BIOPHYSICAL AND CROP MANAGEMENT GRADIENTS DRIVING WITHIN FARM VARIABILITY OF HIGHLAND BANANA YIELDS IN BUTARE VALLEY (SW UGANDA)

BY

ALOU ISAAC NEWTON, B.Sc. Agric. (First Class)

A THESIS SUBMITTED TO THE GRADUATE SCHOOL IN

PARTIAL FULFILMENT OF THE AWARD OF THE DEGREE OF

MASTER OF SCIENCE IN SOIL SCIENCE

OF MAKERERE UNIVERSITY

APRIL 2009

DECLARATION

I, Isaac Newton Alou hereby declare to Makerere University that this thesis is my original work, which has not been submitted for the award of a degree to and in any other academic institution. All sources of materials are duly acknowledged.

--------------------------------------- 20th- 04-2009 ---------------------------------

Isaac Newton Alou **Date**

This thesis has been submitted for examination with our approval as university supervisors

--------------------------------------- 20th /April/2009 ---------------------------------

Moses Makooma Tenywa (PhD) **Date**

Professor, Makerere University

--------------------------------------- 20 April 2009 ---------------------------------

Piet J.A. van Asten (PhD) **Date**

Banana System Agronomist

International Institute of Tropical Agriculture - Uganda

©

DEDICATION

To my uncle Mr. James Edopu for his initiative for further studies, my beloved mother, Mrs. Opio Anne Grace, brothers and sisters who have been at my sides whenever I needed support and encouragement. The Lord Jesus Christ for his Grace and Power, which enabled me to stand true to His Word in all circumstances.

ACKNOWLEDGEMENT

My heart-felt appreciation goes to my supervisors, Dr. J.A. Piet van Asten and Professor Moses Makooma Tenywa for their priceless assistance, guidance, financial support and above all their undisputable commitment to my research right from proposal development to the final write up.
I am also very grateful to every one in the research team; particularly Mr. Walusimbi T. K. Mugaaga (RIP), Dr. Drake Mubiru and staff of TSBF-CIAT Analytical Laboratory Nairobi who assisted in conducting the diagnostic survey and in laboratory analysis, respectively.
Special thanks to Mr. Tendo Ssali for the guidance in part, in data analysis.

I owe many thanks to administrative staff of IITA-Uganda, specifically Ms. Suzan Katebalirwe, Janet Anyango and the rest of the accounts team for their timely services accorded during my field research work.
My dear friends in Jesus Christ at Entebbe Fellowship, I give thanks to God for meeting such a nice group of lovely believers.

Last but not least, I would like to appreciate my research assistant, Mr. Robert Lukwago, household heads of the study farms and contact farmer, Mr. Lucia Kabate for their hospitality and unlimited cooperation throughout the data collection.

Thank you all and the Almighty God bless you, Amen.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS AND ACRONYMS

ABG	Above-ground biomass
BSV	Banana Streak Virus
BOLIDES	Boundary line analysis model
CDL	Cumulative dead leaves at harvest
C:N	Carbon to Nitrogen ratio
CF	Close field or plot
$Cmol_c$	Centimol of charge
cv.	Cultivar
CV	Critical value of nutrient
DRIS	Diagnosis and Recommendation Integrated System
EAHB	East African Highland Bananas
FAO	Food and Agricultural Organization of the United Nations
FEWSNET	Famine Early Warning Systems Network
HI	Harvest Index
ha^{-1} yr^{-1}	per hectare per year
IITA	International Institute of Tropical Agriculture
INIBAP	International Network for the Improvement of Bananas and Plantain
$mgkg^{-1}$	milligrams per kilogram
MAAIF	Ministry of Agriculture Animal Industry and Fisheries
MF	Mid-distance field or plot

MT	Metric Tonnes
NARO	National Agricultural Research Organisation
UBS	Uganda Bureau of Standards
UNBRP	Uganda National Banana Research Programme
UGX	Uganda shillings
P	Phosphorus
p	probability
PMA	Plan for Modernization of Agriculture
RD	Relative distance from homestead
RF	Remote field or plot
RELMA	Regional Land Management Unit
TDM	Total Dry Matter
SDEV or s.d.	Standard deviation
SPSS	Statistical package for social scientists
SAS	Statistical Analysis System
SOM	Soil Organic Matter
WI	Weed infestation index

ABSTRACT

Large within and between farm variability of banana (*Musa* spp., group AAA) yields in Uganda are caused interalia by a complex of soil fertility differences, pests, and light availability. These biophysical factors are again influenced by crop management practices, which show large spatial variability. Previous studies did not sufficiently take into account the large spatial variability in biophysical factors that prevail under on-farm conditions. The objective of the study was to quantify the relative contributions of soil fertility factors, pests and diseases, and crop management practices (e.g. planting density) to banana yield losses within and between farms that cover a range of wealth and slope classes. From a total of 50 farms covered under a preliminary diagnostic survey in Ntungamo district (southwest Uganda), 10 farms representing a gradation of biophysical (slope position) and socioeconomic (wealth status) variability were selected for on-farm monitoring of plant performance in Butare sub county. On each farm, 15 mats of the most dominant genotype (cv. *Enyeru*) were selected for the study along a transect parallel to the slope such that they fell within a range of relative distances (RD), close, mid and remote from the homestead. The crop management, growth from emergence to harvest, pest/disease status and yields of two ratoon suckers were quantified. Soil samples were collected per mat at the start of the study and analyzed for physical and chemical properties following standard laboratory methods. Boundary-line analysis revealed that soil fertility factors collectively contributed to 60% yield limitations, pests accounted for 30.0% and crop management 10.0% of total yield limitations. Among the limiting factors, banana weevil (*Cosmopolites sordidus* (Germar)) damage accounted for the highest (26.7%) yield limitation, soil K/Mg ratio (20.0%), soil pH (16.7%), excessive leaf pruning (10.0%), clay fraction (10.0%), exch. Ca (10.0%), Ca/K+Mg+Ca and nematodes each 3.3%. Banana streak virus, black Sigatoka and leaf spots depressed bunch weights by 21.5%, 17.9% and 16.9%, respectively in severely-infested plants compared to disease-free ones. Low pH and inadequate Ca limited yield improvements only among poor farmers as opposed to high weevil pressure among medium and rich farmers. The former had nematodes as an additional constraint and high soil K/Mg ratio, which also occurred among resource rich farmers. Mat spacing was significantly ($p < 0.05$, $R^2 = 0.904$) negatively correlated with bunch weight, and the heaviest bunch occurred at 2.6 m x 2.6 m (1512 mats ha^{-1}) compared to the recommended 3.0 m x 3.0 m. However, the poor farmers who had significantly ($p < 0.001$) higher plant densities than wealthier ones indicated, proper

spacing should be a greater concern among poorer farms. Pests and foliar diseases could not be attributed, but leaf pruning, to reduced number of functional leaves. Farmers should therefore aim at maintaining nine leaves at bud emergence to maximize yields, amidst the heavy defoliation. Poor farmers should invest in soil fertility management practices that improve soil pH and exchangeable bases availability in addition to proper spacing and weeding since their soils (were of similar inherent fertility in all farm categories) were relatively less fertile than those for wealthier farmers accordingly. Wealthier farmers should allocate their resources for pest control more especially banana weevil and for soil inputs for a good K/Mg balance. They should circumvent heavy defoliation through moderate leaf pruning (gradually remove diseased leaves) and avoid cutting of green leaves for preparing steamed food.
Key words: Yield limitations; Spatial variability; Boundary-line analysis; Relative distance; Wealth classes, Diagnostic survey

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Banana (*Musa* spp) is among the four most important food crops besides rice, wheat and maize in the world (FAO, 1993; 2003) based on gross value of production (Gold *et al*., 2002). Twenty five percent of the total world output of banana is from East Africa (Waller and Eden-Green, 1998). Uganda alone contributes 10% of the world output (FAO, 2001) which is greater than the total production of Kenya and Tanzania combined. Uganda's banana contribution to the world has perhaps increased based on an increase of 9 to 10.5 million t yr^{-1} (FAO, 1994; 2001). More than 75% farmers in Uganda cultivate bananas (Karamura, 1993) on 1.40 -1.51 million ha (PMA, 2000; NARO, 2001) mostly for subsistence on smallholdings (Kashaija *et al*., 1994). The produce of smallholder farmers is both for home consumption (Price, 1995) and the surplus is traded locally for income source (Speijer *et al*., 1999).

Uganda is ranked second to India in annual banana production (FAO, 2005) but leads the world in per capita consumption estimated at 220-460 kg per annum (Zake *et al*., 1999; FEWSNET, 2004). Annual consumption per habitat is estimated at 228 Kg (Bekunda, 1999) making bananas among the most important food crop in the country (MAAIF, 2000; Woomer *et al*., 2002; Kajumba *et al*., 2002). Most bananas or "*matooke*," are consumed as a cooked starch-rich puree (Karamura, 1994). Broadly, banana holds a social, cultural, commercial and nutritional value (Frison and Sharrock, 1999) for both subsistence, semi-commercial and pure commercial farmers (Kalyebara, 2002; Bagamba *et al*., 2004).

It provides a high nutrient food in terms of starch, vitamins and minerals (PNB, 2007); building and construction materials, design

Materials for instance mats and ropes (Mbwana *et al.*, 1998) and firewood; good animal feed (Karamura, 1993) while standing bananas conserve soil from erosion (Karamura, 1993). Such multiple uses probably explain the increase (475,000 ha) in planted area and a corresponding production increase of 4.3 MT for the period 1980-2004 (UBS, 2005).

The increased output is clearly a result of increased extensification (increase in cropped land) rather than due to intensification. Bekunda (1999) reported 4.2 and 6 t ha^{-1} yr^{-1} in 1998 in Masaka and Mukono, respectively, while Smithson *et al.* (2004) reported 3.1-4.9 t ha^{-1} yr^{-1} and 14.4-18.9 t ha^{-1} yr^{-1} in Luwero and Ntungamo districts, respectively. These reported yields were all way below the crop's potential of up to 70 t ha^{-1} yr^{-1}. Farmers have often identified deteriorating soil fertility and weevils as their key problems (Gold *et al.*, 1999a). Bekunda and Woomer (1996) and Sseguya *et al.* (1999) have identified the most serious yield constraints as soil fertility. The other constraints have been reported to be pests and diseases (Talwana, 2002; Gold *et al.*, 2003), deteriorating banana production management (Gold *et al.*, 1999a; Rukazambuga *et al.*, 2002), and moisture stress (Zake *et al.*, 2000; Rufino, 2003; Taulya, 2004) are others.

The aforementioned studies identified causes and mechanisms of yield loss but the majority of these trials do not represent on-farm conditions in terms of crop management practices and spatial variability. Typically, the constraint(s) were introduced or manipulated while in some, specific sites with extremes of factors (e.g. high/low pest pressure) were selected (Gold *et al.*, (2002; Oketch *et al.*, 2004) - atypical of the average smallholder farming systems who are the major banana producers. Whereas Abera *et al.* (1999) and Smithson *et al.* (2001) hold opposing views on the roles played by diseases and pests, reduced management and nutrient deficiencies in banana yields decline. It should also be noted that there are various interactions between and among the yield-limiting factors (Bekunda and Woomer, 1996) that were not considered in the aforementioned studies. For example, poor management to which Rukazambuga (2002) ascribed the observed yield decline also exacerbates pests and diseases (INIBAP, 2001 cited by Gold *et al.*, 2002) and soil fertility decline (Gold *et al.*, 1999). Crop management and soil type perhaps explained site differences in nematode densities in Central Uganda (Speijer *et al.*, 2001). 'Well-managed banana stands have produced stable yields for over three decades, even under low input conditions' (Gold *et al.*, 2002). Rubaihayo *et al.* (1994) supported this postulation although they never stated the pests and disease severity/incidence on the study farms, yet pest damage cause drastic losses (Jones, 2000a). High weevil and nematode pressure reduced the effect on yields of mineral fertilisers (Ssali *et al.*, 2003; Smithson *et al.*, 2001). Variability in local conditions (Lufafa *et al.*, 2003) was not captured in the above studies on absolute and relative contributions of yield-loss factors. The relative contribution of each of the aforementioned constraints under on-farm conditions hitherto remains poorly understood.

1.2 Problem statement

Declining yields have undermined the status of bananas as a sustainable food crop in the East African Highlands (Gold *et al.*, 1999a).Yield limiting factors such as pests and diseases, soil quality problems, show a high spatial and temporal variability within the country, regions, villages and even (and most importantly) within farms. Previous studies on yield loss factors in Uganda often focused on a single constraint (e.g. Rukazambuga *et al.*, 1998; Talwana *et al.* (2003; Gold *et al.* 2004), or tried at best to explain variability in constraints and yields between regions (Smithson *et al.*, 2004) and sometimes between farms (Oketch *et al.*, 1996; Gold *et al.*, 1999a, Oketch *et al.*, 2006). Such studies often assumed that constraints other than the one that is primarily studied are either (i) not important, or (ii) do not vary between treatments and plots. Given the large production gradients within and between farms (which remains unaddressed), any advice on how to increase yields with minimal resource investments should take into account how yield constraints vary both between and within farm(s).

Reduced and low banana yields also result in reduced income (Bekunda, 1999) which makes it difficult for farmers to invest their limited resources to overcome the yield limiting factors. Resource limitations also vary per farmer, as a function of its socio-economic status (i.e. human resources and capital) (Bananuka and Rubaihayo, 1994). The challenge therefore, of prioritising 'which constraint to address first' requires detailed information on the magnitude of each yield loss factor and the relation between these factors.

Most of the existing information is inadequate to answer complex problems banana farmers face. An understanding of how production (yields, pests and soil fertility) and crop management gradients are related will help to identify what management practices would help to reduce yield variability within farms, and thereby substantially increase productivity.

1.3 Objectives

This study was conducted to rationalize the contribution of soil fertility, pests and diseases and crop management practices to the banana yield losses within and between farms that cover a range of wealth and slope classes in a banana producing valley.

Specific objectives of this research were:

- To quantify the contribution of soil fertility factors, crop management, and banana pests and diseases to the yield gap in the farmers' field.
- Evaluate the interactions between soil fertility gradients from the homestead on within- farm banana pest damage and disease severity.
- Determine within-farm variability in banana yield, yield-limiting factors and constraints among farmers of different resource endowment.

1.4 Hypotheses

- Soil fertility factors and banana pests contribute additively to the farm yields.
- There is a negative interaction between soil fertility factors and banana pests; i.e. banana yields decrease and pest damage/disease severity increase with increasing relative distance from the homestead.
- There is larger variability in banana yields and yield-limiting factors among resource poor farmers than among wealthy farmers because input use is higher and more evenly distributed within the latter farms.

1.5 Justification

Partitioning the yield gap will help establish cause-effect interrelationships that will be used to refine models for use in decision support systems. Yield loss is the result of the combined interaction of other factors (Stover, 1996) - a fact that most researchers concur to, but the determination of the relative contribution of each factor assists decision markers establish the actual and/or potential constraints within and across farms. However, even within farms, management varies (Bananuka and Rubaihayo, 1994) often associated with on-farm conditions (Mutsaers *et al.*, 1997; Schlecht *et al.*, 2006) and spatial heterogeneity of the soil (Gold *et al.*, 1994). The need to employ analytical procedures sensitive to such variability is inevitable in this context. This study henceforth exploits and analyses the environmental variability and its effects (Webster and Oliver, 1990) on growth performance of each plant over one cycle to explain the driving factors to yield loss.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Banana production constraints in Uganda

Despite its importance as a cash and food crop (Speijer and Kajumba, 2000) and its other potential uses (RELMA, 1999), banana production is generally declining in Uganda (Van Asten *et al.*, 2004). Reports on banana yield as early as the 1940s and 1950s (Masefield 1949; McMaster, 1962) were attributed to an insect pest (banana weevil) and declining management (Nye cited by Tothill, 1940). Average yields have dropped from 8.5 t ha^{-1} yr^{-1} in 1970 to the current level of about 5.7 to 5.9 t ha^{-1} yr^{-1} (FAO, 2004; MAAIF, 2005). Currently, the actual yields of 5-30 t ha^{-1} yr^{-1} are far lower than the potential yield of 60-70 t ha^{-1} yr^{-1} (Smithson *et al.*, 2001; Van Asten *et al.*, 2004). An equivalent output level realised in 1970 is only possible today with extra 0.5 million hectares (MAAIF, 2005). Banana production is constrained by biotic and abiotic factors, which differ between farmers and between regions (Gold *et al.*, 1993).

Declining soil fertility (Van Asten *et al.*, 2004) resulting from various causes (Smaling, 1993; Rubaihayo *et al.*, 1994; Oketch *et al.*, 1996; Hartemink, 2003) may be the major abiotic constraint (Speijer *et al.*, 1999). Although declining soil fertility is specific to long-lived production systems (Abera *et al.*, 1999), there is evidence to challenge this argument. Smithson *et al.* (2004) found increasing imbalance of K in particular, in the non-traditional production areas of southwest Uganda. Exportation of K in bunches (Van Asten *et al.*, 2004) and other elements are probable causes of nutrient depletion. Soil fertility decline is a widely believed cause for yield loss; unfortunately, this argument is not supported by time series (from non-cross sectional surveys) georefrenced soil sampling and analysis data.

In addition to soil constraints, pests particularly root nematodes and banana weevil borer *Cosmopolites sordidus* (Germar); (Gold *et al.*, 2002) and diseases especially leaf spots (Tushemereirwe *et al.*, 1996) contribute to the observed yield decline. Nematodes-related EAHB yield losses of 15-50% (Talwana *et al.*, 2003) and of weevil damage averaging 42% over a four-year trial (Gold *et al.*, 2004) have been reported. The contribution (whether or not significant) of other limiting factors, interacting with pest damage to the yield loss attributed to pests alone is yet to be quantified.

Gold *et al.* (1999) cited farmer reports to the effect that poor agronomic management of EAHB plantations contributed to the observed yield decline. Rubaihayo *et al.* (1994) and Lufafa *et al.* (2003) concur with the farmers' reports cited in Gold *et al.* (1999). However, there is still controversy over what practices constitute best-bet agronomic management practices for EAHB (Ssali *et al.*, 2003) in relation to the standard practices recommended to farmers (RELMA, 1999; Lufafa *et al.*, 2003). Management in banana production should be viewed in a broad perspective because according to Bananuka and Rubaihayo (1994), such agronomic practices differ even among farms mostly dictated by financial status. Banana management as a function of household wealth of farms is an area that deserves further illumination. The identification of sub-constrains within the framework of major constraints will be of great practical importance in making effective management decisions in smallholder banana based systems.

2.2 Soil quality problems in East African banana (EAHB) systems

The soils on which EAHB (*Musa* spp, AAA-EA) cultivation is most widely practiced are Ferralsols and Acrisols (Van Asten *et al.*, 2004), which have a low inherent fertility (Sanchez *et al.*, 1989). Most banana soils in the region (Rubaihayo *et al.*, 1994; Bananuka and Rubaihayo, 1994; Wortmann and Kaizzi, 1998; Smithson *et al.*, 2001; Rufino, 2003) are old, highly weathered materials with low mineral nutrient reserves (Ssali, 2006). Soil fertility management is maintained by recycling of crop residues traditionally involving mulching (Bekunda and Muzira, 2003). Fortunately, most farmers preferentially transfer annual crop residues and other organic inputs to banana fields making soils in banana plots relatively richer in P and K than soils in other crops' fields (Bekunda and Woomer, 1996; Wortmann and Kaizzi, 1998). Indeed, Rufino (2003) and Smithson *et al.* (2001) observed that banana soils in Uganda have optimum soil fertility. However, bananas grown near the homestead are more often mulched and receive more organic plus other household residues than plots further away (Price, 1995; Rishirumuhirwa, 1997; Bekunda, 1999; Rufino, 2003). Hitherto, within smallholder farms, strong gradients of decreasing soil fertility with increasing distance from the homestead exist (Vanlauwe *et al.*, 2006) although there is a general negative nutrient balance for both nearby and far-away fields (Ssali, 2004). Rufino (2003) and Smithson *et al.* (2001) supported the above findings using foliar analysis and identified K deficiency as a major constraint, often followed by N and Mg in the banana-based cropping systems in Uganda. Nonetheless, there is limited data to support the claim that soil nutrient depletion is one of the major constraints to banana productivity (Smithson *et al.*, 2001). Phosphorus deficiency does not seem to be a frequent problem in the banana growing regions (Van Asten *et al.*, 2004). Likewise, Zake *et al.* (2000) observed strong yield increases at 25-200 kg K ha^{-1} combined at 100 kg N kg ha^{-1} and with less than 100 kg P ha^{-1}

and Rubaihayo *et al.* (1994) reported increases from 2 to 9 t $ha^{-1}yr^{-1}$ when mineral fertilisers alone were applied. The response to mineral fertilisers was reported to be 'less effective' (lower) with high nematode and weevil pressure (Smithson *et al.*, 2000; Ssali *et al.*, 2003). As opposed to low nutrient concentrations in and limited quantity of organic inputs (Batiano and Mokwunye, 1991) used by farmers (Bekunda and Woomer, 1996); the use of mineral fertilisers to correct the deficits and compensate 'moved' nutrients (Smithson and Giller, 2002) is almost inevitable in the near future. Consequently, studies that better explain (i) what constraints are most important, (ii) what the spatial variation of these constraints are and (iii) how the constraints can best be overcome, will be of great value to farmers that have to select where to invest their limited resources to obtain maximum yield increase.

2.3 Soil fertility gradients within small farms and determinants of soil fertility status variability at farm-level

Within smallholder farms in Africa, strong gradients of decreasing soil fertility are found with increasing distance from the homestead (Ruthenberg, 1980; Prudencio, 1993; Vanlauwe *et al.* 2006). Variability in soil fertility at farm scale may be associated with topography, soil types, land degradation (e.g. erosion and leaching) intensities, sharp physical discontinuities (e.g. rocky outcrops), and within farms to land-use history or distance from the homestead and livestock facilities (Tittonel *et al.*, 2005).

Even within the smallest farms in a smallholder farming system, strong fertility gradients exist (CIAT, 2003). In a study in Western Kenya, East Africa, Tittonell *et al.* (2005) observed "even in farms with land areas as small as 0.45 ha, gradients existed where productivity declined with increasing distances from the homestead." The same authors ascribed variability to "distance from the homestead which tended to affect the allocation of production activities and resources." Apparently, the differential long-term management of fields has created these gradients in soil fertility status (Tittonell *et al.*, 2005). Causes for such variability include among others:

- Unequal distributions of organic fertilisers in these farming systems (Bekunda, 1999) in which homestead plots receive more organic inputs and are more often mulched (Van Asten *et al.*, 2004).
- Continuous concentration of organic wastes and nutrients in the small areas around the homesteads (Smaling *et al.*, 1997; Elias *et al.*, 1998; Scoones and Toulmin, 1999) creates these gradients. Organic wastes like bran from pounded cereals, animal manure and other crop residues are deposited to crop plots close to homesteads (Bekunda, 1999; Bekunda and Manzi, 2003) including some household wastes. The latter include kitchen wastes, sweepings and wastes collected from in and around the house (Tittonel *et al.*, 2005), such as ashes from fuel wood (Obiefuna, 1991) and other cooking energy sources, and food leftovers.
- Inadequacies in supplies of both organic and inorganic nutrients have as well created soil fertility gradients within a household (CIAT, 2003). Some farmers typically remove and transfer harvest products/crop residues from their 'outfields' (Wortmann and Kaizzi, 1998) and devote their scarce soil inputs to small market 'infields' (CIAT, 2003). Since the labour effort to carry wastes will be greater as the distance from the house increases (Bekunda, 1999), the wastes are easily thrown within nearby locations.
- The present farmers' judicious management practices ('precision farming') create micro-variability of their fields (Schlecht *et al.*, 2006). Most farmers show preference in removal of organic inputs like biomass (crop, tree and animal products) from fields. For instance, sales or donation of products; exportation of manure and crop residues,

including trees and other biomass transferred out of the household disproportionately impoverish respective source plots. This affects nutrient availability across plots (fields) because such nutrients are not available for recycling as organic inputs to crop plots.

The net end result is large differences in soil productivity over time between these two field types (CIAT, 2003) later reflected in the final yields. Rugalema *et al.* (1994) observed taller and more vigorous plants in homestead plots than from remote fields in northwestern Tanzania. In Masaka and Mukono districts of South-Central Uganda, Bekunda (1999) made a similar observation: "banana fields show a gradient from high yields near the household to lower yields towards the outer field boundaries."

