingen geen kunstmest en meestal geen bodembedekking (26% van de velden). De demonstratievelden hadden hogere opbrengsten, maar de beste resultaten werden behaald waar kunstmestgiften overeenkwamen met nutrientengebreken die met CND werden geidentificeerd. Het verbeterde bodembeheer was erg winstgevend in gebieden waar boeren relatief goede bananenprijzen ontvingen (i.e. Centraal Oeganda) en waar het gewas goed reageerde op de inputs (i.e. Centraal en Zuid Oeganda). In gebieden waar de prijzen laag zijn (b.v. delen van Zuidwest

Oeganda) en de opbrengstverhoging beperkt was, daar waren de voorgestelde technologiën nauwelijks winstgevend. De voorgestelde technologieen zijn accepteerbaar (MRR≥1.00) voor boeren dichtbij de markt (<160 km van Kampala). Kunstmest is waarschijnlijk accepteerbaar in alle regios als de kunstmestprijzen van 2006-2007 (gemiddeld US$ 0.56 $kg^{-1}$ kunstmest) met 50% zouden afnemen. Een verdubbeling van kunstmestprijzen zoals gebeurde in 2008 maakt kunstmest waarschijnlijk niet interessant in gebieden verder dan 100 km van de hoofdstad Kampala. Gezien de huidige prijsontwikkelingen in de lokale en internationale input en output markten, zal intensificatie van de bananenteelt moeten gebeuren dichtbij Kampala, maar niet in de huidige toeleveringsgebieden in Zuidwest Oeganda. Boeren gaven aan dat hoge kunstmestprijzen het belangrijkste obstakel zijn voor het gebruik. Andere belangrijke obstakels voor het gebruik van kunstmest waren (i) slechte beschikbaarheid, (ii) arbeid vereisd voor de toediening en (iii) het geloof dat kunstmest de bodemkwaliteit negatief beinvloed. Het gebruik van demonstratievelden gaf de mogelijkheid om participatieve evaluatie, het aanpassen van de aanbevelingen, en adoptie en adoptatie van kunstmestadviezen gelijktijdig uit te voeren. We concluderen dat er mogelijkheden zijn voor een toenmende gebruik van inputs in bananen systemen in Oeganda, maar dat regionale variaties in gewasrespons, input/output prijzen, en prijsfluctuaties goed moeten worden meegenomen alvorens boeren te adviseren. We concluderen ook dat het gebruik van demonstratievelden de adoptie van alternatieve gewasbeheerstechnieken kan versterken, mits zulke aktiviteiten worden begeleid door gedegen agrononomische en economische evaluatie van de voorgestelde technologiën.

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My family and I moved to Uganda, towards the end of 2004. Being interested in pursuing a PhD, I explored possible research areas and came up with a "draft" proposal aimed at "exploring the shift of banana production from Central to Southwest Uganda".

Towards the end of 2005, I got a job as a consultant on a collaborative project between IITA and USAID funded APEP, whose aim was to improve production in smallholder systems. The project was managed by Piet van Asten. Piet generously allowed me to use data from the project for my thesis and also became my supervisor. With great enthusiasm, he has tirelessly provided academic support, facilitated funding, and has been more than a supervisor. Thank you Piet! This thesis really is "our work". I have enjoyed working with you and hope to continue doing so in the future.

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Lydia

Nairobi, 15 June 2010

# List of Publications

## 1. Journal papers

Wairegi, L.W.I, van Asten, P.J.A., 2010a. Norms for multivariate diagnosis of nutrient imbalance in the East African highland bananas (*Musa* spp. AAA-EA). J. Plant Nutr. (in press).

Wairegi, L.W.I, van Asten, P.J.A., 2010b. The agronomic and economic benefits of fertilizer and mulch use in highland banana systems in Uganda. Agric Syst. 103 (8), 543-550.

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## 2. Technical papers and thesis

van Asten, P.J.A., Lorenzen, J., Wairegi, L., Mukasa, D., Batte, M., Muchunguzi, P., Pillay, M., 2008. IITA/APEP Banana Project Technical Report.