Understanding how to manage the limited nutrient supplies across such fertility gradients is a key component in raising overall productivity in farms. Hierarchically, the sources of variability in soils status of a homestead are the same factors for variation across farms. Thus, these factors are likely to influence recommendations on soil fertility strategies. Indeed de Jager *et al.* (1998), Wortmann and Kaizzi (1998), regard as household level an important scale for storing and transferring nutrients but as well as making farm management decisions (Defoer *et al.*, 2000).

2.4 The major EAHB pests and diseases and associated yield losses

Pests and diseases are serious production constraints in their own right (Gold *et al.*, 2001, 2002; Gowen and Quénéhervé, 1990) but their status reflects, in part, the management system (Gold *et al.*, 2002). The banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curulionidae) is an important insect pest of highland bananas (Stover and Simmonds, 1987; Gold *et al.*, 1993) in Africa (Gold *et al.*, 2001). In Uganda, the pest is implicated in the decline and disappearance of EAHB (AAA-EA) in central areas (Gold *et al.*, 1999b, c). The insect can cause yield losses of up to 100% (Sengooba, 1986; Koppenhofer *et al.*, 1994) through sucker death, toppling and snapping (Gold, 1995; Rukazambuga *et al.*, 1998; McIntyre *et al.*, 2000), and shortens plantation life span (Rukazambuga *et al.*, 1998; Gold *et al.*, 2004) if not controlled. Premature leaf senescence (Ndege *et al.*, 1995) reduced plant size and vigour (Rukazambuga, 1998) are other symptoms of weevil infestation.

Nematodes are as well important pests and represent a key constraint to *Musa* production world wide (INIBAP, 2001) and in East Africa (Kashaija, *et al.*, 2004; Gowen *et al.*, 2005). In East Africa, a complex of migratory endo-parasitic nematodes including *Pratylenchus goodeyi* Sher & Allen, *Radopholus similis* (Cobb) Thorne and *Helicotylecnhus multicinctus* (Cobb) Golden (Gichure and Ondieki, 1977; Bridge, 1988; Sikora *et al.*, 1989; Speijer and Bosch, 1996) attack bananas. Production loss in EAHB caused by these species in Uganda respectively varies from 30% to 50% but can also exceed 50% (Speijer and Kajumba, 1996) and from 15 to 50 % (Speijer *et al.*, 1998, 1999; Speijer and Kajumba, 2000; McIntyre *et al.*, 2000). Gold *et al.* (1994) asserts that attack by the different species is not easily differentiated in the field, implying that a given level of yield loss cannot be attributed to one specific species. Nematodes impair absorption and transportation of water and nutrients, and disrupting plant anchorage (Talwana *et al.*, 2003), resulting in a reduction in bunch weights, loss of bunches due to toppling, increase of crop cycle duration and decrease of plantation longevity (Gowen, and Quénéhervé', 1990; Quénéhervé *et al.*, 1991). Delayed ratooning (Blomme, 2000), stunting of plants, lengthening of vegetative cycle, reduction in size and number of leaves (Speijer and De waele, 1997) are other significant types of damages.

Diseases are limiting factors in smallholder and export production (Jones, 2000a). Among the diseases, banana streak virus (BSV) is by far the most important constraint of highland bananas (Tushemereirwe *et al.*, 1996) and of recent banana bacterial wilt. The same authors reported losses of up to 100% of saleable yield in bananas infected with BSV during early growth stages. Leaf spot diseases caused by species of *Mycosphaerella* result in moderate to severe damage wherever significant rainfall occurs (Jacome *et al.*, 2003) and actual yield losses are not known in on-station trials (Tushemereirwe, 1996) so far but not under different management systems. Only, intercropping bananas with finger millet (Holderness *et al.*, 1999), poor sanitation and pest infestation (Kungu'u *et al.*, 1992) have been reported to exacerbate leaf spot diseases in Uganda and Kenya, respectively. Conversely, mulch and manure through their effects on plant growth are reported to decrease leaf spot diseases (Holderness *et al.*, 1999; Speijer *et al.*, 1999).

Black leaf streak, better known as black Sigatoka (*Mycosphaerella fijiensis*) is the most important fungal disease, of considerable importance in warm areas below 1400 masl (RELMA, 1999). This suggests that the disease might be of minor significance in highland areas of Southwestern Uganda (IITA Foodnet, 2002). De-leafing or detrashing is useful practice for management of black leaf streak but of great limitation in heavy rainfall areas (RELMA, 1999).

2.5 Influence of crop management on pests and disease status, growth and yields of EAHB

Declining yields of *Musa* spp. are also directly attributed to poor management (Gold *et al.*, 1999a; Rukazambuga *et al.*, 2002) of plantations. Okech *et al.* (1997) reported significantly higher bunch yields in 'well'-managed fields and postulated that banana pest problems could be reduced effectively through practicing good plantation management. 'Well' management as however relative, based on compound [categorical attribute] rather than proxy dicators of crop management.

eeds and intercrops compete for soil mineral nutrients and water (Wallace, 1938), which e often low in poor soils as a result the stressed plants are susceptible to more attack ones, 1986). Mulching has been partially successful in weevil control (Oketch *et al.*, 1999; Gold *et al.*, 2002) and the thickness of mulch in plantations has been reported (Gold *et al.*, 999a, b) to affect activity patterns of *C. sordidus*.

Homestead plots are more often mulched than plots further away (Van Asten *et al.*, 2004) combined with moist discarded organic matter plus crop residues favour weevils (Treverrow *et al.*, 1992) more in former than latter plots. Equally, homestead plots receive more organic inputs (Van Asten *et al.*, 2004) like poultry and animal manures, wood ash. Such inputs (wastes) are common in most Ugandan households, which rear poultry and generate wood ash usually from kitchens. Based on Obiefuna (1991) findings, (i) animal manures significantly reduced weevils in Nigeria; (ii) application of poultry farm yard manure and inclusion of wood ash in the manures reduced weevil but also minimised nematode damage, respectively. It could be assumed that a trend with reduced pest and disease incidence near homes is apparent in most banana farms in Uganda. In addition, crop management practices are better frequently done in homestead than remote banana plots (Bekunda, 1999) for instance covering remaining stumps in the soil with hard compacted soil believed by farmers to eradicate weevils (McNutt, 1974).

Just like soil fertility variability within a homestead, the above observations and findings demonstrate the spatial heterogeneity of pest pressure as a function of distance to kitchen.

2.6 Interrelationships between soil factors and banana pests and diseases

There is a clear relationship between soil fertility and expression and severity of diseases (Van Asten *et al.*, 2004), in the sense of the plant's ability to resist disease-pathogens and pests. Several studies have highlighted interactions between soil fertility and pests while others report no direct link. Tushemereirwe (Unpubl.) in Van Asten *et al.* (2004) observed that crop damage due to BSV and black leaf streak disease decreased with improved soil fertility management. Yield losses of 10 and 30% due to BSV ascribed to well and poor crop management respectively (Murekezi, 2005) reflect, in part, the soil nutrients/disease interactions since soil fertility management was a component in that study. Decrease in leaf spot disease due to mulching and manure application (Holderness *et al.*, 1999) could be attributed to the effect of nutrients on plant tolerance, which also suggests interrelations between the soil nutrients and leaf spots.

Likewise, pests do not operate as discrete entities in the field (Stover, 1996) but are intimately associated with soil factors. Soil-bor ne pests, specifically nematodes and the banana weevil, attack plant roots and vascular system reducing the plant's capacity to take up nutrients. Once deprived of the required elements, nutrient stress in the plant may be aggravated (Van Asten *et al.*, 2004), which may lead to severe pest damage. For instance, reduced levels of magnesium and potassium may have weakened resistance to banana weevil (Bosch *et al.*, 1995). The same authors (1996) suggested that weevil damage might be related to plant and soil phosphorus and cation concentration, particularly P, Zn, Mg, K contents and K/Mg ratio. These findings are in contradiction with those of Smithson *et al.* (2003) who found no effect on foliar concentrations or weevil damage at different levels of K and Mg. Equally, Ssali *et al.* (2003) did not find any effect of (in) organic soil amendments on the percentage weevil damage.

Although in both studies, the authors agreed that fertilisers become less effective at high nematode and weevil pressure, more elaboration on soil factors-pests interactions is desirable under on-farm conditions. Low input management systems are typical of smallholder farms (unlike in the above studies) hence such interactions were envisaged to be significant in the study herein reported.

The relationship between nematode damage on plants and nutrient uptake/concentrations (Talwana, 2002) indicated that higher Ca concentrations occurred in nematode-infected bananas (AAA-group) and plants showed better growth. Bwamiki (2004) suggested that mechanisms of nematode suppression are linked to K, Ca, Mn and Zn uptake. Nematodes could partly be mitigated through increased application of plant nutrients (Bwamiki, 2004) with more elucidation of interactions between the parasites and nutrients.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Site description and characterisation

3.1.1 Location

The study was based in Nyakyera sub-county of Ntungamo district (southwestern Uganda) where 67% of banana production in Uganda occurs (Kangire *at al.*, 2000). The district lies between latitudes 0° 52.88'and 0° 53.79' S and longitudes 30° 13.66' and 30° 13.85'E with an elevation range of 600 – 2000 masl (average 1440 masl); one of the highest points being found in Nyakyera sub-county (Ntungamo District Report, 2002). The district was chosen due to its Agro-Ecological characteristics which are broadly representative of the situation found in other tropical highlands of East Africa.

3.1.2. Topography

The sub-location is a "hot spot" for soil loss by water in an area characterised by steep topography, evidence for soil erosion (cf. Appendix 1) is rampant (exceedingly deep gullies), in part, a result of high rainfall (Ntungamo District Profile report, 2000).

3.1.3. Climate

Ntungamo receives 800-1500 mm rainfall per year with a bimodal distribution (March to May and September-December). Average minimum and maximum air temperature range is 15°-28°C. Rainfall record at the study site from 20th February 2006 to 30th September 2007 indicates that precipitation averaged 1036 mm and 676 mm for 11 and 9-month periods respectively, with considerably wet and long second season (Figure 1). Records of the first and early- (August and September) second seasons for 2007 depicted the similar pattern to 2006. Dry periods occurred in July but were extreme in June 2006. Figure 1 shows the monthly cumulative rainfall during the monitoring study period.

Mean daily minimum and maximum air temperatures are 14° and 26°C, respectively (FAO data, World climate). The experience of the producers reveals that the comparatively lower temperatures in upper slope positions compared to those of lower slopes explain a lag in harvest periods on farms located in the former slope positions.

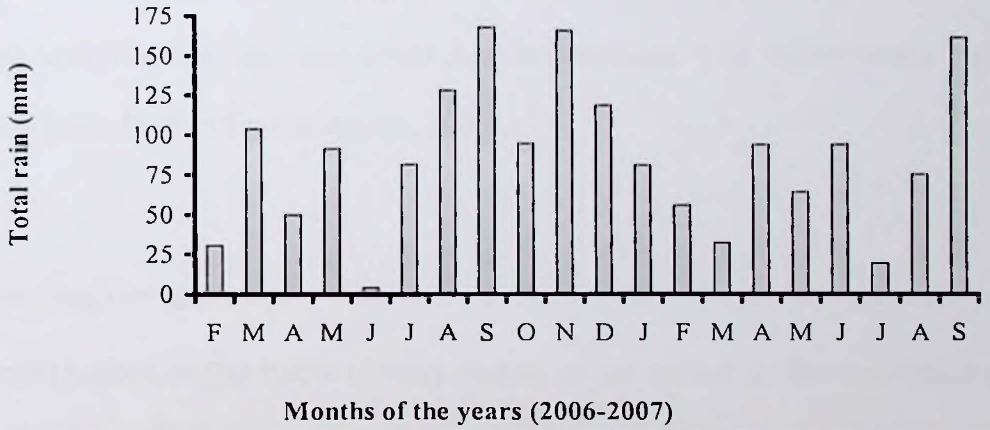

Fig. 1. Total monthly rainfall during monitoring of follower ratoon crops of banana at Butare, Ntungamo district. Data for the period February 2006 to September 2007

3.1.4. Soils and mineralogy

The soils are highly weathered sandy-loams with very low weatherable mineral reserves (Zake, 1993) and belong to the Karagwe-Ankole system (Anon, 1962). The soils in Butare have developed on metacalcareous rocks underlined by granite beds and are very old, that is, rocks date to Proterozoic period (Nyakaana and Katumwehe, 2005). The type of parent material and the long period that these soils have been exposed to weathering, makes such soils to contain low stocks of weatherable bases. The soils are therefore often slightly acidic in nature, have substantial amount of sand and silt, and hence have relatively low to moderate CECs and base saturation. Consequently, nutrient availability in such soils is highly dependent on soil organic matter management. Consequently, it is expected that 'man-made' soil fertility gradients strongly relate to crop performance.

3.1.5. Vegetation

The vegetation is of two broad classes namely Grassland Savannah and swamps. Savannas are of three major types, namely; grassland characterised by short grasses, dry Acacia associated with *Themeda* spp. and moist Acacia associated with *Hyparrhenia* spp. (Anon, 1962; Ntungamo District Profile Report, 2000).

3.1.6. Farming system

The western banana-coffee-cattle farming system is not typical of the traditional cropping systems (Akello, 2002) where originally coffee instead of bananas predominated. Semi-subsistent households primarily undertake banana production. Although locally consumed as staple food (Matooke – steamed banana paste) or beer (IFPR, 2004), increasing demand for bananas in urban areas (IITA Foodnet, 2002) means increasing commercial producers in rural areas. Mixed cropping is common with beans, finger millet, groundnuts and cassava at times associated with bananas (Osiru, 2006). Cattle are a major component of the farming system (Osiru, 2006) in areas where insignificant population pressure is being exerted on land. Poor farming practices (Akello, 2002) including widescale forest clearing, bush burning and over grazing have led to serious land degradation through more importantly soil erosion (Osiru, 2006) at macro-level.

3.2 Overall study approach

The approach used consisted of a combined diagnostic survey of 50 farms in the first phase out of which 10 farms were selected based on relative wealth status of household and physiographic location of the farm for an on-farm banana monitoring study in the second phase. A list of household heads was obtained with the help of key informants including district agricultural officials and local area leaders. The base line survey of the banana-based cropping system identified and described biophysical and socio-economic characteristics of the site. The characteristics included resource endowment, farm size, production activities, household characteristics, landscape features (slope position and description, erosion), off-farm and on-farm income. The information for characterisation and wealth classification as described by Crowley (1997) and Tittonell *et al.* (2005) was adopted.

3.2.1 On-farm verification of production constraints

Established plantations of surveyed farms consisted of plots (n = 66) and a plot was distinguished as a unit of at least 50 mats with similar management and similar biophysical characteristics like slope position. The area (m^2) of each plot was determined, farm size and total banana surface area per farm calculated.

Three bunches per plot (n = 198 bunches) from mature stands were weighed (precision 0.5 Kg) to estimate the actual yields in the farms. The girths (cm) at base and at 100 of seven arvested plants were measured for the purpose of relating growth/yields to biophysical characteristics of a plot.

Weevil and nematode damage at harvest and flowering (n = 7 plants $plot^{-1}$), respectively were assessed according to methods by Gold *et al.* (1994), Speijer and De Waela (1997), and Carlier *et al.* (2002). The severity of foliar diseases was scored using modified Stover (1971) scale and the method proposed by INIBAP (Jones, 1994). The position of youngest spotted leaf was used as an indicator for black Sigatoka severity (Rubaihayo *et al.*, 1994).

From each plot, soil (0-30 cm depth) and foliar samples (lamina 3) were collected on recently flowered plants for diagnoses of most deficient nutrients. The foliar nutrient concentrations were compared with DRIS norms for bananas (Wortmann *et al.*, 1994) to establish the most limiting nutrient (s). Deficiencies of Cu, Zn, B and Mo were detected using lamina 3 concentrations developed by Turner and Barkus, (1977) and Lahav *et al.* (1989).

Socioeconomic information (like family size, livestock, labour and other capital assets), among others, was obtained by using Participatory Rural Appraisal (PRA) techniques (Bhandari, 2003) particularly interviews on farms and observations.

3.2.2 Selection of banana mats for monitoring study

For each of the 10 farms selected for the monitoring study, 15 mats of the most common cultivar (*Enyeru*) were selected along a transect parallel to the slope from the homestead. These 15 plants also covered a range in plant performance. Of the 15 mats selected per farm, 5 mats were selected from each of the relative distances (RD) designated as ‘near’, ‘mid’ and ‘remote’. Each mat was assigned a number for its identity. A map was drawn showing the distribution of selected mats and distance of mats to homesteads. A kitchen, the major and commonest source of organic inputs within a household, was used to determine mat-to-homestead distance. The plant growth from sucker emergence to harvest was monitored on a monthly basis for one follower ratoon ('R1') after mat selection. Data were also collected on crop management and pest damage/disease severity over the monitoring period.

Mat surface area was calculated using the Thiessen-polygon approach. Thiessen polygons define the individual 'regions of influence' around each of a set of points such that any location within particular polygon is nearer to that polygon's point than to any other point, and therefore, has the same value (Heywood *et al.*, 1998). Measures taken are assumed to be more homogenous within (equidistant points of closest mats) to the mat of interest.

Practically, wooden pegs were placed in mid-distances between a mat of interest and the closest plants in the neighboring mats.

Mat surface was then calculated using Hero's formula; area equals the square of the average distance between the four nearest mats (Dildine, 1999).

3.3 Collection and analysis of soil and plant samples

To show and explain variability in nutrient status of soils within and across farms representing biophysical variability in the site (Appendix 1), 3 to 5 soil cores were taken from the 0-30 cm depth in the mat area for each of the 150 selected mats in the study for laboratory analysis at the start of the monitoring phase. The samples were air-dried, processed and analyzed for texture, pH (water), organic carbon (SOC), total nitrogen (N), available phosphorus (P), exchangeable potassium (K), calcium (Ca) and magnesium (Mg) following standard laboratory methods (Okalebo *et al.*, 2002).

All the selected mats were regularly monitored for flower bud emergence and the records kept by a farmers' coordinator resident in the study area.

Foliar samples (0.1 by 0.2 m strips) of inner lamina of leaf 3 (Martin-Prével *et al.*, 1979) were taken from the third fully expanded leaf within 14 days of flowering during the monitoring study for nutrient status assessment.

After solar-drying for one to two weeks, the samples were ground to pass through a 2 mm sieve and analyzed for K, N, P, Ca, Mg and Zn in the laboratory using standard methods. From the laboratory analytical outputs, Diagnosis and Recommendation Integrated Systems (DRIS) indices following Raghupathi *et al.* (2005) procedures were computed using norms and critical values developed for highland bananas (Wortmann *et al.*, 1994) to establish the most limiting nutrient (s).

3.4 Evaluation of farmer management of plantations

Farmers were responsible for all the cultural practices in their plantations, the selected mats inclusive. Mat level management rather than that for the farm level was monitored on a monthly basis using selected indicators detailed below to assess allocation of resources on farms (Schlecht *et al.*, 2006) and within farms (Tittonell *et al.*, 2005).

3.4.1 Animal manure and fertiliser application

Records (frequency, quantity, type, quality) on use of manures within the mat area were taken on monthly basis. Similarly, records by farmer on use of chemical fertilizers were collected in addition to observations made during monitoring.

.4.2 Detrashing or rouging

he number of dead or dried-up leaves hanging on the plant (index of detrashing) was ecorded monthly. Cumulative number of dead leaves at harvest was used to indicate the requency of removal of senescent leaves and sheaths over the growth period of the plant.

.4.3 Intercropping

he number and date of planting of major intercrops in the mats was recorded. For ntercropped mats, component crop density (number of plants m^{-2}) was computed on a nonthly basis. Intercropping bananas with beans, soy beans, finger millet and potatoes, among other crops, is a traditional practice in Butare valley. Some of these crops have been eported to affect differentially banana productivity particularly pest status (Holderness *et al.*, 1999).

3.4.4 Leaf pruning and defoliation

Leaf pruning is the removal of diseased leaves (including those with more green tissue) but some farmers also remove leaves perceived non-functional for alternative uses (Tushemereirwe, 1996). The number of functional leaves (>50% green) was recorded once a month during growth monitoring data-taking and also at flowering to assess the extent of farmers' practice of defoliation, a common practice among most banana farmers in Uganda (Tushemereirwe, 1996).

3.4.5 Mulching

The type (self mulch, crop residues, and hill and swamp grasses) and depths of mulch in the mat area was recorded. Thickness (cm) of mulch was measured at five randomly selected points perpendicular (three points) and parallel (two points) to the direction of mat growth. Cumulative mulch within the mat area at plant harvest was computed from the average monthly mulch depths applied (mulch per month = mean depth of five points).

3.4.6 Spacing and mat density

Spacing is normally reflected by mat area, the basis of computing the number of plants per hectare. The mat area was used to compute mat density (population ha^{-1}). Mats were of different sizes and average values were typical of spacing for each monitored farm.

3.4.7 Weeding

Weed control was entirely by hand-hoeing and hand picking in some mats. The type, height and proportion of mat area (%) covered by weeds was measured. Weeds were noted as either broad-leaved or grasses and heights were taken from exact points where mulch measurements were made. Weed infestation index (no units) was computed as a product of average weed coverage (cm^2) and average weed height (cm). Mat area (cm^2) covered by weeds was calculated as weed coverage (%) × mat area (cm^2).

3.5. Justification of choice of crop management evaluation at farm level

Bekunda and Woomer (1996) and Achan (2002) developed from surveys an inventory of management by farmers. The authors classified farmers into five different management categories (very poor, poor, medium, rich and very rich). Although Lufafa *et al.* (2003) used a parallel approach to attribute yield decline to management, grouping farms by crop management applies to a '*copy, cut*' scenario that is, similar types and levels of crop management are used from farmer to farmer. Considering the range of practices and heterogeneity of levels used among farmers in Butare, proxy management indicators aforementioned for instance mulching were used rather than compounding and branding plantations as 'well' managed.

3.6 Measurement of growth and yield variables

Plants were harvested when farmers perceived bunches as being mature indicative of colour of apical fingers. Yield at harvest, bunch weight, number of clusters and fingers were recorded. Finger to bunch ratio, above-ground biomass, and harvest index were computed. Plant height, leaf number, girths, level of 'high-mat' was measured at flowering as described below.

Height (cm) was measured using a graduated stick of 6 m (precision 5 cm) from the ground surface to the point where the top most pair of unfurled leaf forms a v-shape with last open leaf.

Girths were taken at base (0) and at 100 cm above the ground surface at the fully round part of the pseudostem using a plastic tape measure.

The level of 'high mat' was measured with a plastic tape measure (precision 1 cm). The number of fully opened leaves was counted and recorded. Leaves with broken petioles and those with more than 50% surface necrotic area were considered dead.

At harvest, the pseudostem was cut at the collar and all leaves present trimmed off at the point the lamina spreads out from the stalks. The bunch was cut off at the point of emergence from the pseudostem. The fresh bunch weight (kg) was determined by weighing on a Salter balance (precision 0.5 kg) and yields were expressed as $kg^{-1}ha^{-1}yr^{-1}$ to determine actual yields in the area. The number of hands and number of fingers on the bunch were counted after detaching the clusters. The bunch stalk was weighed and weight of fingers determined as the difference between bunch and peduncle weights.

The total fresh weights (TF) of the pseudostem and leaves were separately recorded in addition to the total fresh weights of the entire bunch for each bunch harvested at maturity. From each of the biomass fractions (pseudostem, leaves, and peduncles), a representative sample was taken immediately after harvest. For the pseudostem, the sample was taken by cutting a 2-3 cm disc from the distal, mid and proximal positions of the pseudostem from each of which a portion was removed to constitute the sample. A similar approach was followed in taking the peduncle samples. For the leaves, sub samples were taken from the close to the apex, mid-lamina and close to the petiole. One finger was sampled from the middle of each of 3 clusters (the second last, mid-bunch and top cluster). Each sampled finger was sliced longitudinally down the middle then one half discarded while the other was retained to constitute the finger sample.

Sub samples (150-200g) of all above-ground organs were solar dried to constant weight and moisture content (% MC) determined. The % MC was used to correct the TFs to dry matter (1-%MC × TF) yield of each component and total dry mass (TDM) of fruit and pseudostem determined. The TDM of peduncle and fingers was summed to give TDM of bunch.

The above-ground biomass was determined by adding the TDM of bunch, pseudostem and leaves. Harvest index was calculated as the ratio of bunch to above-ground TDM (Ssali *et al.*, 2003).

3.7 Pest and disease assessments

The major and most prevalent banana pests and diseases in the farmers' fields from the survey were assessed as described below.

3.7.1 Nematode damage

Nematode status was determined at flowering according to Speijer and De Waela (1997) and Carlier *et al.* (2002). Roots were excavated from a 20 cm x 20 cm x 20 cm hole dug at the base of recently (+14 days) flowered plants. Observations were made on number of functional and dead roots and root necrosis (Speijer *et al.*, 1998; Speijer and Ssango, 1999).

Nematode damage assessment consisted of selecting randomly five primary live roots, reducing their length to approximately 10 cm and splitting them longitudinally.

One-half of each of the five roots was scored for root cortex necrosis; each of the five root segments representing 20% i.e. (the necrosis in each root segment was estimated out of 20%, for 100% for the five root segments). The damage was expressed as percentage of dead roots and necrotic tissue.

3.7.2 Weevil damage

Weevil damage to the banana corm was assessed at harvest time using the cross-sectional method (Gold *et al.*, 1994; Speijer and Gold, 1996). Two cross-sections were made at the collar (pseudostem/corm junction) and at 10 cm below the collar. For each cross-section of the corm, the percentage of surface area consumed by weevil larvae (galleries) was estimated independently for the central cylinder and the outer corm. Total weevil damage per plant harvested was derived by averaging the damage scores for the upper and lower sections of the corm.

3.7.3 Foliar and fungal disease severity

The severity of leaf spots on the plants was assessed using the Stover (1971) scale [0: no disease, 1: < 5%, 2: 6 -15%, 3: 16 -33%, and 4: > 33% symptom severity]. Modifications were made using a scoring system 0-4 (not visible, mild, moderate and severe respectively). Banana streak virus severity was evaluated using Dahal *et al.* (1998b) method with the same modification to the Stover scale. The number of youngest spotted leaf was used as index for black Sigatoka severity (Rubaihayo *et al.*, 1994). Observations were on external symptoms like occurrence of lesions on plant for BSV and leaf spot diseases severity (Seem, 1984; Filajdi'c *et al.*, 1994) for disease expression. Considering periodicity of disease expression, severity was treated as a mean of monthly scores but the value was similar to a single score at flowering.

3.8 Data processing and analysis

The data were entered into Microsoft Excel Spreadsheet and preliminary analysis (descriptive and transformations) was performed. Data from survey and monitoring studies were analyzed separately but using the same statistical packages. Analyses were performed with SPSS Release 11 for Windows (SPSS Inc. 2001) and SAS version 9.1 (SAS® Institute Inc. 2003). Correlation and regression (Gomez and Gomez, 1984) of yields and all biophysical parameters was performed to establish the relationships among variables. Socioeconomic characteristics of farms from the survey were subjected to similar analysis and to ANOVA. Characteristics like resource endowment, production goals and constraints (Tittonell *et al.*, 2005) and income strategies (Reardon and Vosti 1995; Ellis, 2000) distinguishing wealth classes were used to develop a farm typology.

3.8.1 Quantification of the contribution of soil fertility factors, farmer management, banana pests and diseases to the yield gap in the farmers' field

Soil fertility, farmer management and disease and pest effects on yield are intricately interwoven. In order to partition them, the boundary analysis approach developed by Schnug *et al.* (1996) (BOLIDES) was used to obtain the line of best performance representing the maximum yields under various levels of soil nutrients, pest damage and management indicators. A boundary function is written as:

$$Y = Min\{f(X_1), f(X_2), \ldots f(X_N)\}$$

ere Y refers to yields of bananas determined by yield-influencing factor present in ative) minimum amount (von Liebig, 1863); and $f(X_i)$ is the maximum attainable yields n independent variables $i = 1,2,3,..N$.

principles and procedures (Webb, 1972; Lark, 1997; Schnug *et al.*, 1996) used to select fit boundary lines were:

Selecting significant ($P < \infty$) correlations with $r > ^{-(+)} 0.30$ between factors (pests and diseases, soil nutrients, management practices) and yields. Removing outliers, a critical step to BOLIDE fitting, even more so than in traditional regression analysis, was done

Grouping (was by relative distance) of data points according to their predictor values, i.e. sorting the independent in ascending or descending order for positive and negative correlations respectively

Creating boundary points using the BOLIDES algorithm, IF (logical_test, value_if_true, value_if_false). Comparing yield values within each group and with successive maximum values and those which did not fit observed trend were discarded

Identification of the ''maximum-yield subset''; the data subset representing maximum yields at each predictor value

Fitting of a curve to the maximum-yield subset (boundary points) was by hand for only straight-line regression (Casanova *et al.*, 1999) and quadratic polynomials (Schnug *et al.* 1995, 1996). For non-linear functions, logistic/sigmoid-type models like Richards generalized functions;

$Y_t = a\left(1 + b\left(\exp\left(-Kt\right)\right)^m\right)$ (IITA, 2002) were used to obtain reasonably good fits by least uare procedures.

ne minimum yield predicted by any of the individual, single-response boundary lines (e.g. unch weight-pH function) at each relative distance was taken to be the yield prediction at t location. Henceforth, the constraint to yields was identified and its occurrence within-d among farms counted. Yield limitation of each factor was expressed as a percentage of yield limitations. The modal performance in predicting yields was tested and a graph of ual versus potential yields at each RD plotted.

3.2. Determination of within-farm variability in banana yield and constraints among rmers belonging to the different wealth classes

ta of all yield variables were analyzed as randomized complete block design. Analysis of riance was performed with RD as sub-plot treatment, farmer resource endowment as main pt and individual farm as a replicate or block using SAS version 9.1. Fisher's *t*-test (LSD) as used for separation of means.

e model $Y_{ij} = \mu + T_i + \beta_j + E_{ij}$ considered yields as a function of relative distance to mesteads, farmer wealth class and their interaction, where:

= observation for each of the farms

= overall mean

= effects due to relative distance, i = close, mid, and remote

= effects due to wealth class, j = poor, medium and rich

$_j$ = variation within relative distances and wealth classes (i.e., error term).

e null hypotheses (H_o: $\sigma_1 = \sigma_2 = \sigma_3$), 'equal variability of yield(s) within farms from the ree wealth classes exists' was tested using the Levene's test of homogeneity of variance evene, 1960) in One-way (in randomized blocks) ANOVA. Yield and growth parameters hich varied significantly (Levene's test, $P < \infty$) between wealth classes were noted; and means of groups (wealth class) were compared using t test to confirm which variances differed significantly between wealth classes.

The most frequently yield-limiting factors (constraints) with RD from homestead and among farms of different resource endowment was determined from BOLIDES.

CHAPTER FOUR

0 RESULTS

1 Diagnostic survey (study approach one)

1.1 Household characteristics

he characteristics of the 50 surveyed households from two villages in Butare parish, in ;yakyera sub-county of Ntungamo district are shown in Tables 1a and 1b. Three farm types, oor, medium, and rich were identified based on the local criteria that were obtained during ıe PRA. The household wealth features and production levels differed between these three lasses. Mean (0.43 ±0.27 ha) arable land differed significantly ($p < 0.05$) between ousehold wealth classes. The majority (70%) owned more than 0.43 ha. The rich compared) the medium and the poor types, farmed more land (mean = 0.61 ha vs. 0.52 ha and 0.37 a) and owned more livestock units (9.95 vs. 6.97 and 5.57 units).

ll farmers cropped bananas on 70% of their arable land for consumption and selling <50%) of the bunch harvests. All the rich farmers were engaged in selling bananas, while ome 75% of the medium and 47% of the poor farmers sold part of their produce (Table 1a). Iouseholds mostly (above 82% farmers in each class) supplemented the income from anana fruit sales with off-farm earnings.

Ionetheless, sources of income varied between the wealth classes and the fraction of armers earning from a source differed significantly ($p < 0.05$). For instance, the wealthy ouseholds generated most of their income from bunch sales and a sizeable proportion 40%) received a salary compared to less than 4% and none of the medium and poor useholds, respectively. In addition, the rich received support from their families living sewhere. Although, land rental were not a popular source of revenue (<10% rented out nd), its frequency among the rich households was roughly two and five times more than nong the medium and poor households, respectively. The medium households who were e majority, were significantly ($p < 0.05$) more engaged in trading merchandise than the or and rich. Besides, half of the medium level farmers worked on wealthier farms and few pended on selling charcoal. Poor farm types had charcoal selling as the main income urce in addition to selling labour on wealthy farms, apart from their own. Although usehold production objectives did not vary much, yields were higher on wealthy than orer farms. The mean weight of three bunches from plantations of rich households was 5 and 4.3 kg greater than for bunches from plantations belonging to medium and poor useholds, respectively (Table 1b).

ble 1a: Household characteristics of banana farmers in Nyakyera sub-county (50 useholds surveyed)

aracteristic	Farm types		
	Poor	Medium	Rich
	n = 28	n = 17	n = 5
rm description			
rm size (ha)*	0.37±0.04	0.52±0.05	0.61±0.07
nana surface(ha) *	0.24±0.03	0.37±0.04	0.43±0.09
). banana plots*	1.5±0.11	1.4±0.08	2.0±0.30
). of children	6	6	8
vestock units*	5.57±1.8	6.97±1.6	9.95±3.4
come strategies			
f-farm revenues / income)	82	89	100
rcent that sell bunches	47	75	100
rm salary (%)	0	3.6	40.0
ll labor (%)	29	54	40
ll charcoal (%)*	45.45	19.4	12.5
ade in merchandise (%)*	13.6^{a}	38.9^{ab}	12.5^{ab}
ented land (%)	4.5	13.9	25.0
mily support (%)*	18.2^{a}	52.8^{b}	87.5^{b}

ignificant at $P < 0.05$, values followed by same letters are not significantly different
%, 50% and 60% poor, medium and rich farmers, respectively owned cattle (mean = 3, 4 d 5) respectively. Average livestock units for each livestock category was computed as; proved cow = 1, local cow = 0.8, goat = 0.2, sheep = 0.1, pig = 0.4, and chicken = 0.01.

ple 1b: Banana yields from established plantations, soil status and management ource use (Mean ± SDEV) in June 2006 in farms belonging to different wealth sses

aracteristic	Farm types*		
	Poor	Medium	Rich
centage of farmers ceiving yield increase	6.0	7.0	60.0
ıch weight (kg)	15.6±1.1	15.0±0.78	19.9±2.87
bunches harvested/month†	36	41	41
th at base of harvested nt (cm)	61.3±1.8	61.5±1.4	64.0±4.0
ganic C (%)	1.32±0.11	2.25±0.92	3.89±2.4
al Soil N (%)	0.14±0.01	0.18±0.03	0.27±0.12
eevil corm damage (%)	3.3±0.5[a]	5.4±0.4[ab]	4.7±0.7[ab]
nge of weevil damage (%)	2.1- 4.5	4.5 - 6.3	2.3 – 5.9
matode root necrosis (%)	4.3±0.5	4.6±0.4	4.4±0.8
it spacing (m)	2.2±0.11	2.3±0.54	2.4±0.07
cent that hired labor *	23.5	42.9	100
nily labor	2.14±0.23	3.44±0.36	1.88±0.35

gnificant at $P < 0.05$, values followed by same letters are not significantly different
riteria used: house quality = *f (mud/bricks, thatched/iron sheets, cement/earth floor, int/no paint, door and window type).* † based on farmers' estimate

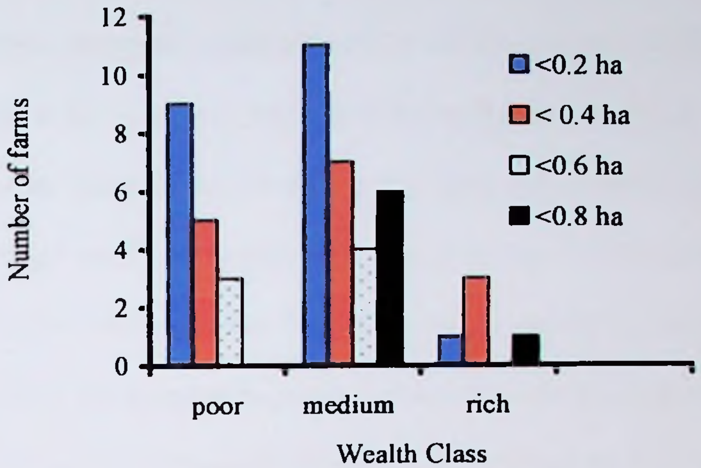

Fig. 2. Banana plantation sizes within and between wealth classes

4.1.1 The primary causes of declining banana yields as described by farmers (50 households interviewed)

Farmers have different perceptions on banana yield trends over the years. Sixty percent of the farmers state that yields are declining while 28.6% said that the yields are stable. However, some 12.2% said there is an increasing trend in yields, largely the rich farmers (Table 1 b), but gave no reasons. Farmers were simply asked to compare what they have experienced since plantations establishment. Comparison was not by quantifying the amount of yields but farmers reported from their production experience for at least the past three years. Farmers' estimate of monthly number of bunches harvested was used to show possible differences in annual yields. On average, farmers estimated that they harvested some 36 bunches per month. The average fresh weight of three randomly picked bunches (n = 198 bunches) on a 0.33 ha banana plot[1] was 15.7±4.7 kg, ranging from 5 to 60 kg.

[1] Plot was distinguished as units with similar management and similar biophysical characteristics (position on slope) with a minimum of 50 mats

-oduction was constrained by a number of factors and the causes of declining yields stated farmers were logically categorised into major problems (Table 2). Pests and diseases ere considered the most important constraint with a weighted score of 294 on a 1-5 ranking ale. The banana weevil (*C. sordidus*) was identified as the major pest in all farms. Ninety percent of the farms were aware of this insect pest and related this to pseudostem apping. Weevil damage on recently harvested plants (mean = 4.7% corm necrosis) was ghly variable (3.3-51.4%) across farms. Only 20% of the farmers knew about nematodes though they mentioned nematode-associated losses. Nematode-related damage of root ortality (%) on seven recently flowered plants per plot averaged 16.8 ±1. Root necrosis eraged 4.48% but varied from 0.86-11.71%. Toppling was observed in 23.5% of the rveyed banana plots.

he proportion (%) of farm plots with major diseases was: Banana streak virus (74.5%), isarium wilt (60.4%), black Sigatoka (74.5%) and matooke wilt (50%). Except for BSV d Fusarium wilt that were severe (score ***) in 15.2% and 26.2% of the plots sampled, gatoka (*Mycosphaerella fijiensis*) and matooke wilt severity was of minor importance. armers perceived soil fertility status as a secondary factor in decline of banana yields and osion was observed as the most important soil problem (Table 2). Farmers used digenous indicators (not presented) for instance, weed types, stoniness, leaf color, crop gour and yields to rate soil fertility. Deteriorating management associated with lack of ganic inputs (mainly mulch and manure) and less attention paid to plantation management ere mentioned among other constraints to banana production as well as bad weather specially hailstorms, winds and drought) and economic limitations of funds or capital.

ble 2: Banana production constrains as identified by 50 farmers in the sub-locations

Ntungamo district

nstraint	% farmers who ranked the constraint					Weighted score*
	rank1	rank2	rank3	rank4	rank5	
sts and diseases	50.0	52.0	30.6	15.6	7.7	294
or soils	24.0	26.0	51.0	64.1	87.2	276
teriorating management	16.0	14.0	14.3	11.1	0	100
onomic constrains	4.0	8.0	2.0	6.7	2.6	40
d weather	6.0	0	2.0	2.2	2.6	21

alculated as follows:

$$= \sum_{i=1}^{5} f_i x_i$$

–score attributed by farmers (from 1-most important to 5-least important)

- number of farmers attributing a given score or rank

urce :(adopted from Bagamba *et al.*, 2003 *Baseline survey, Lwengo and Nyabubare bcounties 2001)*

.3 General soil and foliar nutrient status of bananas in Mujwa and Mugwanjura llages

e slope position categorized as 'upper' (summit, upper), 'middle' and 'lower' (lower and lley bottom) of a farm had no significant ($p > 0.05$) effect on soil status of farms selected the diagnostic survey. Only small differences in all soil fertility indicators between the pe positions were noted, with farms on 'middle' slope having slightly higher C and N lues than those in the upper and lower slope positions, respectively (results not presented).

e major physical and chemical characteristics of the soils from the 66 plots sampled in the o villages and ratings of soils are presented in Table 3a. Soil pH varied from 5.5 to 6.2

n a median pH of 5.8 and organic matter (SOM) content ranged from 1.4 to 6.2%, dian = 2.14%. The total N content varied from 0.08% to 1.11% with a median of 0.15%; ractable P (mean = 32.0 mg kg^{-1}) highly varied between plots and exchangeable K raged 0.87 cmol(+)kg^{-1}.

l tests that were significantly correlated with soil C were total N, exchangeable Mg ($p <$ 1, $r = 0.972$, $r = 0.939$) and exchangeable Ca ($p < 0.05$, $r = 0.288$), respectively.

ble 3 a: Soil chemical data (0-30 cm) of surveyed farms (= 66 banana plots sampled) two sub-locations in south western Uganda

perty	Mean	Range	Classification†
	5.8	5.5-6.2	Slightly acidic
l Organic matter (%)	2.50	1.37-6.19	Moderate
ch. Ca (Cmol$_c$ kg^{-1})	4.61	2.8-7.4	Low
ch. Mg (Cmol$_c$ kg^{-1})	0.71	0.1-4.3	High
ch. K (Cmol$_c$ kg^{-1})	0.86	0.2-2.5	Moderate
ail. P (mg kg^{-1})	32.0	0.7-123.5	Medium*
tal N (%)	0.17	0.08-1.11	Moderate

ings for tropical soils as cited by Okalebo *et al.* (2002) do not apply to K in banana soils, **Source:* Lahav Turner (1983)

e incidences of foliar nutrient deficiencies by DRIS norms (Angeles *et al.*, 1993) and the itical Value (CV) ranges (Lahav and Turner, 1993 cited in Angeles *et al.*, 1993) are given Table 4 b. Phosphorus concentrations in 3rd lamina were generally within the CV range in banana stands. Equally, K concentrations fell within the critical value range in all plots : foliar Mg was below the range in only 8 plots. Banana stands were deficient in S (62 ıts), Cu (65 plots) while Zn deficiency was apparent in all banana plots. Using, critical rient level interpretations by Lahav and Turner (1983) and Lahav *et al.* (1981), Mn, Ca l Fe were found to be adequate for banana production in most plots. Ca excess was not dent with K or Mg to Ca ratio falling within the CV range (results not shown).

ıble 3 b. The incidence of DRIS deficiencies in existing banana ratoons at two sub-

;ations (N = 66 plots) in Ntungamo

	P	K	Mg	Ca	†S	Cu	Zn	Fe	Mn
	---------------%-------------------------------				-------mgkg^{-1}------------------				
ean value	0.18	2.83	0.32	0.78	0.21	6.47	10.87	142.0	756.9
ꝚIS									
ırm* (%)	0.23	3.04‡	0.41	0.8	NA	NA	NA	NA	NA
/ range	0.12- 0.41	1.66- 5.40	0.25- 0.46	0.25- 2.10	0.23	9.0	18.0	8.0	25.0
ɔts:									
low CV ıge	0	0	8	0	62	65	66	0	0
ꝚIS ficiency	64	66	54	34					

ı not available; *Angeles *et al.* (1993) for P, Mg, Ca; ‡Source for K (Wortmann *et al.*, 1994), †Lower limits S and micronutrients (Lahav and Turner, 1983)
/ (critical value) range from 24 published sources cited in Angeles *et al.* (1993);
some plots, leaf contents were above the CV for some elements

4. Relationships between plant performance and biophysical factors

ch weight and plant growth parameters (girth at base and at 100 m) at harvest, plant ients concentrations at plot level, varied considerably between farms but all the plant formance indicators were not significantly ($p > 0.05$) related to biophysical factors in the s. Among biophysical parameters (soil fertility, nematode damage at flowering, leaf spot ases, weeding intensity and mat spacing), only weevil corm damage bore a relationship n pseudostem girth. Scatter plots (not shown) revealed that girths at harvest (Y) of most ivars tended to decrease with increasing levels of mean corm necrosis (X) from ividual plants in a plot. Girths of plants at harvest for cultivar Enyeru decreased as:

$$= -0.2963X + 72.193\,.$$

On-farm monitoring (study approach two)

1 Soil fertility status within farms selected for the monitoring study

ls were mostly sandy clay loams and sandy loams (19.3% samples). The results of soil lysis of banana mats in three relative distances (also called 'plots'); close, mid-distant remote from the homesteads are presented in Table 4. Banana mats near the homestead significantly ($P = 0.03$) higher soil exchangeable K than distant mats. Soil pH was lower organic matter (%) was higher in close than in mid-distant and in remote plots but the erences were not statistically significant ($p > 0.05$). Similarly, soil N, available P and hangeable bases were higher in banana mats closer than far away from the homestead. rrelation analysis indicated that available P decreased significantly ($p < 0.05$, $r = -0.288$) h the distance from the homestead and so was exchangeable K ($p < 0.01$, $r = -0.456$).

ɔth soil P and K exhibited high variability within short distances (Figure 3 and Table 4) of -e homesteads.

able 4. Soil chemical and physical properties (0-30cm) within farms (N=120 samples)

oil property	ᶠRelative distance from of plot from the kitchen: Close (20.9±9.2 m)	Mid-distant (37.2±12.4 m)	Remote (54.7±14.9 m)	Mean±SDEV (37.63±18.50 m)	Ratings
oil organic ıatter (%)	2.97±0.66	2.68±0.65	2.97±0.69	2.87±0.67	Moderate
'otal N (%)	0.12±0.04	0.12±0.04	0.10±0.00	0.11±0.03	Low
H	5.4±1.4	5.6±1.5	5.7±1.4	5.6±1.4	Slightly acidic
vail. P (mg g^{-1})	32.77±15.92	26.10±22.26	25.99±13.96	28.29±17.65	Medium
xch. K mol.(+)kg^{-1}	1.10±0.43	0.75±0.28	0.71±0.23	0.85±0.36	Very high
xch. Ca mol.(+)kg^{-1}	2.08±1.13	1.91±1.17	1.98±1.07	1.99±1.10	Very low
xch. Mg mol.(+)kg^{-1}	1.42±0.93	1.32±0.97	1.37±0.96	1.37±0.94	High
lay+Silt (%)	34.6±7.0	34.7±4.7	33.7±2.8	34.3±5.0	SCL

I in 1:2.5 soil: water suspension; C by acid-dichromate digestion; Ca and Mg by Mehlich 3 extraction ixture; K and P by bicarbonate-EDTA; SDEV (plot) indicates amount of variability within a relative distance om homestead; SCL stands for sandy clay loam; †Kitchen was considered for determining average distance om homestead 'he above soil properties differed significantly ($p < 0.001$) across farms but differences vere not significant (Dunnett's t-test, $p > 0.001$) within most farms except a few (Figure 3).)ifferential fertility gradients between farms was neither clearly explained by age nor by ize of the farms. With respect to age, only soil exchangeable K increased in the order of ırm age (higher in older than recently established farms accordingly). Within farms, the radients in all soil parameters were negative though not significant ($p > 0.05$) with ncreasing distance from homesteads, except in two farms (whose gradients are not shown in ig 3). These farms had residential houses relocated or shifted (in last 10 years as pproximated by the owners) leading to superimposed soil fertility gradients. It was hence ifficult to explain observed gradients using distances from the present and previous omesteads. However, soil organic matter decreased systematically away from the previous esidential house (in one farm) and available P was generally higher in locations near than istant from the previous old houses (in both farms). Generally, no gradient was apparent for ny measured soil property on the two farms, even with soil available P which was highly ariable (65.0-458 mg kg^{-1}, mean = 252.2 mg kg^{-1}).