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## 3. Proceedings and posters

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# PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

The C.T. De Wit Graduate School PE&RC
PRODUCTION ECOLOGY & RESOURCE CONSERVATION

### Review of Literature (5.6 ECTS)

- Assessment of soil fertility management opportunities in East African highland cooking banana (Musa spp. AAA-EA) production in Uganda; presented and discussed at Makerere University Soil Science Department (2006)

### Writing of project proposal (7 ECTS)

- Assessment of management practices and opportunities in East African highland cooking banana (Musa spp. AAA-EA) production in Uganda (2007)

### Post-graduate courses (5.6 ECTS)

- Use of fertilizers and biology crop inoculants for sustainable crop production (2003)
- Use of Decision Support System for Agro-technology Transfer (DSSAT) to predict crop yields (2007)
- IITA Statistics course on computerized data analysis – general statistics, multivariate analysis, regressions, statistical packages for data analysis (2008)

### Laboratory training and working visits (4.3 ECTS)

- Individual field training course on methods to assess plant performance, pest and disease pressure, soil fertility, plant nutrient status, and farm management practices; IITA, Uganda (2006)
- Laboratory methods for soil and plant analysis; National Agricultural Research Organisation, Uganda (2007)

### Invited 2 reviews for proceedings of the Afnet symposium

- Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Facts in Arusha, Tanzania (2007)

### Deficiency, refresh, brush-up courses (2 ECTS)

- IITA Agricultural economics course on data collection methods and analytical approaches and tools (2007)
- CART Data mining statistical package (2009)

### Competence strengthening / skills courses (2.8 ECTS)

- Project and time management (2001)
- Scientific writing and communication; Uganda (2006)

### Discussion groups / local seminars / other scientific meetings (9 ECTS)

- IITA-Uganda, National Agricultural Research Institute and APEP-USAID seminars and meetings (2006-2009)
- Graduate seminars; Makerere University (2007/8)
- Monthly meetings of PhD students; Makerere University (2007/8)
- ‘Recommendations for banana and coffee’ workshop; APEP-USAID (2008)
- APEP-USAID ‘End of Project Presentation to Stakeholders’workshop (2008)

### International symposia, workshops and conferences (5.6 ECTS)

- Afnet Symposium: Innovations as Key to the Green Revolution in Africa Exploring the Scientific Facts; Arusha, Tanzania (2007)
- Banana and plantain in Africa: Harnessing international partnerships to increase research impact; International conference, Mombasa, Kenya (2008)

### Supervision of MSc students (12.6 ECTS)

- Methods of assessing plant performance, pest and disease pressure, soil fertility, plant nutrient status, and farm management practices; 30 days (2006-2009)
- Data entry, cleaning, exploration; 10 days (2008-2009)
- CND/DRIS Training course; 1 day (2009)
- Boundary Line Analysis to Quantify yield gaps; 1 day (2009)

### Supervision of MSc student

- Influence of production risk on productivity of bananas in Uganda; 7 days

# Curriculum Vitae

Lydia Wanja Ireri Wairegi was born in Kenya in 1963. She attended Mount Saint Mary's Primary School, Nakuru High School for ordinary level and Alliance Girls' High School for advanced secondary school. She graduated from the University of Nairobi with a BSc. in Agriculture in 1987. She then worked at the Kenya Agricultural Research Institute (KARI) between 1987 and 2001 as research assistant. She managed and collaborated in various multi-disciplinary research and development projects in Kenya, participated in scientific meetings. While at still attached to KARI, she studied at the Nairobi University and obtained a MSc. Degree in agronomy in 2001. Her research focused on use of rhizobium inoculum in intercropped maize and beans. In 2001, she moved to Zambia with her family. She worked for Cropserve Zambia Limited from 2003 to 2004, as a technical marketing expert on biological crop inoculants. This was as a volunteer attached to Voluntary Service Overseas (VSO). She conducted countrywide promotion of crop inoculants in collaboration with non-governmental organizations (NGOs), governmental organizations and farmer groups. In the period from 2005 to 2008, she worked at the International Research Institute of Tropical Agriculture (IITA), in Uganda as a consultant on a USAID funded project jointly carried out between IITA and the Agricultural Productivity Enhancement Programme (APEP). She conducted on-farm studies, participated in scientific meetings and published scientific papers. Currently, she conducts short-term assignments for the Consortium for Improving Agriculture-based Livelihoods in Central Africa (CIALA) project managed by IITA.

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