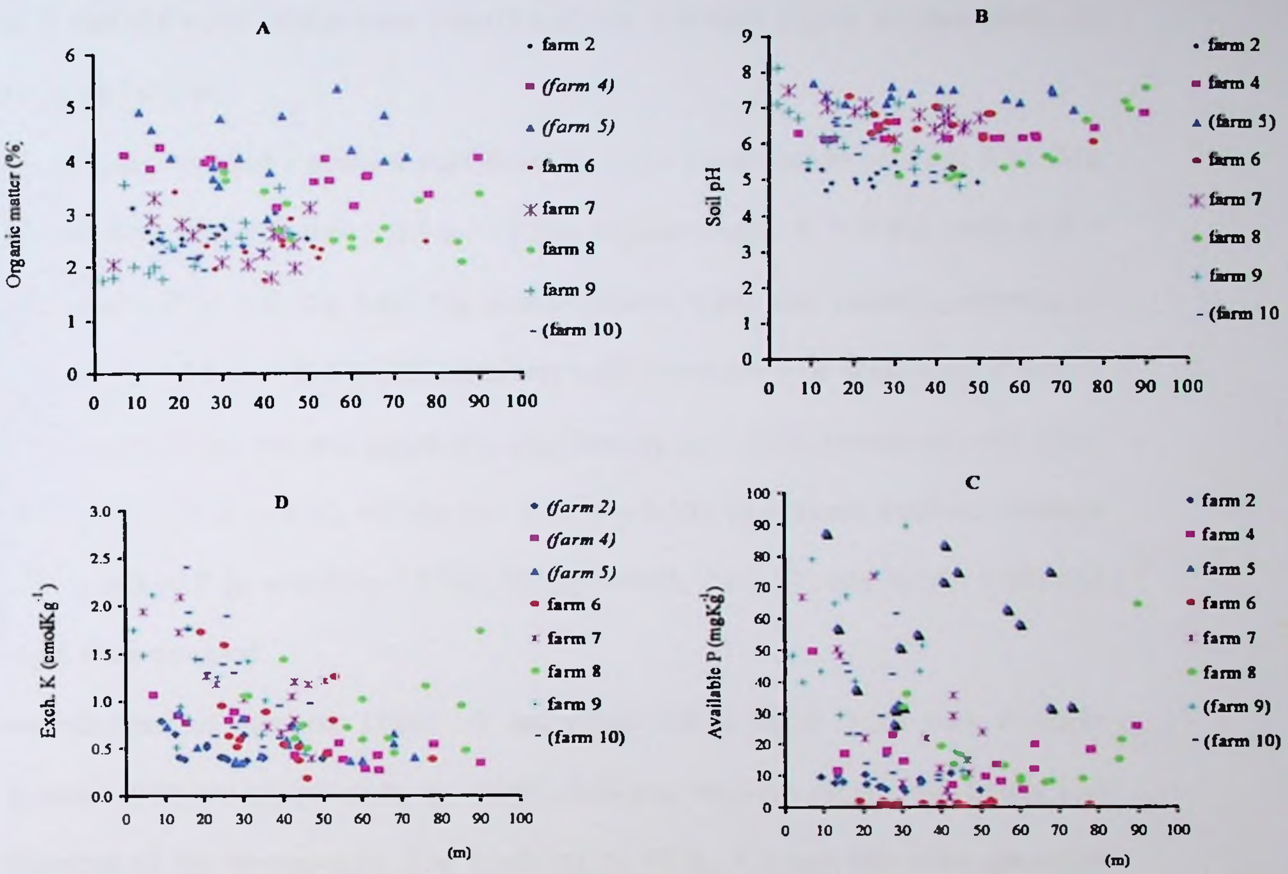

Fig. 3: Soil fertility gradients within farms (n = 120 composite samples). Relationships between selected soil properties, soil organic matter (A), pH (B), available P (C) and exchangeable K (D) with distance (metres) from the kitchen. Parenthesis () indicates significantly ($p < 0.001$, Dunnett's t-test) different farms for each property. Farms in italics are not significantly ($p > 0.001$) different by the same t-test of group comparison.

4.2.2 Foliar nutrient status within farms and relationship with biophysical factors

The levels (%) of leaf P: 0.06 - 0.21, K: 2.01 – 4.59, Ca: 0.14 -1.11, and Mg: 0.19 -0.61 and most nutrient ratios, apart from K/N, K/P, Ca/K and Ca/P highly significantly ($p < 0.001$) varied across farms. Although levels of N, ranging 1.49 to 3.22% (mean = 2.49%) differed nificantly ($p = 0.008$) across farms; levels of foliar N and also K were not significantly (p .05) influenced by slope position of the farms (results not presented). Nonetheless, mean els of leaf nutrients were not statistically different between farms on the three slopes cept for P and Ca only, which were significantly ($p < 0.001$) higher in plantations on per than on mid slopes.

rrelation analysis revealed a positive significant ($p < 0.01$) association between foliar Mg th soil parameters, Mg ($r = 0.61$), pH ($r = 0.58$), organic matter ($r = 0.40$), total N ($r =$ 32) and available P ($r = 0.33$). Leaf Mg concentrations were also related positively to ulch thickness ($p < 0.01$, $r = 0.26$) and negatively with nematode root necrosis ($p < 0.05$, r -0.24). As expected, soil pH was positively significantly ($p < 0.01$) correlated with foliar vels of P ($r = 0.45$), K ($r = 0.35$) and Ca ($p < 0.05$, $r = 0.19$). Significant positive relations etween leaf levels of P ($p < 0.05$, $r = 0.36$), Mg ($p < 0.01$, $r = 0.37$) and K ($r = 0.23$) and inch weight were detected.

lean concentrations of nutrients (Table 5) and ratios within eight farms with a single rtility gradient were not significantly ($p > 0.05$) different between close, mid-distant and mote distances of the homesteads. The levels of N, P, K, Ca and Mg were generally milar in the three relative distances. DRIS analysis revealed a positive index of foliar K of magnitude far above zero in all the distance classes (Table 5). Nitrogen deficiencies and ation imbalance (with low Ca in particular) increased when moving away from the omestead.The converse was observed with respect to foliar P deficiencies which decreased om close to remote areas from the homesteads.

_ble 5. The foliar nutrient levels (mean±SDEV) compared with DRIS norms in

oking bananas and DRIS indices in cultivar Enyeru at Butare farms

D from e kitchen	Nutrient expression (%) and DRIS indices				
	N	P	K	Ca	Mg
ose	2.51±0.35	0.15±0.03	3.48±0.61	0.66±0.14	0.35±0.09
	2.02	*-11.65*	*18.48*	*-7.47*	*-1.38*
1id-stant	2.44±0.26	0.14±0.02	3.46±0.53	0.67±0.18	0.35±0.09
	-2.78	*-8.84*	*20.29*	*-7.78*	*-0.90*
emote	2.49±0.20	0.15±0.02	3.44±0.54	0.65±0.21	0.36±0.09
	-0.92	*-9.98*	*17.33*	*-9.01*	*2.58*
lean	2.48±0.27	0.15±0.02	3.46±0.55	0.66±0.18	0.36±0.09
RIS rm†	3.15	0.25	3.04	1.13	0.48

ource: DRIS norms in bananas grown in highlands of East Africa (Wortmann *et al.*, 94). DRIS indices are in italics and the magnitudes (irrespective of sign) indicate the trient status compared to the optimum

:.3 Yields of banana (cv. *Enyeru*) in the monitored farms at Butare

e yield characteristics of banana-growing farmers at the study site are presented in Table Mean yields were 13.52±4.17 kg bunch^{-1} and ranged from 4 – 37.0 Kg of fresh bunch ight. Yield variables at harvest, particularly the above-ground biomass, numbers of gers and clusters per bunch were significantly positively ($p < 0.01$, $r > 0.7$) related to nch weight. Bunch weight was significantly ($p < 0.01$) correlated with measured growth rameters with plant height ($r = 0.70$), girth at base ($r = 0.82$), girth at 1m ($r = 0.74$), and mber of functional leaves ($r = 0.47$) at flowering. Similarly, biomass yield was nificantly positively ($p < 0.01$, $r > 0.6$) correlated with plant height, girth at base and at n, and number of functional leaves ($r = 0.39$) at flowering. Maturation days (mean = 135 ys) differed significantly ($p = 0.04$) between farms. The period from flowering to harvest, s significantly ($p = 0.025$) longer on farms located in the upper slope- (140 days), mid- pe positions (135 days) than in the lower slope positions (132 days).

ble 6. Banana yield parameters at Butare valley in Ntungamo district

eld component	Minimum	Maximum	*Mean±SDEV
sh bunch weight (kg)	6.6	37.0	13.5±4.2
mber of clusters	6	10	7±1
mber of fingers	60	161	106±24
ger to bunch ratio	0.60	0.90	0.88±0.04
ove-ground biomass DM (kg)	4.1	17.5	8.28±2.84
rvest Index*	0.25	0.82	0.40±0.08

an values computed from 90.7% (n = 272) plants that reached maturity at time of data compilation.
lculated as TDM of bunch/ total above ground dry matter

.4 Banana growth and yields within farms

thin farms, plant performance in terms of growth and yields was generally higher in ser than in mid and in remote plots, according to relative distance of the homesteads. nt height, girth at base and at 1m of flowered plants differed significantly ($p < 0.05$) ween close, mid-distance and remote plots of the homestead. Close areas of the mesteads had significantly ($p < 0.05$) higher banana growth in terms of taller, thicker and ore vigorous plants than mid-distance and remote locations.

owever, differences between mid-distance and remote plots to homesteads were not atistically significant ($p < 0.05$). Bunch characteristics were also better in close than in the her two areas of the farms (Table 7). Bunch fresh weight was 0.6 and 2.2 kg higher in oser than in mid-distance and remote areas respectively.

cept for the number of fingers, all other yield components, like biomass, did not differ gnificantly ($p > 0.05$) between the relative distances of the homesteads. The number of ngers was significantly ($p = 0.025$) higher from bunches in closer than remote plots (Table . Finger filling was slightly greater in stands from distant than close locations of the omestead.

Table 7. Means (± SDEV) of banana yields in three distance classes within farms

Yield component	Relative distance from homestead		
	Close	Mid-distance	Remote
Bunch weight (kg)	14.37±4.64	13.88±3.62	12.26±4.07
Number of fingers*	114±25[a]	108±23[ab]	94±19[b]
Finger to bunch ratio	0.89±0.02	0.86±0.07	0.89±0.02
ABG biomass (kg)	8.50±2.41	8.70±3.20	7.63±2.92
Harvest Index (Bunch/ABG)	0.39±0.05	0.40±0.13	0.40±0.04
Mat area (m^2)	4.1±1.0	3.7±0.7	3.9±0.9

SDEV (distance class) is the standard deviation used to show variability of yield in the same relative distance, *statistically different at 5%; values followed by same letters in a row are not significantly different. ABG stands for above-ground biomass computed on dry weight basis

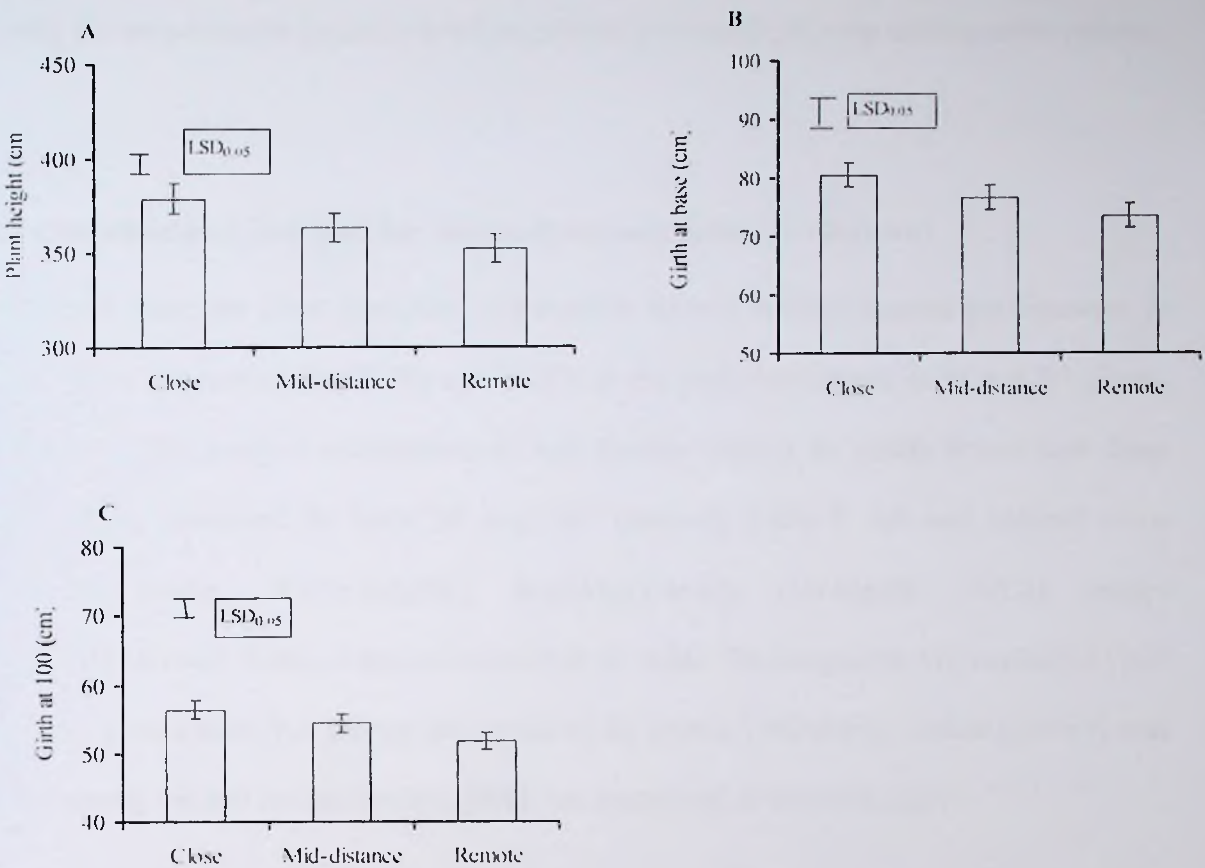

Fig.4. Banana (M and R1) growth at flowering within farms with a single productivity gradient: differences in plant height (A), pseudostem circumference at 100cm (B) and at base (C) between plots in three relative distances of the homestead. Vertical bars indicate mean (n = 5) ± s.e

The follower ratoons, designated as *R1* of existing stands (*M* plants) were monitored from sucker emergence to harvest for growth and yields quantification. The major biophysical factors affecting banana yield(s) were established and the most yield-limiting soil factors, pests and management factors determined. However, most M plants were monitored for about 1-2 months prior to flowering hence little data was collected on crop management of the existing stands. Therefore, to understand the contribution to yields of all the different actors across farms and compare constraints among wealth classes of farms; results from or only R1 are presented in sections below primarily to highlight crop management aspects.

.2.1 Contribution of soil fertility factors to banana yields (cv. *Enyeru*)

oil factors were the most important biophysical factors driving banana performance in Butare valley accounting for 70.0% and 60.0% of the yield limitations in M and R1 plants, espectively. The relative contribution of soil fertility factors to yields determined from 3OLIDES are presented for both '*M*' and '*R1*' plants in Table 8. All soil nutrient ratios C:N, K/(Ca+Mg), K/(Ca+Mg+K), Mg/(Mg+Ca+K), Ca+Mg+K, K/Ca) except Ca/(Ca+Mg+K) and K/Mg, were not correlated to yields. Exchangeable Mg explained yield ariability across farms but did not limit yield of R1 plants. Unlike Mg, exchangeable K was either among the soil factors limiting yield, nor correlated to bunch weight.

Nevertheless, soil K/Mg was the most critical yield-limiting soil factor. Soil pH was the econd most critical factor to K/Mg among soil factors that limited banana yield. Although oil carbon and total N were significantly ($p < 0.01$) correlated ($r = 0.42$) to bunch weight, anana yields were neither determined by the percentage of SOM nor by the concentration f nitrogen in soils.

Table 8. Soil fertility (0-30 cm) properties determining banana (M and R1 plants) yields and their relationship with bunch weight (R1) in Butare

Soil attribute	Yield limitation (% plots constrained by factor)		Soil parameter correlated ($p < 0.01$) to bunch weight
	M	R1	
pH	20.0	16.7	0.423
Exch.Ca	10.0	10.0	0.597
Exch. Mg	6.7	0	0.511
K/Mg ratio	20.0	20.0	-0.409
Ca/(Ca+Mg+K)	3.3	3.3	0.599
Clay	10.0	10.0	-0.415
Total	**70.0**	**60.0**	

4.2.1.1 Influence of soil pH on banana yields

Bunch weights tended to increase with increasing pH values in the range 5.1 to 6.2 (Fig. 5). The mean bunch weights for four quartiles of pH ranging from 5.0 to 7.4 shows an increase in yields for every five-fold increase in soil pH (Table 8). However, below pH 5.3, weights of bunches were less than the mean weight (13.5 kg) with the smallest bunch (10.2 kg) recorded at pH value 5.0. At high pH values, there was no effect of decreasing acidity on bunch weight, which remained constant at 20.3 kg from pH 6.2 to 6.8, although 20.4 kg occurred at pH value of 7.2.

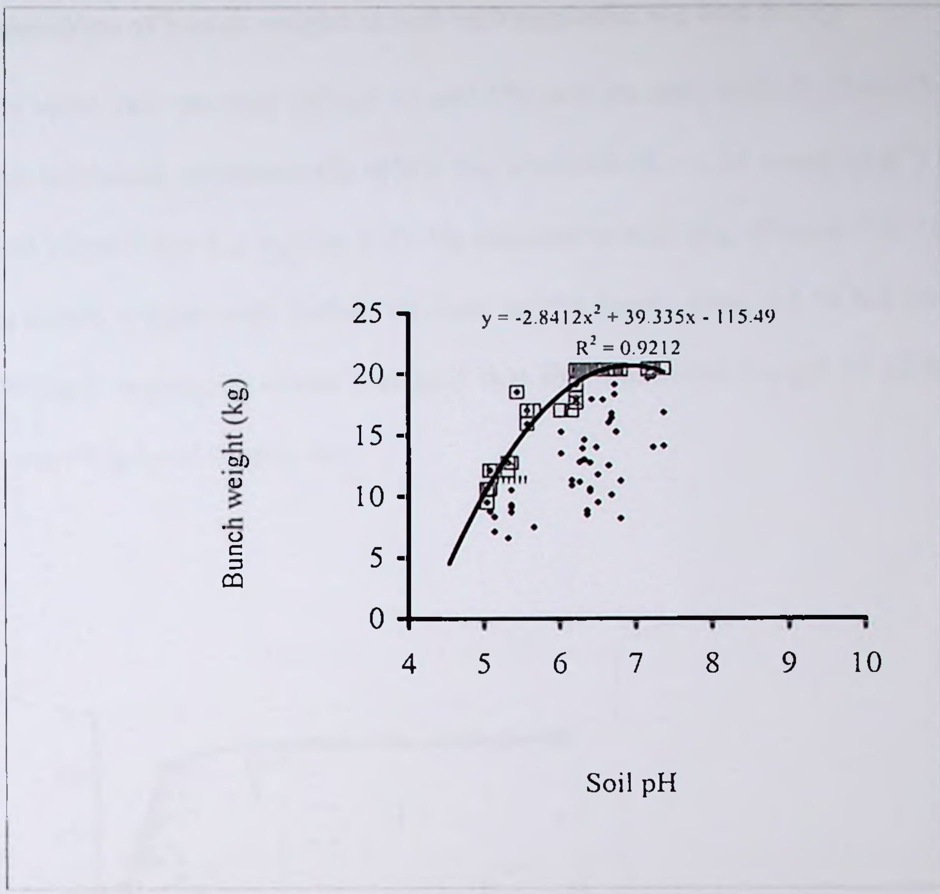

Fig.5. Effect of soil pH on bunch weight

Table 9. Predicted maximum bunch weights (Mean ± SDEV) obtained in the pH range (5.0-7.4) from relative distances† (N = 30) as derived from BOLIDES

Soil pH range	Mean pH	Bunch fresh weight (Kg)
5.0 - 5.6	5.3	13.2±5.9
5.6 - 6.3	6.0	18.0±1.1
6.3 - 6.9	6.6	20.4±1.3
6.9 - 7.4	7.2	20.5±1.4

† Yield predictions were made at relative distance level

2.1.2 Relationships of bunch weight to soil exchangeable Mg and K/Mg

anana yields were also strongly related to soil Mg and its ratio with K (Table 8 above). unch weights increased, exponentially at low Mg levels (0.36 – 1.04 cmol(+)kg^{-1}) from 9.4 20.1 kg, and slightly (by 1.1 kg) for a 21.1% increase in soil Mg. (Figure 5a). There was o change in bunch weight with further increase in Mg levels from 2.3 to 6.8 cmol(+)kg^{-} The fitted logistic regression curve indicated that the maximum weight of 22.6 kg was ttained at former Mg level (Figure 6a)

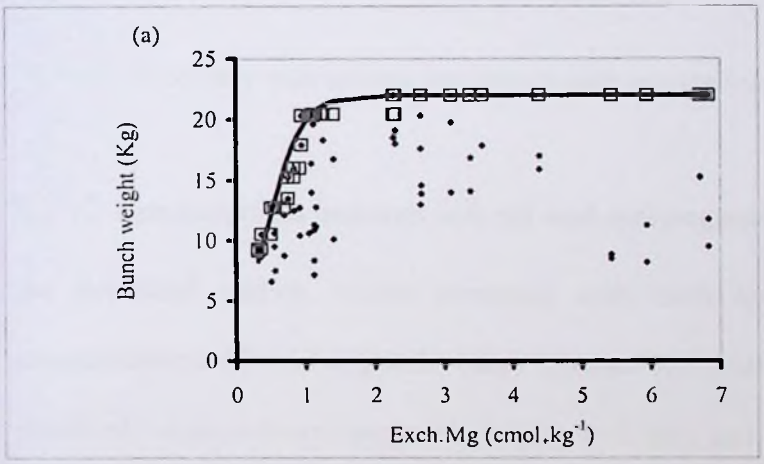

Figure Fig.6a. Fitted logistic regression curve on boundary points of bunch weight on soil exchangeable Mg

(Figure 6b) shows a drastic decrease in bunch weights with increasing K/Mg ratio. The maximum bunch weight (22.0 kg) occurred at 0.15 but higher yields could be achieved at lower K/Mg ratio. Indeed, by extrapolation, a yield increase of 1.0 kg would be equivalent to a decrease in K/Mg ratio from 0.15 to 0.125.

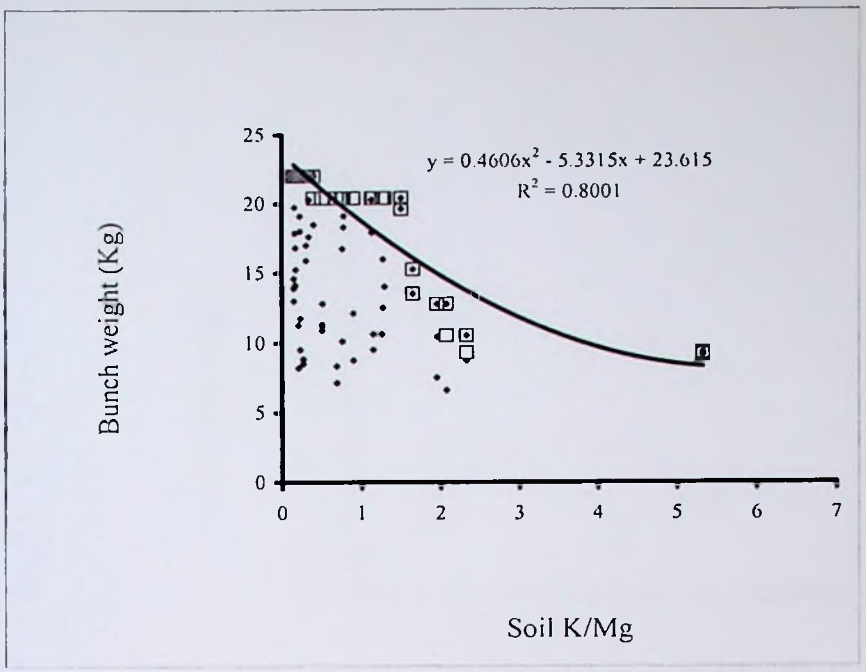

Fig. 6b. Boundary relationship showing bunch weight response to soil K/Mg ratio

4.2.1.3 Interrelations between soil pH and exchangeable bases on banana yields

As described earlier, yields increased with both increasing soil pH and increasing concentrations of exchangeable bases (except K). Soil pH was significantly ($p < 0.01$) positively related to exchangeable Mg ($r = 0.588$) and Ca ($r = 0.731$) but not to soil K. Figure 7 shows that while soil Mg tended to increase with soil pH, increases in K levels were insignificant or not apparent. Consequently, increasing K/Mg ratio (1.01 – 1.93) corresponded to increasing pH values in the range 5.7 to 6.4 (K/Mg ratio declined beyond pH 6.4). From computations, bunch weight (kg) significantly decreased from 18.7 to 15.1 at respective K/Mg ratio, as shown in Figure 6a above.

Generally, decreases in K/Mg ratio occurred beyond pH 6.4, but were not considerable and likewise increase in bunch weight was not substantial; the values were approximately equal (results not shown).

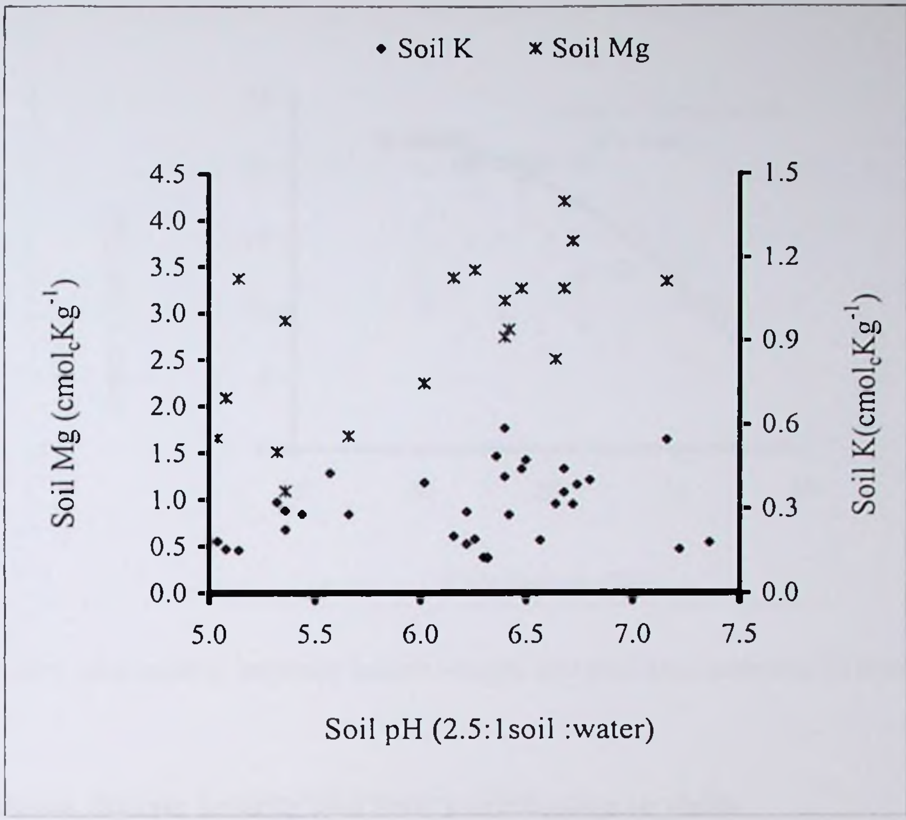

Fig. 7: Scatter plots showing the relationships between soil exchangeable Mg and K with increasing soil pH. Data points are average (n = 5 sampled mats) values from 30 locations

4.1.2.4 Influence of soil clay fraction on bunch weights

The average bunch weight for soils with clay contents between 18.5% and 21.4% was the same. However, the relationship between bunch weight and clay fraction appeared to be strongly negative ($p < 0.01$, $R^2 = 0.847$) above 21.4 % clay (Figure 8). Boundary line analysis further revealed differences in bunch weight between areas with clay fraction from about 23.2% to 28.0% clay. In addition, areas with extremes of clay contents > 28% had bunch weights well below average.

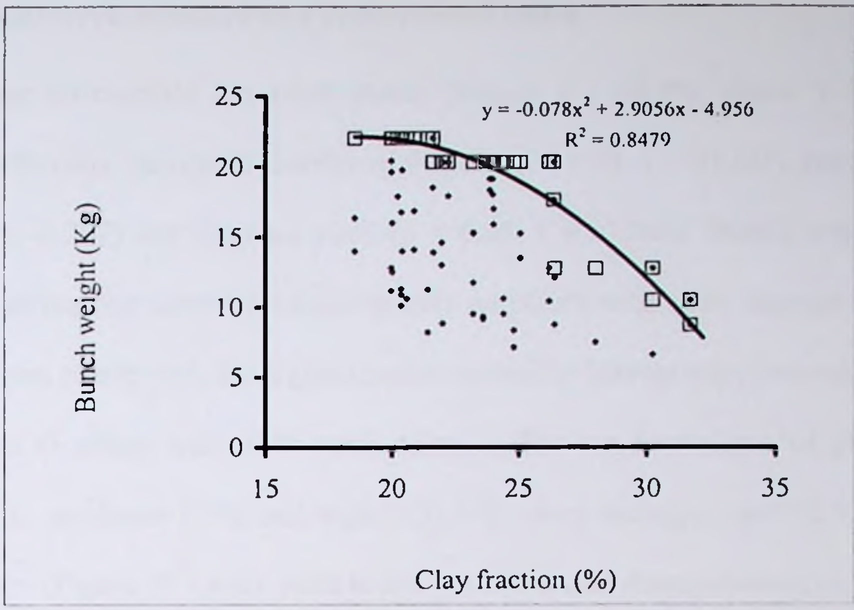

Fig.8. Boundary relationship between bunch weight and soil clay contents in banana plots

4.2.2 Pest status, disease severity and their contribution to yields

Banana pests accounted for (30.0%) of the yield limitations in the farmers' fields. Although soil factors collectively were the primary yield determinants, the banana weevil accounted for the highest proportion of 26.7% yield limitations compared to all the important factors affecting yields. Nematode yield losses (minus plant toppling) amounted to 3.3% of total limitations in bunch weight. Further, nematodes caused a 7.3% and 5.3% (11 and 8 plants) yield loss due to toppling in 'R1' and 'M' cycles, respectively.

Although diseases were not among the primary limiting factors, they reduced bunch weight. Increasing severity however did not significantly ($p > 0.05$) reduce bunch weight and other yield components (data not shown). Banana streak virus, black Sigatoka and leaf spot diseases depressed bunch weight by 21.5%, 17.9% and 16.9% respectively in severely affected plants compared to disease-free ones.

4.2.2.1 Banana weevil pressure and yield-related losses

Weevil damage on recently harvested plants (Range: 0 - 66.5%; mean: 7.4% total corm necrosis) significantly decreased number of fingers ($p < 0.01$, $r = -0.483$), number of hands, ($p < 0.05$; $r = -0.297$) and biomass yield ($p < 0.05$; $r = -0.269$). Bunch weight decreased linearly with increasing weevil pressure, mostly on plants with corm damage > 5% (Figure 9). Bunches from plants with the highest corm necrosis at harvest were reduced in weight by 54.1% relative to plants with <5% corm damage. The bunch weights of plants with the lowest (<1.4%), moderate (5%) and high (>31.9%) corm damage were 22.0, 20.1 and 9.2 kg, respectively (Figure 9). Other yield losses included, mat disappearance (n = 8) of which 5 occurred in R1 and plant snapping (n = 2) in the same cycle. Assessment of corm for weevil necrosis on plants which died prematurely revealed a much higher damage in the inner rhizome (maximum = 95% and mean = 34.2%).

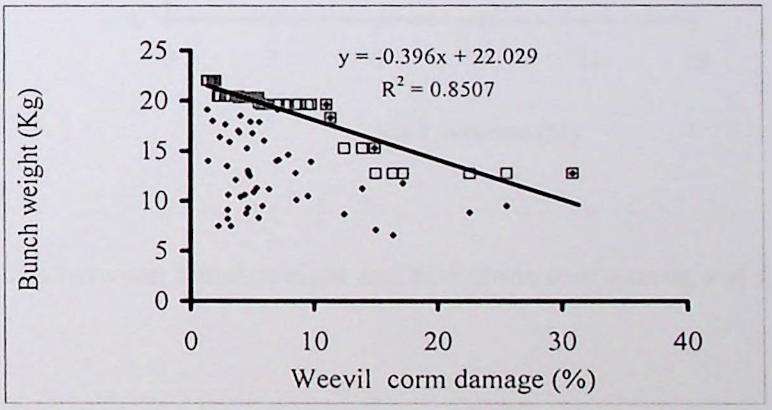

Fig.9. Boundary relationship between bunch weight and weevil corm necrosis at harvest: Plants that died pre-harvest were excluded in the relationship

4.2.2.2 Nematode infestations and yield losses

Root necrosis due to nematode damage ranged from 0- 17.6% with an average of 6.4% and root mortality at flowering highly varied (0 – 80%, mean = 23.26±12.58). Root necrosis was strongly related to bunch weight ($p < 0.05$, $r^2 = 0.765$) and also negatively correlated ($p < 0.01$, r -0.426) to the above-ground biomass. Bunch weights tended to gradually decrease with increasing nematode infestation (Figure 10). However, a small increase of 3.0% necrosis from 6.2 % was projected to reduce bunch weight by 15.9%.

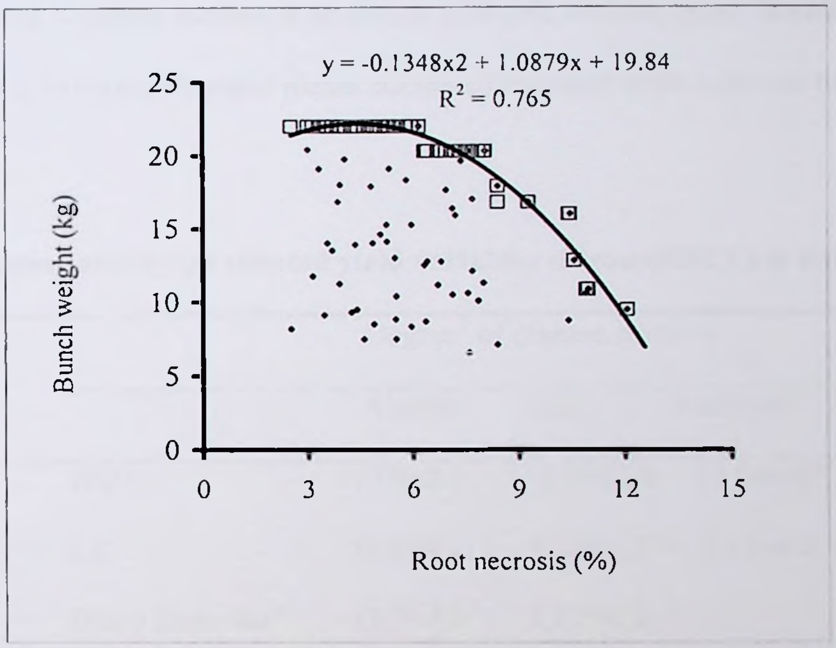

Fig. 10. Relationship between bunch weight and nematode root necrosis at flowering

4.2.2.3 Severity of banana diseases and influence on yields

Banana streak virus and leaf spots were the most common diseases observed on the plants during the monitoring study. Of the 88.8% plants which showed LS symptoms at flowering, plants (mean = 29.4%) with mild, moderate and severe degrees of LS were approximately

(±2.5%) equal. Ninety eight percent plants showed BSV symptoms and 45% had high severity. .

Black Sigatoka was observed on only 5% of the plants mostly on the youngest leaf numbers 8, 6 and 10 in the order of increasing frequency.

The severity of the diseases above did not reduce yields significantly ($p > 0.05$), although the number of clusters in particular was higher in non-diseased than diseased plants (Table 10). There was a significant ($p = 0.000$, T value = 7.36) difference in number of hands in a bunch with black Sigatoka incidence on plants with and without spots. Bunch weights were also depressed in severely-diseased plants compared to plants with mild and no symptoms of BSV and LS.

Table 10. Disease severity on selected yield variables (Mean±SDEV) at harvest

Yield component		Degree[†] of disease severity			
		Absent	Mild	Moderate	Severe
Bunch fresh weight (Kg)	BSV	17.9±0.0	12.4±2.28	13.2±4.07	14.0±8.4
	LS	15.8±4.2	11.9±3.2	14.5±4.8	13.1±3.8
	Black Sigatoka*	13.7±4.0	11.2±6.2		
Clusters	BSV	9.0±0.0	7.3±1.0	7.5±0.76	7.4±0.94
	LS	8.0±0.8	7.4±0.9	7.2±0.9	7.2±0.7
	Black Sigatoka*	7.5±0.8	6.3±0.5		
ABG dry weight (Kg)	BSV	9.1±0.0	7.32±2.3	8.5±3.4	8.4±2.6
	LS	9.3±4.2	7.3±2.5	8.8±2.9	8.2±2.1
	Black Sigatoka*	8.4±2.8	6.5±2.9		

* P = 0.000 (Matched paired T test, d.f =57), [†]*Source:* Jones (1994) severity scale (0) absent, (1) mild, (2) moderate and (3) severe, ABG stands for above-ground biomass

4.2.3 Crop management aspects in banana plantations at Butare

The levels of farmer management practices, intercropping, deleafing or detrashing and mulching, did vary between farms but these practices were not related to banana yields. Mats were weedy for 2 to 12 consecutive weeks and on average, weed duration was 7 successive weeks or 36 days. Weeds covered 15 - 80% of the mat area (2.4 - 6.2 m^2) equivalent to a weed index (114 – 2100). Weed growth, in terms of height (cm) and coverage (% mat surface) on average was 11.39 cm and 45.0%, respectively. About 75% of the mats were intercropped with common beans (81 mats), sweet potatoes (9 mats) and some (21) mats had maize, millet and pumpkins. The densities (plants m^{-2}) for all intercrops except common beans were less than 1.0, thus the density of beans was considered and averaged 8.4 (±1.1 s.d.). Generally, bean intercrops were removed prior to harvest, mean duration on mats was 53 days.

Banana residues or self mulch was the dominant material (80% of mat surface) used for mulching of bananas. However, self mulch was supplemented with other external mulch materials, largely crop residues in most mats. Mulch thickness ranged between 1.0 - 2.7 cm covering 37.6 - 74.9% of the mat area Thickness and coverage of mulch were significantly ($p < 0.01$, $r = 0.77$) related.

The removal of old leaves and sheaths largely depended on the frequency of weeding. Cumulative dead leaves appended on the plant at harvest were significantly correlated ($p < 0.01$, $r = 0.46$) to frequency of weed observations in a mat.

There were no additions of inorganic fertilisers in all the study farms. Animal manures (cow dung, goat pellets and chicken droppings) were not deliberately applied around banana mats. Rather, such organic inputs were often dumped within adjacent areas to homesteads which seemed to be convenient and labour saving to the farmers.

4.2.3.1 Contribution of crop management practices to banana yields

The cultural practices which were related to yields and explained yield variability between farms were spacing, leaf pruning, weeding and replanting (indicative of plant density, number of functional leaves, weed index and age of the plantation, respectively).

Bunch weight was significantly related ($p < 0.05$; $r = -0.314$) to mat density. The regression: $Y = 18.47 + -1.75e^{-3D}$, $p < 0.01$ of bunch weight (Y) on plant density (D), explained 8.31% (R_{adj} = 0.0831) of the variability in bunch weight. Boundary relationship between bunch weight and mat density (Figure.11) indicates that heaviest bunch (22.3 kg) occurred at plant density 1512 (2.6 m × 2.6 m spacing) and high densities (1,961- 4,993 mats ha^{-1}) resulted in a drastic decrease in bunch size from 22.9 to 16.0 kg, accordingly. Bunch weight was however unaffected between 2,102- 2,906 mats ha^{-1}(2.2 m^2 - 1.9 m^2 mat area). Interestingly, the spacing of 3m × 3m (1,111 mats ha^{-1}), gave mean bunch weight of 21.5 kg, which is 1.2 kg lower than that at the higher density of 1512 mats ha^{-1}. In spite of the strong decrease in bunch weights with increasing plant population, there was no yield limitation due to high plant densities.

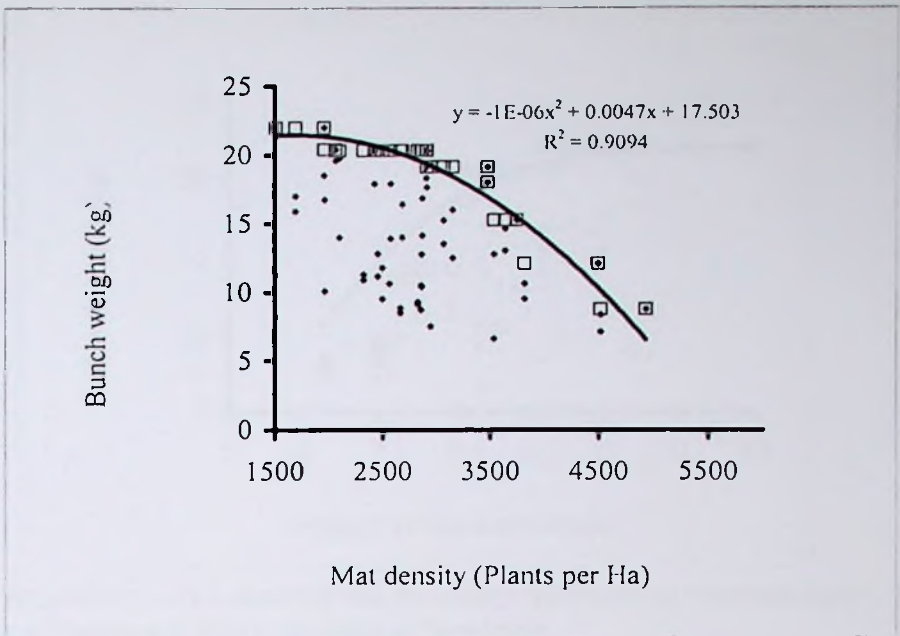

Fig. 11. Boundary relationship between bunch weight and banana mat density

A tenth of the total yield limitations in follower ratoons (and13.3% in 'M' stands) was attributed to few functional leaves. The number of functional leaves (defined as >50% green and with unbroken stalk) at flower bud emergence ranged from 5 to 12 (mean = 8.7±1.2) between farms.

The number of standing leaves at flowering was positively and significantly ($P < 0.01$) related to bunch weight ($r = 0.583$) and to above-ground biomass ($r = 0.464$). Bunch (kg) weight increased exponentially (11.0 to 18.5) at low leaf numbers (6.3 to 8) and slightly (lag-phase) with more leaves, to a maximum of 21.9 kg for 12 leaves (Figure 12).

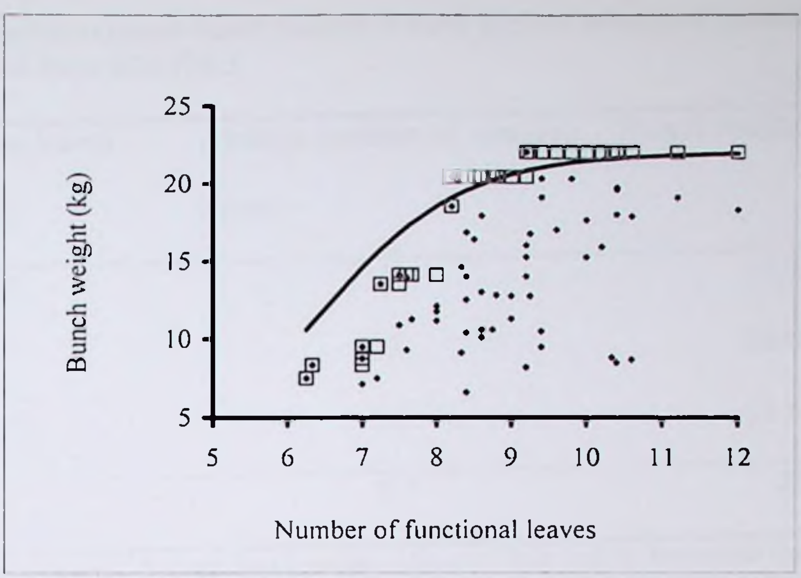

Fig. 12. Fitted regression curve showing the boundary relationship between bunch weight and the number of functional leaves present at flowering

Hence, bunches from banana plants with 50% less leaves than the maximum at flowering were reduced in weight by 58% (Table 11). The relationship however, diminished and disappeared after nine leaves in spite of further increase in number of functional leaves as indicated by a constant bunch weight of 21.8 kg. Therefore a 50% increase in bunch weight corresponded to an increase in number of leaves from 6 to 9.

Table 11. Predicted maximum bunch weight in three distinct ranges of number of functional leaves* as derived from BOLIDES

Range of standing leaves	Average number of standing leaves	[†]Bunch weight (Kg)±SDEV
6 – 8	7	14.6±5.6
9	9	20.6±0.5
10 – 12	11	21.8±1.7
Mean	8.7	20.1

*Leaves present at flowering, [†]Average bunch weight calculated from logistic regression equation

However, no significant correlations appeared between the number of functional leaves present at flowering and severity of foliar diseases and root and corm damage. The number of functional leaves was only negatively related with weed infestation index ($p < 0.05$, $r = -0.339$) and root mortality ($p < 0.01$, $r = -0.368$).

Although weed pressure was not significantly ($p < 0.05$) related to bunch weight, weed infestation in the mat area was negatively correlated ($p < 0.05$, $r = -0.337$) to above-ground biomass yield. The scatter data in Fig. 13 indicates that biomass yield decreased with increasing weed index (WI), but was not apparent in less weedy-mat (less than 400 WI). From boundary-line analysis (graph not shown) average dry matter (17.5 kg) in weed-free mats was the same for mats infested by weeds at 700 WI. However, a 36% increase in weed index was equivalent to 50% loss in biomass yield, comparing yields at weed indices 794 and 1252.

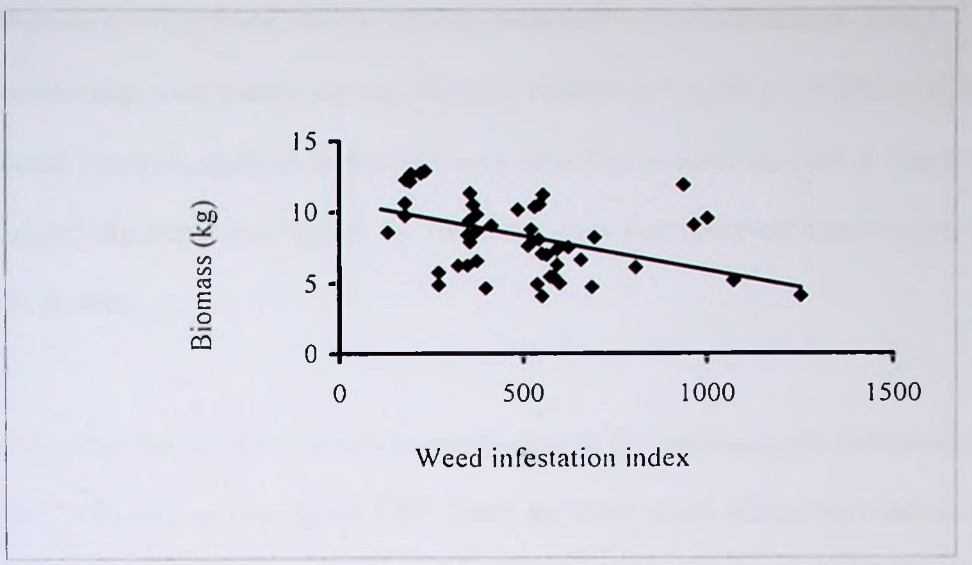

Fig. 13. The relationship between weed infestation index and above ground biomass yield at plot level

The age (4-90 years) of the plantations was not a yield limiting factor and yield variables were not statistically different among farms of different ages. Bunch weight was significantly ($p < 0.01$) different, only between farms of age 4, 50 and 90 years.

4.2.3.2 Influence of crop management practices on pest damage, disease severity and soil nutrient status of plantations

Removal of old leaves from plants significantly ($p < 0.05$) influenced positively the severity of foliar diseases. Mulch coverage (% mat surface) and thickness (cm) influenced negatively weevil pressure and positively nutrient concentrations in the soil.

Weevil damage to the banana corm was positively and significantly ($p < 0.01$) correlated with mulch cover ($r = 0.31$) and depth ($r = 0.38$) in the mat area. Increased levels of mulch thickness away from homesteads ($p < 0.01$, $r = 0.38$) positively affected weevil pressure within farms. Such an effect was reflected by increased ($p < 0.01$, $r = 0.27$) weevil corm necrosis moving from near to remote distances to the homestead. Soil Ca and Mg (prior to monitoring) were positively significantly related ($p < 0.01$; $r = 0.38$, $r = 0.36$) to thickness of mulch material, applied in the mat area after the monitoring period respectively. Initial soil Ca and Mg status was higher for the same mats that received more mulch thickness (results not shown).

Mulching also influenced weed growth around the banana mats indicative of a significantly ($p < 0.01$) strong correlation (R^2= 0.80) between weed infestation index and mulch depths (Figure 14). Regression of weed infestation levels on cumulative mulch (mean depths at harvest) explained only 12.9% of the variability of weed growth in mats; boundary-line analysis revealed that lowest to moderate weed infestation (WI = 0 and 600) were found in mats mulched between 2.0 and 3.0 cm respectively (Figure 14).

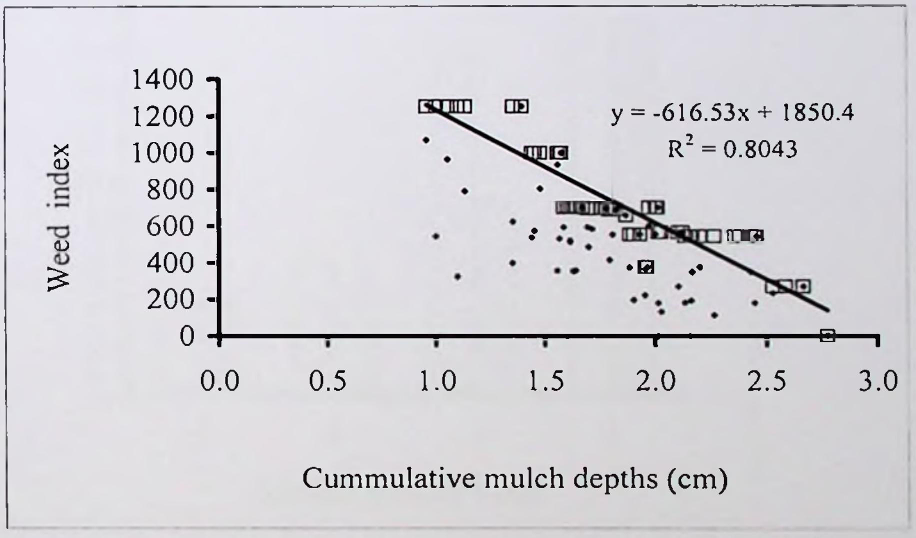

Fig. 14. Boundary relationship showing the effect of mulch depths on weed infestation in different relative distances

The severity of leaf spot (LS) disease and banana streak virus (BSV) was significantly influenced by crop sanitation levels of rouging or detrashing. The total number of old leaves was significantly ($p < 0.05$) higher on severely diseased than non-diseased plants with leaf spot diseases at flowering (Figure 15). Number of dead leaves (mean = 4) on plants with no foliar symptoms of LS was significantly lower than on plants with severe (17), moderate (15) and mild (6) symptoms.

Similarly, comparing plants that showed BSV symptoms, the disease expression was significantly ($P < 0.05$, $\chi^2_{test} = 26.6$) influenced by cumulative dead leaves (CDL) on the plants. Generally, higher severity (score ***) of BSV was noted on less rouged (17 CDL) plants and CDL was consistently higher on plants which had severe, moderate, and mild chlorotic streaks respectively (Figure 15).

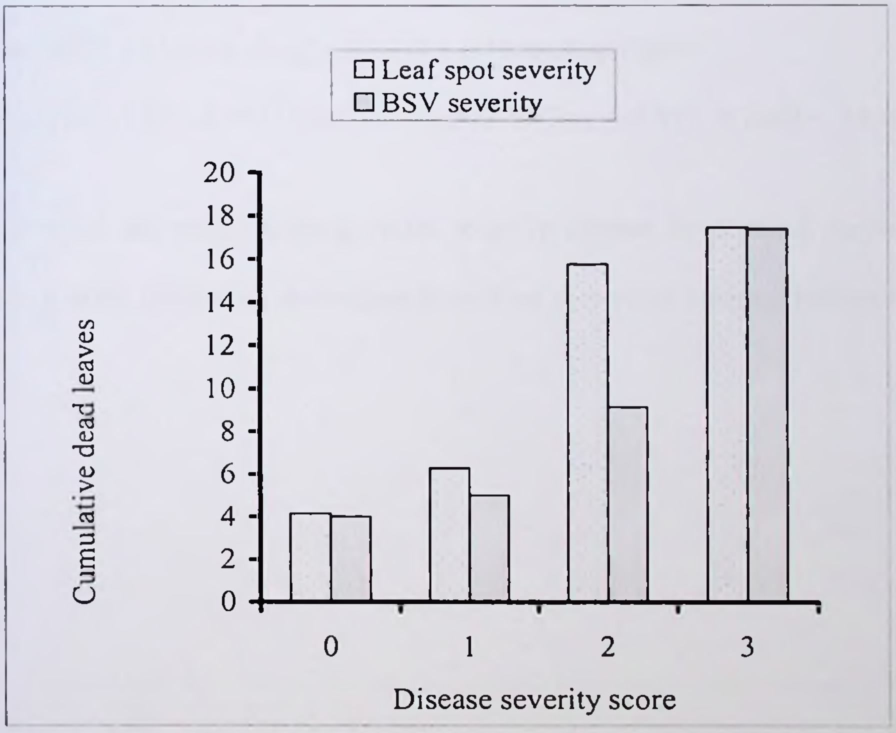

Fig.15. Cumulative number of hanging leaves at harvest on plants with varying degrees of disease severity

4.3 Boundary line model performance

Figure 16 shows that the yield potentials determined by multivariate boundary line model were attained with biophysical factors investigated. The relationship between actual and expected yields (R^2 = 53.05%) is a good fit of the boundary line model.

Excluding non-yield limiting factors (SOC, total N, Mg, banana density and weed index) which were related to yields, multiple regression between yields (bunch weight) and soil fertility factors ($R^2 = 0.328$; $p < 0.01$), and with pests ($R^2 = 0.108$; $p < 0.044$), as well with crop management aspects, leaf pruning ($R^2 = 0.223$; $p < 0.000$) was significant ($R^2 = 0.536$; $p < 0.000$). Soil fertility factors collectively explained 26.3% ($R_{adj.}$ = 0.263) of the variability in bunch weight (Y), in a relationship below:

$$Y = 1.115\ pH - 0.783\ Exch.Ca - 0.203\ \%Clay - 0.595\ K/Mg + 24.405\ Ca/(K + Mg + Ca) + 3.406$$

However, the model linking yields to all its related biophysical factors, resulted ($R^2 = 0.54$; $p < 0.000$), indicating the insignificance of non-yield limiting factors to model performance.

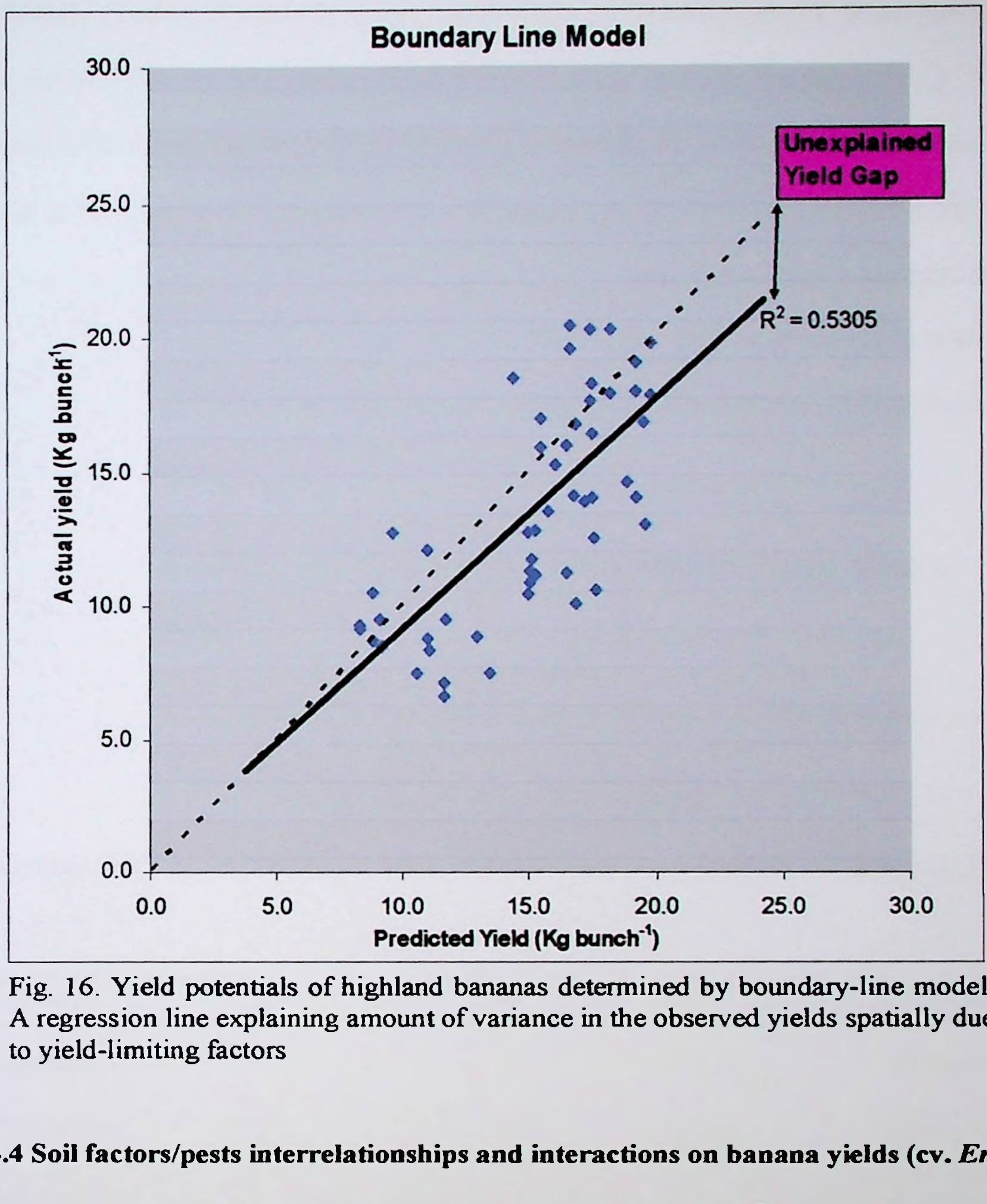

Fig. 16. Yield potentials of highland bananas determined by boundary-line model. A regression line explaining amount of variance in the observed yields spatially due to yield-limiting factors

4.4 Soil factors/pests interrelationships and interactions on banana yields (cv. *Enyeru*)

Significant relationships were observed between soil fertility factors and nematode, and weevil damage and disease expression on the plants. Yields were also determined by the interactions between some soil factors and pests.

4.4.1. Pests and soil fertility status within farms

Soil fertility parameters generally decreased with increasing distance from homesteads within farms as elucidated earlier (section 5.2.1). Pest pressure significantly ($p < 0.05$) decreased with increasing absolute distance from homesteads. Within farms, nematode root necrosis decreased ($r = -0.330$) and weevil corm damage decreased ($r = -0.265$) with increasing distance from the homesteads. There was no significant difference in pest damage between relative distances (Appendix 2). However, mean root necrosis and weevil corm damage was generally higher in closer than either mid-distant or remote relative distances of the homesteads (Table 12).

Table 12. Mean nematode and weevil damage ±s.e. (n = 40) from three relative distances within farms

	Relative distance from the kitchen*			
Pest damage (%)	Close	Mid-distant	Remote	Mean±SDEV
Root necrosis	7.06±0.58	6.73±0.57	6.08±0.56	6.62±2.28
Root mortality	25.45±1.9	23.3±2.2	23.0±1.9	23.9±8.0
Corm damage	7.43±1.83	5.17±0.76	6.14±0.79	6.25±4.92

* A kitchen was used to determine the distance between a mat and homestead since it was the major source of organic wastes within households

4.4.2 Interrelationships between soil fertility factors and pests between and within farms

The necrosis and number of dead roots due to nematode damage were negatively correlated to most soil properties (Table 13). Root cortex necrosis (%) significantly ($p < 0.01$) decreased with increasing soil fertility parameters as indicated by significantly negative correlations between nematode damage and soil properties (Table 13). Using multiple linear regression models, the model:

Root necrosis (%) = 0.216 pH - 0.249 SOC +12.362 Total N + 1.072 (exp.-2) + 0.112 exch. K – 1.319 exch. Ca + 5.307exp^{-2} Silt -5.307exp.$^{-3}$ distance to homestead + 6.562, explained 32.7% ($p = 0.000$) of nematode status between farms (Appendix 3). The relationship was further analyzed using stepwise regressions where root necrosis was regressed against factors (soil pH, SOC, total N, avail. P, Ca, Mg, silt, distance to homestead).

Root necrosis (%) = [-0.986 Ca + 12.445 Total N + 7.228, r_{adj}. 0.353; Root necrosis (%) = -0.556 Ca + 7.956, r_{adj}. 0.298, $p = 0.000$]; soil exchangeable calcium explained 29.8% of the relationship between soil factors and nematode status.

Soil available P ($r = 0.47$) and organic carbon ($r = 0.46$), and leaf P ($r = - 0.34$) and Ca ($r= -0.32$) were significantly ($p < 0.01$) positively and negatively related to weevil corm damage respectively. Leaf spot severity on plants was significantly ($p < 0.01$) correlated with soil pH, organic matter and total soil N (Table 13).

Black Sigatoka incidence on plants varied significantly ($p = 0.000$, T value = 57.6) with proportion of clay particles.

Table 13. Interrelations between soil fertility factors and pest damage in bananas

	Correlation to soil factor						
Pest status (%)	Soil pH	SOC (%)	Total N	Avail. P (ppm)	Ca	Mg $cmol_cKg^{-1}$	Silt (%)
Root necrosis	-0.41**	-0.43**	-0.35**	-0.41**	-0.56**	-0.47**	-0.33*
Dead roots	-0.32*	-0.30*	0.33*	-0.29*	0.34**	-0.31*	-0.26*
CS damage	n.s.	0.46**	0.29*	0.47**	0.37**	0.41**	0.62**
IX damage	n.s.	0.51**	0.33*	0.50**	0.40**	0.46**	0.66**
Leaf spot severity†	-0.44*	-0.45*	-0.41*	Nil	Nil	Nil	Nil

†severity expressed as a score (+, ++, +++), n.s. (not significant)
*Significant at p < 0.05, ** Significant at p < 0.01, CS (Cross sectional) and IX (inner cylinder) damage

4.5 Banana yields within farms of different levels of resource endowment

4.5.1 Yield trends within and across farms of different wealth classes

Generally banana yields at harvest differed but not significantly ($p > 0.05$) within farms as well as among farmers of different wealth classes (cf. Appendices 5A and 5B). However, within farms, the number of fingers was significantly ($p < 0.05$) higher only in CF than in RF (Appendix 4B iii). Similarly, differences in plant growth at flowering though significant ($p < 0.05$) within farms, were not statistically larger in closer than in mid-distant plots (data not shown).

Comparing yields among farmers from three wealth classes, mean bunch fresh weight and cluster specifically were greater in rich than in medium and poor types of farmers according to their resource levels (Table 14). Other bunch characteristics and biomass were larger in wealthier than poor farms; the trend was not in the order wealthy > medium > poor (cf. Appendix 4C iii-v).

The magnitude of yield variability was larger within farms of the poor than those for the medium and rich households in relation to resource endowment (Table 14). The Levene's test for homogeneity of yield variables was not significant ($p > 0.05$) among wealth classes (Appendix 4C) except for the number of hands (Levene's test, $p = 0.0383$). Hence, variability in number of hands was significantly higher within farms of the poor than medium and rich categories.

Table 14. Yield trends (mean ± SD) within farms (n = 8) belonging to three wealth categories

Level of resource endowment in farm[‡]	Yield variable	Average values of yield variables in three RD of the homestead: Close	Mid-distant	Remote	Mean± SD
Poor	Bunch weight	14.5±5.3	14.5±4.9	10.8±3.6	13.25±(4.59)
	No. clusters	7.8±1.3	7.5±1.2	6.7±0.8	7.33±(1.12)
n = 3	Number of finger	119.2±24.8[a]	114.8±21.9[b]	83.8±18.0[b]	105.9±(25.6)
Medium	Bunch weight	14.3±5.0	13.1±4.1	13.7±3.7	13.54±(4.37)
	No. clusters	7.6±0.9	7.3±0.8	7.4±0.7	7.40±(0.79)
n = 3	Number of finger	115.6±27.1[a]	108.0±31.9[b]	105±17.9[b]	108.1±(24.9)
Rich	Bunch weight	13.7±3.1	14.9±1.5	13.0±5.0	13.89±(3.27)
	No. clusters	7.6±0.2	7.5±0.6	7.2±0.9	7.44±(0.58)
n = 2	Number of finger	108.7±8.4[a]	110.7±6.3[b]	99.7±17.4[b]	106.7±(11.7)

[‡] Two farms (medium class) were not considered because of superimposed fertility gradients which affected yield trends from analysis. Eight farms had never shifted homesteads in history and had single productivity gradient

(Squared deviations) from group means are in parenthesis represent the magnitude of within-group variability, values followed by same letters in a row are not statistically significant at $P < 0.05$

4.5.2 Foliar nutrient status among farms of different resource endowment levels

The nutrient concentrations in the leaf except for N ($p = 0.003$) did not significantly ($p > 0.05$) differ among rich, medium wealthy and poor farms. The level of leaf N in plantations belonging to poor farmers was statistically similar to those of the rich farmers, which was significantly higher than in those of medium farmers (Table 15). However, rich farms had significantly higher leaf Ca and Mg than medium farms. There was no N imbalance in only plantations of poor farms while Mg deficiency occurred in those of medium farms. P and Ca imbalances (negative indices) occurred in plantations of all the wealth classes, but the magnitudes were larger in poor than medium and rich farms accordingly.

Within farms, leaf Mg was higher though not significantly in close distances from homesteads of rich farms (0.39%) than in similar areas of medium (0.35%) and poor ones (0.34%). Likewise, Mg and Ca in mid-distant (0.41% and 0.79%) and in remote areas (0.39% and 0.79%) respectively, of rich farms were relatively higher compared to values in corresponding distances of poorer farms. That is, leaf Mg was 0.36 % vs 0.31% and Ca was 0.61% vs 0.63% in MF of medium and poor farmers, respectively and Mg 0.38% vs 0.35% and Ca 0.64% vs 0.60% in RF, respectively. DRIS indices within plantations of different wealth categories are not presented because a missing nutrient ratio (s) rendered computation of a nutrient index by relative distances difficult.

Table 15. Mean (±SDEV) of foliar nutrient concentrations and DRIS indices among farms of different resource endowment levels

Nutrient (%)	Wealth category	Mean	DRIS indices
N	Poor	2.60 ±0.29[a]	0.78
	Medium	2.36± 0.28[b]	-5.24
	Rich	2.52±0.15[ab]	-3.62
P	Poor	0.14±0.03[a]	-10.45
	Medium	0.15±0.02[ab]	-8.89
	Rich	0.16±0.01[b]	-7.18
Ca	Poor	0.64±0.24[ab]	-9.28
	Medium	0.64±0.14[a]	-6.41
	Rich	0.73±0.15[b]	-6.44
Mg	Poor	0.37±0.10[ab]	0.96
	Medium	0.33±0.06[a]	-2.99
	Rich	0.38±0.11[b]	1.03
K	Poor	3.37±0.70	17.99
	Medium	3.57±0.51	23.52
	Rich	3.48±0.51	16.21

Means followed by similar letters within a column indicate statistically ($P > 0.05$) similar levels of nutrients between wealth classes

4.5.3 Abiotic factors explaining yield differences among farms of different wealth classes

Differences in yields among wealth classes of farms were explained by some of the biophysical factors which affected yields between farms. Factors including number of functional leaves, weevil damage, soil K/Mg ratio and % clay did not significantly ($p > 0.05$) differ between farms of different wealth classes (Appendix 4).

Among soil fertility factors that significantly ($p < 0.05$) varied with wealth class of farms were, pH, exchangeable Ca and Mg. Mean soil pH was significantly ($p = 0.0191$) higher in plantations of the rich than in those of the medium and poor farmers. But plantations belonging to the medium and rich farms had no significant differences in soil acidity (Table 16). The rich farms had significantly ($p = 0.0027$) higher exchangeable soil Ca than those for medium and poor farmers, respectively. However, mean soil Mg in plantations of poor farms was nearly double that in plantations of medium class farmers and the difference was significant ($p = 0.0038$). However, the Mg content in rich farmers' plantations was not different from the levels in poor farms (Table 16).

Banana mat density in poor farmers' plantations was significantly ($p < 0.0001$) higher and 1.4 times more than that in wealthy farmers' plantations, which was similar to that in medium farmers' plantations (Table 15). Nematode root necrosis was significantly lower in wealthy farmers' plantations than that in poor and medium farmers' ones although the differences were not significant.

Table 16. Means ±SDEV of selected factors in farms according to level of farmer resource endowment

Average values of yield-determinants of farms, a function of wealth class			
Abiotic factor	Poor	Medium	Rich
Soil pH	5.8±0.7 [a]	6.2±0.5 [b]	6.5±0.7 [b]
Exch.Ca (cmol(+)kg^{-1})	1.94±1.17[a]	1.58±0.58[b]	2.88±1.41[c]
Exch. Mg (cmol(+)kg^{-1})	1.66±0.93[a]	0.94±0.31[b]	1.92±1.35[ab]
Nematode root necrosis (%)	7.3±2.7[a]	7.2±1.9[a]	4.6±1.0[b]
Plant density (plant ha^{-1})	3884±649[a]	2655±442[b]	2716±323[b]

Means followed by same letters in a row are not significantly different at $P < 0.05$
Exch. K among farms was approximately equal

4.5.3. Biophysical factors limiting banana yields within farms of different levels of resource endowment

The abiotic factors, which limited yields among rich farms, were different from those that restricted yield improvements among medium and poor farms. Across wealth classes, soil fertility factors accounted for 50%, 60% and 77.8% of the total yield limitations in rich, medium and poor farmers, respectively. Pests were equally important among rich and medium farmers contributing $^1/_3$ of yield limitations in the respective wealth classes but of least significance (22.2%) among poor farms. Yield limitations due to crop management aspects were less important across wealth classes mostly in medium (13.3%) and rich (16.7%) classes than previous factors. Soil fertility, pests and management related constraints were even more distinct with respect to relative distances to the homesteads of different farm types.

4.5.3.1 Soil yield-limiting factors

Soil pH was not a yield limiting factor among rich and medium farms but a major constraint among poor farms occurring in all distances of their homesteads (Table 17). All mid-distance areas in poor farms had yield limitations due to pH and $^1/_3$ of close and remote distances of their homesteads had pH limitations.

There were no yield limitations due to soil exchangeable Mg content across all wealth classes. Soil Ca was not a yield limiting factor among the rich farmers but constrained yields among medium farms in mid-distance and remote areas to the homesteads. Conversely, similar areas to homesteads of poor farmers had no Ca yield limitations. Soil K/Mg ratio was not yield limiting among poor farmers, but was limiting in all distance classes from the homesteads of rich farmers. Half of the CF, MF and RF of latter farms had soil K/Mg limitations as opposed to 40% and 20% CF and MF in farms of medium class.

Table 17. Percentage of areas limited by soil fertility factors within farms of high, medium and low resource endowment

Soil parameter	Yield limitation (% locations[†] constrained) within farms of from three wealth classes			
		Poor	Medium	Rich
	RD to homestead			
pH	Close	33.3	0	0
	Mid-distant	100	0	0
	Remote	33.3	0	0
Exch. Ca	Close	33.3	0	0
	Mid-distant	0	20	0
	Remote	0	20	0
Exch. Mg	Close	0	0	0
	Mid-distant	0	0	0
	Remote	0	0	0
K/Mg ratio	Close	0	40	50
	Mid-distant	0	20	50
	Remote	0	0	50

[†]The number of relative distances (RD) constrained by a soil parameter within a wealth class was expressed as a fraction of N distances in a wealth class e.g.100% means all mid-distances of poor farms had yields limitation of pH

4.5.3.2 Yield-limitations due to pests

Banana weevil damage was a common constraint to yields across all wealth classes. Rich farmers had similar yield limitations in close and remote areas from the homesteads which were more than those limitations from respective distances of medium farmers (Table 18). Medium farmers had nematodes as an additional constraint only in RF from their homesteads. Although the CF and MF areas of poor farms were not constrained by the pest, it was however a critical constraint in remote areas to their homesteads.

Table 18. Percentage of areas limited by banana pests within farms of different levels of resource endowment

Pest	Yield limitation (% locations constrained) within farms of three wealth classes			
	RD to homestead	Poor	Medium	Rich
Banana weevil	Close	0	40	50
	Mid-distant	0	20	0
	Remote	66.7	20	50
Nematodes	Close	0	0	0
	Mid-distant	0	0	0
	Remote	0	20	0

4.5.3.3 Crop management aspects

There were no yield limitations due to fewer functional leaves at flower bud emergence among poor farms and in CF to homesteads of other two wealth classes. A fifth of MF in medium farms had yield limitation due to few functional leaves which was of the same magnitude to that in RF to their homesteads. The rich had 50% MF whose yields were limited by few functional leaves.

CHAPTER FIVE

5.0 DISCUSSION

5.1 Diagnostic survey

5.1.1 Household characteristics

The characteristics of the 50 surveyed households showed important socio-economic and biophysical aspects in banana production. Land holdings per household are generally small and bananas were produced on small plots, << 0.5 ha (Uganda Ministry of Agriculture, 1992; Gold *et al.*, 1999a). The observed differences in terms of household objectives, production activities and income strategies were good indicators of farmer resource endowment or household wealth. Classical indicators of household wealth included land hectarage, size of plantations, % salary earners, hired labour and yield trends.

There exists a strong link between household wealth class, biophysical factors (some constraints), and banana yields. Heavier bunches on wealthier (medium and rich) farms corresponded with higher soil C and N levels in their banana plots and significantly more livestock units. This could be interpreted as a consequence of manure inputs in plantations of wealthier farmers as suggested by Bekunda (1999).

The rich farms sourced income from family support, better paying activities and salaries, as opposed to the poor who were more engaged in time-demanding activities particularly charcoal burning and selling. Medium farms also had better income from trade in merchandise or shop than poor ones. Wealthier farms owned more resources which were further used to pay more labour. Obviously, higher levels of resources and slightly better soils in richer than medium and poor farms respectively, implied more productivity and higher yields. This partly confirms the contrasting experience on yield trends (Table 1b) among farms of different wealth class. Moreover, most richer than medium and poor farmers worked with social groups dealing with bananas as one of the priority crops (results were not presented) meaning that wealthier farms received at least advise on banana production.

The above findings indicate strong relationships between biophysical and socioeconomic factors that determine banana yields (Bashaasha, 2001) suggesting that understanding spatial variability of (a)biotic factors, in relation to yields, by farmer resource endowment is very important.

5.1.2 Yields, constraints and farmer perceptions of production constraints

The mean bunch weight 15.7 Kg (±4.7 s.d.) in the study area approximates[2] to yields 29 t ha^{-1} yr^{-1} which falls within the range in Southwest Uganda (Van Asten *et al.*, 2004). However, bunch weight range of 5 to 60 kg between farms and large variation indicates that yields are much lower than 29 t ha^{-1} yr^{-1} in most farms. Since bunch weight was determined on small sample of 3 bunches from a plot of 0.33 ha, perhaps the selected bunches were not representative of a plot in terms of size.

Farmer perceptions of causes of low yields are interesting when comparing to the verifications in the survey. Banana weevil (*Cosmopolites sordidus*, Germar) was considered the most important constraint to yield decline. Mean corm necrosis (4.6±0.3%) on recently harvested plants was slightly greater than the 4.5% threshold in banana plantations, hence weevil pressure was moderate (Gold *et al.*, 1994). A recent study by Wairegi *et al.* (unpubl. data) reported mean weevil damage of 3.6% in 180 plots across four regions in Uganda with minimal difference between the lowest affected region (3.0%) and the region with highest

[2] assuming 1bunch/mat/yr is harvested

average damage (4.2%). Hence, the Butare study site seems more severely affected by weevils than what is generally found in Uganda. Root necrosis averaged 4.5%, which is less than 6.4% considered as critical level (Speijer *et al.*, 1994). Nevertheless, root necrosis though lower than the levels reported in other three regions (Wairegi *et al.*, unpubl. data), is however much greater than the 3.3±0.7% reported by the same authors in the Southwest region. However, it is frequently realised that farmers' perceptions of soil pests are poor (CGIAR, undated) and this explains farmers' low awareness about nematodes in spite mentioning toppling. Diseases are equally important to pest on surveyed farms since their incidence and severity was high. Determining the effects of foliar diseases like BSV among others on banana yields is therefore important. Soil fertility was perceived as a secondary constraint in decline of banana production but, foliar analyses indicate nutrients are limiting in most plots, thus the problem of nutrient deficiencies actually exist. Low soil fertility may not be actual problem on some farms where plantations existed for a minimum of three years as stated by Abera *et al.* (1999). Looking at the socioeconomic indicators and their link to soil status in farms (Table 1b), findings suggest that the problem may be more serious in poorer farms.

Deteriorating management of plantations could be attributed to limited access to hired labour in most households coupled with small sized families to provide labour (Table 1b). According to Bagamba *et al.* (2003), activities, for instance weeding and crop sanitation involved in banana production, generally demand a lot of labour, implying that such activities were perhaps less frequently undertaken among poor farmers.

5.1.3 Soil fertility status and foliar nutrient concentrations of established banana plantations

According to Foster (1971) and Lahav and Turner (1983), critical values for soil pH, organic matter, total N, available P and exchangeable Mg are 5.2, 3.0% 0.18%, 15 $mgkg^{-1}$ and 0.5 $cmolkg^{-1}$ respectively. The pH of the soils in the study area generally is slightly acidic (Brady, 1990; Okalebo *et al.*, 2002). The medium pH of 5.8 is within the range of 5.5–7.0 for good nutrient availability (Landon, 1984). Nonetheless, soil pH had no correlation to foliar cations which could imply that pH values in that range did not significantly influence availability to plants of exchangeable bases.

SOM contents (mean = 2.50%) are moderately high (Okalebo *et al.*, 2002) but are below the critical value of 3.0% for optimal banana production. Therefore, adding organic material to the soil is crucial to improve the soil C status; and also increase exchangeable bases (Stevenson, 1986) since SOM/cations relationships were apparent. Significant negative correlation between %SOM and concentration of foliar micronutrients is probably due to the formation of micronutrient-organic complexes of low solubility (Steven, 1991).

The soil analysis results also indicate that low available phosphorus is not a problem in most farms, but low N and low Mg (sufficient in only 17 plots) are inadequate for banana production. However, high levels of P antagonize uptake of Fe, Zn and Mn (Shahandeh *et al.*, 2003) and this may lead to deficiencies of the micronutrients.

Nitrogen deficiencies might be an actual soil fertility problem *per se* basing on soil N tests [no leaf N compositions]. Potassium is critical to banana production as bananas take it up in greater quantities than all other nutrients combined (Turner *et al.*, 1989). Landon (1991) suggested soil exchangeable K values in range (0.32-0.74 $cmol_c kg^{-1}$), as adequate for bananas while Walmsley *et al.* (1971) cited 0.4 $cmol_c kg^{-1}$ as the critical level for soil K. By either criterion, soil K was adequate in most sites (Table 3a).

Foliar P and K levels were deficient in banana stands on all locations according to diagnostic norms of 0.23% for P (Angeles *et al.*, 1993) and 3.04% for K (Wortmann *et al.*, 1994) considered as optimal for banana production, although soil tests suggested a moderate-high supply for both elements from most plots. However, some banana stands (27 plots) were adequate in potassium. Therefore, the interpretation of foliar analysis with DRIS norms indicates that P and K occurred often as limiting nutrients. The critical nutrient level by Lahav and Turner (1983) also suggested that sulphur deficiency in particular, was a key constraint in banana stands on nearly all plots. The DRIS norm for foliar Mg (0.41%) cited by Angeles *et al.* (1993) indicates that banana stands were adequate in Mg in only 14 plots (Table 4).

The foliar results indicate Cu and Zn deficiencies diagnosed although of minor significance to other nutritional obstacles (Table 3b) are potential serious problems that may require further investigation.

5.1.4 Yield (s) variability in relation to biophysical factors at plot level

Soil quality indicators within a farm seemed to vary highly/considerably hence it was difficult to explain the observed variation in bunch weights, growth and foliar nutrient concentrations to average values of soil quality indicators at plot level. Perhaps this was due to the low number of samples per plot (3 -7) and yet variability within farms was high. The data suggest that quantifying within farm variability in pest status, soil fertility and yields will require a more detailed study and sampling within farms, if yields/soil quality relations are to be well described. This would also lead to quantification of contributions of factors to observed yield variability.

5.2 On-farm monitoring (study approach two)

5.2.1 Soil fertility status within the farms

Soil textural analysis indicates that the soils are sandier; with sandy clay loam being the most represented class. In this study, strong fertility gradients existed within short-distance (< 40 metres) variability of homestead (cf. Fig. 3) and were less pronounced in distant locations to the homesteads. The observed gradients in soil fertility were, but not striking, in these small sized farms (< 0.5 ha) of Butare compared to those elsewhere (Prudencio, 1993; Tittonell *et al.* 2005). However, in agreement with earlier study findings in Uganda banana systems (Wortmann and Kaizzi, 1998; Bekunda, 1999), the small variability within farms for soil fertility indicators could be explained by distance effects. The soils data suggest that observed gradients were man-made based on high variability in nutrient levels within close distances. The % silt+clay was low and similar in all distances to homesteads, hence organic matter management could be attributed to the observed gradients in soils of similar inherent fertility.

Except for available phosphorus and exch. K (Fig. 3 c-d), soil analysis results of carbon did not clearly reflect distance-homestead effects perhaps because more organic inputs may be higher near than away from the homestead, but the inputs there are also more N rich and therefore the organic matter turnover is faster. Hitherto, SOM but not K and P is kept at the same level to distant areas. Phosphorus is a very stable or insoluble (Holford, 1997) but also a good quality indicator of soil organic C content (Frizano *et al.*, 2003) accumulation. Thus available P fairly well illustrated (Fig. 3 c) the long term effects of organic matter addition.

This concurs with Bosch *et al.* (1996), who observed high P values in particular within close distances to homesteads, which was also evident in this study.
Household wastes and crop residues are concentrated around homesteads (Smaling *et al.*, 1997; Elias *et al.*, 1998; Scoones and Toulmin, 1999) as such P accumulated in these near-homesteads soils. Therefore, from an application point of view, it is better to prioritise P-containing inputs like poultry droppings in remote areas to homesteads to circumvent further imbalances due to excess P in soils close to homesteads.

In general, soil laboratory results showed that fertility gradients exist within the farms in the study, but the variability was not significant ($p > 0.05$) within relative distances.

5.2.2 Concentrations of foliar nutrients in banana plantations diagnosed

The significant positive correlations between foliar nutrients and soil pH showed the influence of soil pH on nutrient availability in the soil (Steven, 1991). The significantly higher leaf P and Ca levels detected in plantations on upper slopes correspond to high SOM content of the farms. The levels of foliar Ca and N concentrations are well below the DRIS norms of 1.13% and 3.15% established by Wortmann *et al.* (1994) respectively. In comparison to P and Mg levels which are fairly close to optimum levels of 0.25% and 0.48% in bananas respectively. However, diagnosis of nutrient imbalance with DRIS indices (Raghupathi *et al.*, 2005), overall suggest that P is the most deficient nutrient followed by Ca, Mg and N in that order, with K not. Results contrast studies (Smithson *et al.*, 2004; Ssali *et al.* 2003; Zake *et al.*, 2000) in banana cropping systems which indicated phosphorus as opposed to potassium deficiencies as uncommon and frequent problems respectively. Detected P deficiency in spite of adequate soil supply indicated that hindrance to its uptake occurred because according to Steven (undated) soil test P and plant P are highly correlated, irrespective of other factors.

Within farms, N and Mg indices contrast Ssali *et al.* (2003) findings of low N and Mg levels in treatments receiving potassium-rich organic residues; in light of a balanced N in only close distances to homesteads. Further, it also seems that Mg imbalances in close areas are not very obvious (index = -1.38) compared with other nutrients. The slight Mg deficiency in adjacent locations to homesteads could be attributed to high K (consequently antagonizes Mg uptake) input from banana peelings frequently discarded to nearby areas. From personal observations, other residues including animal manures were discarded to convenient areas; the N balance in only CF therefore supports the significance of manure application for alleviating N deficiencies.

Foliar nutrient concentrations fall outside or within the sufficiency range due to other causes notably pest damage on roots. In spite of no strong evidence for pest pressure and cropping practices effects, except for nematodes and mulch depths on foliar Mg; soil tests best explain the observed nutrient deficiencies. Mean foliar K concentration was well above the critical norm (Wortmann *et al.*, 1994) for bananas resulting from adequate supply (Walmsley *et al.*, 1971; Landon, 1991) from soil (Table 4); therefore absence of K deficiency and greater balance was not surprising. As opposed to very low soil Ca levels (Okalebo *et al.*, 2002) which corresponded to low Ca (0.66%) detected in plant tissue, foliar Mg fell below the DRIS norm in spite of high soil Mg status (Okalebo *et al.*, 2002) which was strongly significantly correlated to leaf content. The low leaf Mg (0.36%) than the DRIS norm of 0.48% (Wortmann *et al.*, 1994) could be attributed to the imbalances between soil Mg and K (Delvaux, 1995; IPNI, 2008) detected, that is, a high K level reduces uptake of Mg regardless of soil Mg test (Steven, undated, Jones *et al.*, 1991). Soil cation imbalance was further confirmed by foliar K/ Mg ratio twice greater than the norm of 5.2 (Wortmann *et al.*, 1944) supporting that possible nutrient antagonism occurred. Foliar nutrient expressions indicated, a well-balanced Mg/Ca (Angeles *et al.*, 1993) and Ca/Mg ratio lower than 2.5 (Wortmann *et al.*, 1994) to suggest any Ca excess which leads to a Mg deficiency (Jones *et al.*, 1991). Meanwhile nematode root damage could have accentuated Mg deficiency indicative of significant negative correlation. Nutrient ratios with exception of only K/P and K/N are far below the DRIS norms indicating occurrence of hindrances to plant uptake.

5.2.3 Banana yields and growth in Butare plantations

Banana yields (bunch fresh weight) highly varied between (s.d. = 4.17 kg) and within (s.d. = 4.11 kg) farms. This large within-farm variability in small sized farms (< 0.5 ha) indicates that there is a lot of potential for yield improvements in many farms. The mean bunch weight of 13.5 kg is comparable to the average yield of 15.7 kg per farm obtained under farmers' conditions during a diagnostic survey in 2007 in southwest Uganda by Wairegi *et al.* (unpubl. data); therefore yields in the study area are typical of the region. The mean bunch weight of 13.5 kg is equivalent to an annual yield of 23.8 t $ha^{-1}yr^{-1}$, which is much lower than the potential yield of 60 to 90 t $ha^{-1}yr^{-1}$ in Uganda (Van Asten *et al.*, 2004). According to FAO-[(Purseglove, 1985; 1990], a crop harvest of 25 tonnes/ha/yr of fresh fruit removes 28 kg N, 7 kg P and 78 kg K per hectare per year. Lopez and Espinoza (1995, 2000) determined that 45 t ha^{-1} of bunch yield removes 80 kg N, 9.6 kg P and 256 kg K ha^{-1} and 70 t ha^{-1} removes 10 kg Ca and 20 kg Mg $ha^{-1}yr^{-1}$. Analogous, with bunch yield range of 15 – 23.8 t $ha^{-1}yr^{-1}$ in Butare, between 25.3 – 42.2 kg N, 3.0 – 5.1 kg P, 81.1 – 135 kg K, 2.0 – 3.4 kg Ca and 4.1 – 6.8 kg Mg ha^{-1} $yr^{-1}$are removed annually from farms. The farmers are threatened with further decline in yields from nutrient 'export' based on the high dry matter partitioning in bunches.

All growth parameters at flowering showed significantly strong ($r > 0.5$) correlations with bunch weight, the best yield predictor ($p < 0.01$, $r = 0.823$) was pseudostem circumference at base of flowered plants. Similar results have been reported by García *et al.* (1980) with respect to relationships between yield and pseudostem circumference. Contrary to McIntyre *et al.*, (2003) and Smithson *et al.*, (2001) findings from a single and 10 cultivar(s) respectively, in this study yields were not strongly correlated ($r < 0.5$) with the number of functional leaves compared to other growth parameters, at flowering.

5.2.4 Within-farm variability in yields: explaining differences in bunch size and crop growth

Heterogeneity in crop performance, for instance growth within farms, is ascribed to the existence of soil fertility gradients and also to differential day-to-day management within the farms (Tittonell *et al.*, 2006). The significantly higher growth in CF than in MF and RF from homesteads could be attributed to little or no attention in terms of crop husbandry in remote areas leading to significantly poor plant growth and finally small bunches. These findings support visual observations in surveys elsewhere (Rugalema *et al.*, 1994; Bekunda, 1999) of differential banana performance within homestead fields.

The observed soil nutrient gradients, except for potassium (Figure 3), were not strong to result in significant decreases in yield with increasing distance from homesteads.

High and low bunch weight in close and remote areas respectively, could partly be ascribed to decreasing soil fertility status within farms (Table 4 and Figure 3) but mostly to management intensities, which corresponds to larger variability within closer than other areas from homesteads. Therefore, yield variability within the farms mainly resulted from differences in soil fertility management, usually a consequence of dumping household organic wastes mostly in near distances. More and frequent concentrations of organic wastes and nutrient inputs in areas closer to homesteads (Scoones and Toulmin, 1999) than in remote ones resulted in improved soil conditions and better plant performance in former than in latter areas.

Despite higher growth in terms of taller-vigorous plants in closer than in distant areas of homesteads, harvest index was slightly less (0.39 vs. 0.40), respectively. Hence, nutrients absorbed by plants are simply translated into more biomass at anthesis than fruit filling stages of growth.

5.2.5 Influence of soil parameters on banana yields

Of the various soil chemical properties that limited banana yields, K/Mg ratio was the most important constraint, followed by soil pH, clay content, exchangeable Ca and Mg and Ca/(Ca+Mg+K) as described in details below.

5.2.5.1 Effect of soil pH on yields

Although the median soil pH of 6.3 was within the range 5.5-7.0, for adequate nutrient availability (Landon, 1984; Lopez and Espinosa, 2000), adequate banana performance in terms of yields were however constrained at low pH. The lowest bunch weight of 13.2±5.9 kg attained in the pH range 5.0 – 5.6 was a clear indicator of the effect of strong soil acidity on banana yields. At pH values less than 5.5, toxic levels of Mn, Zn, and Al may be released

(Tisdale *et al.*, 1990 and RELMA, 1999) and liming becomes paramount due to aluminium problems (Sanchez, 1976). The former authors stated that availability of primary nutrients also decreases with lowering of pH below 5.5. Henceforth, less optimal and moderate availability of macronutrients and non nutrient elements, respectively are likely causes of low bunch weight at pH less than 5.5. The pH value of 6.2 could be the optimum for banana yields in the study area given the yield of 20.4±1.3 kg. Above this value, yields did not increase despite further pH increase within favourable range. Nevertheless, Stephens (1970, cited by Nkedi-Kizza *et al.*, 2000), rate pH 6.2 as high for most crops production in Uganda; therefore heavier bunches than 20.3 kg may be attained at pH less than 6.2, if low levels of other nutrients are corrected.

5.2.5.2 Interactions of pH and/or soil exchangeable bases on yields

Based on critical levels of K cited by Landon (1991) and Walmsley *et al.* (1971), soil exchangeable K was adequate to limit banana yields. It was thus not surprising to observe no correlations of soil K concentration to yields in Butare plantations. Moreover, interpretation with critical levels for banana soils regarded as 'high' (McIntyre *et al.*, 2000) also confirms that median soil K is approximately high. Therefore, based on the 'Law of the minimum' (von Liebig, 1863), a response of yields to soil K was thus absent.

The strongest yield response (exponential phase, Figure 6a) occurred where soil Mg concentrations were less than 1.04 $cmol_+kg^{-1}$. At higher soil Mg levels, bunch weight increases were less pronounced; especially above 2.3 $cmol_+kg^{-1}$of soil Mg. The flat-phase of the curve indicated that potential yield improvements of soil Mg are not evident, largely due to cation imbalance. Soil Mg levels of 2.3 – 6.8 $cmol_+kg^{-1}$ were equivalent to 0.4 - 0.2 K/Mg ratios respectively, which exceeded the critical ratio of 0.06 - 0.125 (Lopez and Espinosa,

2000) considered optimal for banana nutrition. Bunch weight increase with soil Mg did not occur despite values being in optimal range, indicating that plant uptake of Mg was depressed due to an imbalance with soil K (Delvaux, 1995). Hence, yield limitations of soil Mg also occurred at levels (>2.3 $cmol_{+}kg^{-1}$) above the critical level.

Increase in K/Mg ratio and corresponding yield reduction with increasing pH implied that high soil K/Mg ratio hindered possible yield improvements at higher pH levels.

5.2.5.3 Influence of clay fraction on bunch weight

The strong relationship ($p < 0.05$, $R^2 = 0.87$) between bunch weight and clay content could be explained in terms of the effect of clay proportions on root penetration and soil aeration. High bunch weights were associated with soils having a lower proportion than 18.5% clay (Figure 8). Clay content less than 15% corresponds to sandy loam (FAO, 1998) soils which are well aerated. Sandy loam soil was not dominant (represented only 29% sampled locations). Therefore; it is likely that high clay contents above 23.2% created poor aeration and consequently adsorption of nutrients (particularly bivalent- Ca and Mg) in the soil (Figure 8). Mean clay content was below 35% considered to fix K^+ (Ngakanou, 1987) and entrap NH^+_4. Soils were thus of negligible K fixing power and a yield limitation due to high clay contents was mostly due to inadequate aeration and nutrient imbalance.

5.2.6 Contribution of banana pests and diseases to yields

Yield losses collectively attributed to banana pests (weevil and nematodes) and diseases were second to soil fertility factors. Banana weevil could however be the first indicator of yield constraints in Butare since weevils accounted for nearly a third of the total yield limitations. Although diseases are not a major threat *per se*, bunch weight depressions (16.9% - 21.5%) at the observed severities signify that yield losses could go up if plants with severe symptoms increased. With less than 50% plants severely affected, that is severity in fields is moderate, by BSV and more than 20% bunch weight depression, the disease is a potential constraint to yields.

5.2.6.1 Banana weevil damage levels and related-yield losses

Weevil damage to the central cylinder and corm (means = 7.4%) was well above 3% and 5%, respectively interpreted as low by Gold *et al.* (1999). Therefore, weevil damage was high in Butare plantations causing significant reductions in bunch weight and accounting for the highest yield limitations. The significant and negative correlations ($p < 0.05$) of all yield variables and weevil damage supported the postulation: weevil damage to the inner rhizome has the greatest impact on yields (Rukazambuga, 1999). The impact of high weevil damage was also illustrated by the drastic linear ($R^2 = 0.850$) decrease in bunch weight (Figure 9) which showed that weevil could grossly reduce yields in most farms. The high variability in the pest status within farms, coupled with common mat disappearance, also indicates that weevil is a more serious problem than other constraints in farms. Weevil yield-limitations quantified are in agreement with farmer's perception in the survey that this pest was the most important constraint to banana production.

5.2.6.2 Nematode damage and -related yield losses

Root mortality (23.6%) associated with nematode damage is considerably high. The necrosis of total root cortex in functional roots (6.4%) was higher than the threshhold level of 5%

root necrosis in banana plantations (Speijer *et al.*, 1994). Although nematodes caused slight damage, < 25% necrosis to plants (Gowen *et al.*, 2005), it was however surprising that slight nematode damage significantly reduced yields (Figure 10). Moreover, low nematode pressure contributed to considerable yield limitations. Bunch weight was strongly related ($R^2 = 0.765$) to nematode damage levels, suggesting that nematodes could cause significant reductions in bunch weight when the pressure is high. Considerable reductions in bunch weights with small increments of 3% in root necrosis signify the potential yield losses from nematodes. In addition to toppling which occurred at low nematode pressure, collectively indicate the significance of nematodes as potential constraints in the study plantations.

5.2.7 Influence of crop management practices on EAHB yields (*cv.* Enyeru)

Crop management practices on the farms appeared to have the least direct influence on yields of bananas. Mat spacing and leaf pruning directly influenced bunch size while above-ground biomass yield was directly affected by weed incidences.

5.2.7.1 Cultural practices affecting banana yields

Absence of clear relationships between yields and some cultural practices does not rule out the effect on yields with practices. Rather, potential effects on crop performance were obscured by both low levels of practices employed and other factors (high weevil pressure and fairly fertile soils). Weeds directly influenced biomass yield indicative of a significant correlation between weed pressure index and above-ground biomass. The reduction in above-ground biomass (ABG) by 50% in weedy mats relative to clean ones is the effect of weed competition for nutrients, water and light with crops (Zimdahl, 1999) which was pronounced at high weed pressure. Reductions in biomass yield reflect the need to better control weeds for good harvest since above ABG was highly correlated to bunch size.

The densities and duration of the major intercrops was low and short, respectively, hence competition with bananas for nutrients and water (Wallace, 1938; NARO, 1998) was probably too insignificant to affect bunch sizes. Likewise, mean mulch depths at harvest in the banana stools were too low, less than 5 cm, to directly influence bunch weight.

5.2.7.2 Influence of mat density on banana yields

Although there was no yield limitation due to high mat densities, bunch weight was highly correlated ($P < 0.05$, $R^2 = 0.904$) to plant population. Higher mat densities than 1,961 plants ha^{-1} resulted in drastic decreases in bunch weight (log-phase of the curve) owing to excessive competition for nutrients, water and light (Padian *et al.*, 2007). The mat density of 1512 (spacing at 2.6 m) gave a higher bunch weight than 1,111 (3 m by 3 m) mats per ha suggesting that optimum mat density could be attained at former spacing. The agronomic recommended spacing of bananas is 3 m by 3 m (NARO, 1998), but in view of maximising bunch weight, results above (Figure 11) demonstrate that farmers in Butare could adopt between 2.3 m and 2.7 m spacing for an additional 0.5 to 0.8 kg of bunch, respectively. Soils were adequate in most nutrients (Table 4) particularly in K; the most critical nutrient to banana yields (Turner *et al.*, 1989), thus bunch size reduction at high mat densities could primarily be attributed to reduced radiation use efficiency.

5.2.7.3 Effect of leaf pruning on EAHB yields

Linear correlation analysis indicates a moderately strong ($r > 0.4$) association between bunch weight and biomass, and the number of functional leaves at flowering. The number of functional leaves generally reflects photosynthetically active leaf area (Smithson *et al.*, 2001); therefore the increase in yields indicative of bunch weight can be attributed to proper fruit filling of photosynthates (Soto, 1985; Robinson, 1996). The initial strong increase (log-stage of the S-curve) in bunch weight indicated that there was a yield limitation due to fewer than 9 leaves compared with slight and negligible increase in the second and third upper (10-12) ranges of leaf number, respectively. Although the minimum number of functional leaves at flowering to achieve maximum yields is 12 (Robinson, 1996; Tushemereirwe *et al.*, 1996); according to the latter authors, the threshold leaf number for maximum yields may be lower than 12 in EAHB. Therefore, farmers can optimise yields (Table 11) by maintaining at least 9 leaves at flowering. Nonetheless, farmers in Butare should target to maintain up to 12 leaves at flowering because, a banana plant requires more leaf tissue than needed for maximum fruit yield for it to build a strong pseudostem, capable of supporting the bunch (Stover and Simmonds, 1987). Findings above are consistent with earlier studies (Ostmark, 1974; Pillai and Shanmugavelu, 1977; Shatyarayana, 1986) elsewhere, and rather recently (Tushemereirwe, 1996), which demonstrated that leaf pruning of bananas caused severe yield reduction. The latter author in a trial at Kawanda station reported a significant bunch weight reduction (26.5%) when leaf spots-free plants (cv. Mbwazirume) were defoliated from 4 and 2 leaves at flowering.

The number of leaves was neither related to leaf diseases, as stated by Karamura and Karamura (1995), nor to nutrient concentrations, nematode and weevil damage as suggested by Tushemereirwe (1996). The weak correlation with weed index, suggested that weed competition, induced negligible moisture and nutrient stresses which slightly affected leaf development. Reduction in the number of leaves per plant attributed to farmers' practices of deliberate defoliation (Tushemereirwe *et al.*, 1996), which was evident in the study site from personal observations. The same authors stated that most farmers remove heavily spotted leaves (yet functional) before and at flowering, for use as mulch or for wrapping food for steaming. For this study site, leaf defoliation by farmers for mainly food preparation was responsible, for low bunch weights and yield limitations.

5.3 Interactions between banana pests and diseases with soil fertility parameters

5.3.1 Pests and soil fertility status within farms

It was hypothesized that soil fertility and yield declines, and pest pressure increase moving from adjacent areas to further away from the homestead. From literature (Obiefuna, 1991; Treverrow *et al.*, 1992; Van Asten *et al.*, 2004), it was expected that weevil and nematode pressure would be low, and soil fertility would be high, near homesteads. However, as for nematode and weevil pressure, the trend was different over both absolute and relative distances from the homesteads. Although weevil damage (5.17% corm necrosis) was comparatively low (Gold *et al.*, 1999) in mid-distance areas, weevil damage did not correspond to any soil parameter in the same distance (cf. Table 4).

Contrary to Rubaihayo *et al.* (1994) who found high weevil pressure in closer than remote areas from homestead due to favourable-moist conditions, the significant increase in weevil damage with distance from the homestead could be partly attributed to surprising increase in mulch thickness and coverage away from the homesteads. Like discarded organic materials from households which favour weevil activity (Gold *et al.*, 2000), surface mulch increases soil moisture (McIntyre *et al.*, 2000) creating a humid microenvironment (Gold *et al.*, 2003), thereby explaining the observed higher weevil pressure in adjacent than remote areas of the homesteads.

The within farm interrelations of soil fertility parameters and pests were not very obvious with respect to distance from the homesteads since crop management, which varied within farms, also directly influenced the pest status.

5.3.2 Soil fertility parameters/ pests interrelationships between and within farms

Decreasing nematode damage associated with increasing levels of soil nutrients, specifically N, P and K, could be attributed to increased plant vigor and hence more tolerance to nematode attack.

The combined effects of SOM on plant vigor, that is, nutrients supply (Brady, 1990) and good water holding capacity (Stevenson, 1986) explained why nematode damage decreased with increase in SOM. The relationship of nematode necrosis and soil carbon in this study concurs with Oketch *et al.* (1996) findings from a survey in Southwest Uganda, who reported a decline in root necrosis due to nematode damage with increase in SOM.

The interrelation between nematode root necrosis and soil carbon in particular, also strongly suggests the importance of organic materials application for reducing nematode infestation in close areas from the homesteads. Heavy use of kitchen refuse could reduce the high nematode damage in close locations from the homesteads; as such wastes decompose to form organic matter and related compounds.

The strong negative relationship of soil Ca ($r > -0.5$) and leaf Ca, with root necrosis and much variation (30%) in root necrosis explained by soil Ca, supports their role in plant resistance. Calcium is required in the structural integrity of the cell wall (Marschner *et al.*, 1997) and is required in a plant's defense mechanism (Bosch *et al.*, 1996). Thus low soil Ca levels likely led to lowered resistance reflected by high nematode damage levels at low cation concentration.

Similarly, Talwana (2003) and Bamwiki (2004) suggested from study findings that host plant tolerance to nematodes could be improved by increased supply of plant nutrients, particularly soil calcium.

The relationship between soil available P and weevil damage was substantiated by Bosch *et al.* (1996) who related the role of P in the formation of *gel,* to host plant resistance against weevil attack. These findings are in agreement with those of Bosch *et al.* (1996) who reported a positive significant ($P < 0.05$, $r = 0.406$) correlation between soil P and weevil number in highland bananas in Kagera region Tanzania. Banana weevil is also sensitive to moist soil conditions (Tinzaara, 2005) besides plant nutrition (Okech and Gold, 1996). High water retention capacity is a unique property of SOM (Brady, 1990), which explains the moderately strong positive relationship ($r = 0.464$) between %SOM and weevil damage, besides supplying 50-55% soil phosphorus.

Disease expression in plants is also directly related to soil fertility (Tushemereirwe *et al.*, 1996). Therefore, the negative significant relationships between LS disease severity and soil parameters indicated increased plant vigour/ tolerance and less disease expression in vigorous plants. The severity of leaf spot diseases was hence lower on banana plants grown on more fertile soils (high levels of SOM, total N and available P) than on those on less fertile soils.

5.3.3 Influence of crop management practices on pest and disease status of EAHB

Poor crop management practices have been shown to exacerbate the effects of banana diseases (Murekezi, 2005). Detrashing and rouging are widely recommended measures for management of fungal (RELMA, 1999) and foliar (Daniell *et al.*, 2001) diseases, respectively. According to Tushemereirwe (1996), the expression of all above ground infections is affected by, among other factors, relative humidity through its effect on symptom development. Humid conditions are associated with more dry leaves appended on the plants. Older leaves acted as a barrier to radiation or air circulation, thereby increasing humidity and favored host predisposition to diseases (Fig. 15). Similarly, Kungu'u *et al.* (1992) found that poor sanitation exacerbated leaf spot diseases in highland bananas in Kenya. The significantly strong ($p < 0.01$, $R^2 = 0.803$) relationship between weed infestation and mulch depths could be interpreted as weed-growth suppression effect (Figure 14); resulting from exclusion of light for shoot growth (Zimdahl, 1999), evident in highly mulched mats. Obiefuna (1991) and Speijer *et al.* (1991) attributed increases in banana production (reduced nematode infestation and heavy bunches) to effect of mulch on weed control. Findings not only demonstrate the significance of mulching for weed control but also reflect its indirect role in enhancing banana yields (cf. Figure 13).

5.4 Fitness of boundary-line for analysis of yield responses

Much of the variance (53.1%) in the observed yields has been explained by quantified biophysical and crop management gradients. Although the r-square value is not one (not perfect), it indicates a good fit of the model. The unexplained yield gap is the contribution of unmeasured factors, for instance cultivar yield potential which perhaps limited yield improvements. It is known that bananas require large amounts of water (Robinson, 1995,

1996) and on average 25 mm of rainfall per week; equivalent to 1300 mm yr^{-1} (Purseglove, 1985) is the crop's requirement. Rainfall record at the catchment (Figure 1) is well distributed with no prolonged droughts and it is typical of most banana-growing areas in Uganda, where annual rainfall are below 1300 mm (Oketch *et al.*, 2004).. According to Oketch *et al.* (2004), >50% yield losses in EAHB occur where annual rainfall is less than 1000 mm, not typical of the study site. Further, the same authors attributed strong temporal variation in banana yields to fluctuations in rainfall with time (years). Against this background, the effect of water on yields is arguably a more temporal than spatial aspect (this study was done in one catchment), an understanding of which requires long-term data of both rainfall and yield.

The multivariate model considers each point in the field separately (Shatar and McBratney, 2004), the results are truly RD-specific; potential yields are thus a function of the most yield-limiting factors at that RD rather than basing on the whole-farm, which is a collection of varying biophysical and crop management factors.

5.5 Yield trends within and between farms from different levels of resource endowment

The observed yield improvements in rich farms compared to medium and poor wealth class farms, (Table 14) reflect differential input use due to farmer level of resource endowment (cf. Table 1a). The results also suggest that input use is only not higher but also more evenly distributed within rich farms than within medium and poor types. It was notable with the number of fingers with significantly large variation within poor farms (119, 115, 84), than medium (116,108,105) than rich ones (109, 110, 100), respectively. The number of fingers was thus a better indicator than bunch weight of yield variability within farms of different resource levels.

The above results support the study hypothesis of large within-farm variability in poor than medium and rich farms owing to higher levels of resource endowment and to uniform distribution of inputs in wealthier farms. The results also suggest the rationale for uniform distribution of inputs, especially within resource-poor farms if general yield improvements are to be realized from such farms.

5.5.1 Nutrient deficiencies in plantations of three wealth classes

Levels of foliar nutrients (except K) in plantations of all the wealth classes are below the DRIS norms established by Wortmann *et al.* (1994). The considerably higher leaf Mg and Ca in plantations of richer than the other two wealth classes, is a reflection of higher SOM (Table 1b), soil pH and bases (Table 16) partly associated to more animal manure production on the richer than on other farms. Specifically, increasing soil pH is known to partially correct a Mg deficiency (Steven, undated) by increasing Mg uptake. Together with base cations which SOM supplies (Stevenson, 1986), explain the appreciably high Mg and Ca levels in plantations of rich farms. Deficiencies of foliar P and Ca appeared more among poorer than medium and rich farms, respectively. Foliar N and Mg are however fairly balanced in plantations of poor farms with critical deficiencies of N among wealthier farms.

5.5.1 Yield limiting factors determining differences in yields among farmers from the wealth classes

Despite significant differences in soil pH between wealth classes, mean pH values (5.8, 6.2 and 6.5) are all sufficient (Lopez and Espinoza) to explain yield differences observed. Similarly, mean values of soil exchangeable Ca and Mg are well below the optimal range for good yields (Landon, 1984). However, it was evident that yield improvements in wealthier farms (Table 14) resulted from significantly higher soil Ca levels and to an extent significantly lower nematode pressure in richer farms than in poor and medium ones (Table 16). With the exception of rich farms, nematode root necrosis was higher than 5% threshhold level in banana plantations (Speijer *et al.*, 1994) of the poor and medium farms.

Differences in bunch weights could be explained by mat spacing since plant density was highly significantly greater in plantations of poor farms than in those of medium and rich ones, respectively. Spacing has a strong impact on light, water, and nutrients use by banana plants (Torquebiau and Akyeampong 1994; Pandian *et al.*, 2005). Higher plant densities in poor farms implied greater competition of especially nutrients available in low amounts (mainly Ca and Mg), thus small bunches compared to wealthier farms in which mats were well spaced.

5.6 Yield limitations within farms of different resource endowment

The incidence of yield limitations from homesteads within farms followed a trend that was dependent on farmer resource endowment. Among soil parameters, pH was a classical indicator of differential inputs (mainly soil organic inputs/wastes) use in poor farms, medium and in rich ones. Soil pH limitations occurred only in poor farms and this was supported by a mean pH value lower than that in the other two wealth classes (Table 15). The occurrence of pH limitations could be related to build-up of soil acidity which also results from decomposition of organic matter (Brady, 1990). The implication is that: the effect of dumping organic refuse (e.g. waste foods, ‘left-overs’ and other vegetable matter) was stronger in smaller farms (0.37 ha) belonging to the poor, than in large ones (0.52 and 0.61 ha) of the medium and rich classes, respectively.

Farmers in the study area mostly recycled banana residues, bunch peelings inclusive for soil fertility management and such residues are rich in K (Van Asten *et al.* (2004). Rich farms produced more residues, as they also had high yields, than medium and poor ones, respectively owing to high resource endowment, hence had the most yield limitations of K/Mg ratio.

CHAPTER SIX

6.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Highland banana yields (14.3 t $ha^{-1}yr^{-1}$) of the most dominantly grown genotype (*cv.* Enyeru) on established plantations in the study site are low. Yields in this major banana producing catchment/ valley of Butare, Ntungamo district were mostly constrained by soil fertility-related parameters contributing 60% yield limitations, pests and diseases accounted for 30% and crop management practices 10.0% of total yield limitations.

Yields, yield limitations and constraints were different between and within farms in wealth classes (rich, medium and poor) dictated by farmer resource endowment as highlighted below.

6.1 Key study findings on most important constraints

- Although soil fertility parameters collectively contributed the largest fraction of yield limitations, banana weevil (*C. sordidus* Germar Coleoptera) was the most single important (26.7% yield limitations) factor. Weevil corm necrosis (0% to 66.5%, mean = 7.4%) on plants harvested was high. Bunch weight strongly significantly ($p < 0.05$, $R^2 = 0.850$) decreased with weevil damage. From boundary line analysis (BOLIDES), the maximum and minimum bunch weight at the lowest and highest weevil damage, respectively was 22.0 kg and 9.2 kg. This was equivalent to a 54.5% reduction in bunch weight and a cash loss of UGX 1, 300 (US $ 0.764) per bunch at farm gate price. Eight mats that disappeared were heavily attacked by weevil during the monitoring study, in addition to observed stunting in infested plants.

- Soil fertility parameters which limited yields were K/Mg ratio (20.0%), pH (16.7 %), clay fraction (10.0%), exchangeable Ca (10.0%) and Ca/K+Mg+Ca ratio (3.3%), of the total limitations. Nitrogen and potassium levels were rather adequate, being well above critical values to limit yields though only N was positively significantly ($p < 0.01$, $r = 0.424$) correlated to bunch weight. Low concentrations of exchangeable bases, low soil pH, high K/Mg ratio and clay percentage, limited yield improvements. DRIS analysis indicated there were no deficiencies of K, and N imbalances, except in close areas from homesteads, and deficiencies of foliar P are more severe than of Ca and of Mg, respectively.
- At soil exchangeable Mg concentrations less than1.04 $cmol_c kg^{-1}$, the strongest yield response occurred but no yield improvements resulted despite increase in Mg levels within the optimum range. This was explained by an evident cation imbalance (high K/Mg ratio) which usually depresses uptake of soil Mg.
- The response of bunch weight to soil pH indicated that yield improvements were constrained by low pH values 5.0 – 5.6 and this was attributed to decreased availability of nutrients and partly to moderate solubility of non-nutrient elements. Although it was possible to harvest 10.2 kg at mean pH value 5.0, an increase in pH to 5.6 corresponded to a 50.0% bunch weight increase. In addition, yield improvements were enhanced with small increments in pH up to 6.4, but further increase in pH did not change soil Mg and yields. The results strongly signify liming at pH < 5.6 to overcome hindrances to yield improvements. On practical and economic points of view, farmers might not afford commercial lime but can use locally available soil amendments like wood ash to raise pH appreciably in a long run.

- Like soil pH, clay content is an equally important yield-limiting whose effects on yields can be addressed (clay fraction can not be changed). The strong decrease ($P < 0.01$, $R^2 = 0.847$) in bunch weight with increasing clay content was attributed to inadequate soil aeration. The causes (nutrient imbalance and poor aeration) of yield limiting due to high clay fraction can be improved by enhancing water infiltration through soil conservation practices.
- Yields were also limited (3.3%) by nematodes and root necrosis significantly reduced bunch weight ($p < 0.05$, $R^2 = 0.765$) and linearly decreased biomass ($p < 0.01$, $r = -0.426$) in spite of the root damage which was insignificant (< 25% root necrosis). The findings suggest that nematodes could cause significant reductions in bunch weight and other yield variables when the pressure is high. Yield limitations due to nematodes should be of a concern based on the slight damage on plant roots at bud emergence.
- Banana streak virus, black Sigatoka and leaf spot diseases depressed bunch weights by 21.5%, 17.9% and 16.9%, respectively in severely affected plants compared to disease-free ones. Only 45% and 26.7% of plants showed severe (score ***) symptoms of BSV and leaf spot diseases respectively, thus disease severity in plantations was low. The expression of these diseases was exacerbated by poor crop sanitation. Leaf rouging (indicative of cumulative dead leaves) was less frequently undertaken and disease severity was significantly influenced by the number of dead leaves hanging on the plant at harvest. The extent of leaf rouging largely depended on how often a mat was weeded, thus high levels of sanitation in plantations will be paramount in keeping disease severity at low levels.
- Among crop management practices (mulching, mat spacing, weeding, intercropping and manuring), only leaf pruning contributed to yield limitations. Spacing however

significantly strongly ($P < 0.01$, $R^2 = 0.909$) reduced bunch weights especially at high densities (2,906 – 4,933 plants ha^{-1}). Bunch weight (kg) gradually reduced as, 22.3, 22.8, 21.7 and 16.6 with decreasing mat area (increasing plant population) from 1512, 1906, 3500 and 4993 mats ha^{-1}, respectively. The mean bunch weight at 1512 mats ha^{-1} (2.6 m x 2.6 m spacing) was 0.8 kg heavier than the weight attained at 1,111 mats ha^{-1} (3.0 m x 3.0 m spacing) suggesting that the former spacing should be maintained for bunch weight maximisation.

- Yield improvements were constrained by few functional leaves at flower bud emergence. The mean bunch weight in plants with half the maximum number of 12 leaves at flowering was 58% less. However, farmers should target to maintain at least nine leaves at flower bud emergence, even for other cultivars grown than Enyeru, to optimize bunch weight. Leaf number is not used as a taxonomic tool (Karamura and Karamura, 1998). The number of leaves did not relate to foliar and fungal diseases, neither to weevil nor to nematode damage. It was however observed that farmers excessively pruned functional leaves for other domestic uses. Farmers should guard against deliberate leaf removal for other household uses and also heavy defoliation of bananas as a management practice either for disease control or for mulch material.

6.2. Key study findings on within-farm variability in yield, limitations and constraints by farmer resource endowment

- Yields were higher among rich farms than medium and poor ones, respectively, but within-farm variability of yields was larger among farms of lower resource endowment, following the order: poor > medium > rich. Banana yields in close distances from homesteads were approximately equal among farmer groups but the large within-farm variability of yields apparent in the poor and medium small-sized farms, was attributed to uneven distribution of scarce inputs which were concentrated in closer areas. Hence yields in CF were similar in all wealth classes.

- Banana weevil was a critical constraint to yield improvements among rich and medium (but not poor) farms, occurring in close distances as well in remote (for the rich) and mid-distances (for the medium) to their homesteads. Weevil limitations which occurred in only close distances from homesteads of rich farms could be interpreted as an additional impact of dumping of moist refuse (wastes/wash water, discarded foods and vegetable matter) generated from their households.
- Low soil pH and inadequate exchangeable Ca were critical constraints to yield improvements especially among poor farms, with pH limitations occurring in all relative distances and for Ca in only close distances from their homesteads. Phosphorus imbalances were larger in plantations of poor farms than in those of medium and rich ones, respectively.
- There were no yield limitations attributed to soil K in all farm types and foliar K was equally well-balanced. Only wealthier farms had high soil K/Mg ratio as an additional yield-limiting factor. Though soil Mg did not limit yields, there was however an imbalance of foliar Mg in medium farms.
- In terms of crop management, the rich and medium farms had significantly ($p < 0.001$) lower plant densities than the poor ones. Wealthier farms thus used better mat spacing although mat densities were higher (spacing was < 3 m × 3 m) in all farm categories.
- Poor farms had no yield limitation of few functional leaves at flower bud emergence unlike medium and rich ones. The former had yields limited by few leaves in MF and RF

(equivalent to 20% of respective relative distances). The rich had half of the remote areas from their homesteads with yield limitation of few functional leaves.

The survey study findings (5.1.1) revealed that the local criteria chosen by farmers for wealth classification (poor, medium and rich) were appropriate. The farm typology developed was also helpful in linking production levels to constraints. Therefore, to address some of the above constraints faced by farmers in the study area, answers should be based on farmer resource endowment as this ensures allocation of resources to most critical constraint (s).

Poor farms should invest their meager resources in soil fertility management, focusing on practices that improve soil pH and exchangeable bases. They should as well target at improving agronomic practices, specifically proper mat spacing. Rich and medium farms should allocate the higher resources endowed (in addition to returns from bunch sales) to pest control, mainly to the banana weevil which was a serious threat in both farms and nematodes in medium farms. They should complement cultural practices used with pesticides for weevil control. Proper leaf pruning should be followed by wealthier farms because few banana leaves at their farms significantly reduced bunch weight at harvest.

In a nutshell, BOLIDES revealed that banana weevil, high soil K/Mg ratio especially at low pH, low soil pH, few functional leaves at bud emergence, high clay contents, inadequate soil exchangeable Ca and its imbalance (Ca/K+Mg+Ca) are actual constraints (in order of most to least important) in the banana producing valley. The most deficient nutrient was P (and not K), followed by Ca, Mg and N, respectively. The findings indicate and suggest that nematodes, banana streak virus (Badnavirus), low soil Mg and low N, and high pH (> 6.4) are potential constraints to banana yield improvements.

study findings suggest the following future research areas:

There is need to quantify temporal variation in yields and yield loss factors.

Simple fertilizer trials with different rates of P in areas of high and low pest damage to determine optimum fertilizer P application rate and establish interactions.

Profile studies in relative distances of homesteads to explain the foliar P deficiencies despite high soil P status.

REFERENCES

Abera, A.M.K., Bagamba, F., Gold, C.S., Karamura, E.B. and Kiggundu, A.1999. Geographic shifts in the highland cooking banana (*Musa* spp., group AAA-EA). *International Journal for Sustainable Development and World Ecology* 6:45-59

Achan, L.P. 2002. Biophysical and socio-economic factors influencing soil and water conservation practices in a banana-based micro-catchment of the Lake Victoria Basin, M.Sc. Thesis, Makerere University, Kampala

Akello, Grace. 2002. The Role of Micro-Credit in Addressing Land Degradation in Uganda. In:*Policies for Sustainable Land Management in the East African Highlands.* In:. Benin, S., Pender, J. and Ehui, S. (Eds.). International Food Policy Research Institute and International Livestock Research Institute Washington, D.C. and Nairobi, Kenya:

Angeles, D.E., Summer, M.E and Lahav, E. 1993. Preliminary DRIS norms for banana. *J. Nutr.* 16: 1059-1070

Anonymous. 1962. Flora and Fauna Atlas of Uganda. Department of Lands and Surveys, Entebbe, Uganda. pp. 8-10, 22-25

Bagamba, F., Ruben, R., Kuyvenhoven, A., Kalyebara, R. Rufino, M. Kikulwe, E. and Tushemereirwe, W.K. 2004. Determinants of Resource Allocation in Low input Agriculture: The Case of Banana production in Uganda. Paper presented at the American Agricultural Economics Association Annual Meeting, Denver, Colorado, August 1-4, 2004

Bagamba, F., Karamura, E., Gold, C.S., Barekye, A., Blomme, G.,Tushemereirwe, W.K. and Tinzaara, W. 2003. Socioeconomic assessment of pest management practices in Lwengo sub-county, Uganda. In: Blomme, G., Gold, C. and Karamura, E. (Eds.). *Proceedings of the workshop on Farmer-participatory testing of IPM options for sustainable banana production in Eastern Africa*, held in Seeta, Uganda, 8-9 December 2003

Bhandari, B.B. 2003. Participatory Rural Appraisal. Module 4. Institute for Global Environmental Strategies.18p

Bananuka, J. A. and Rubahaihayo, P.R. 1994. Banana management practices and performance in Uganda. In E. Adipala, M.A. Bekunda, J.S. Tenywa, M.W. Ogenga, and J. O. Mugah (Eds.). *Proceedings of the First International of Crop Science Conference for Easten and Southern Africa,* Kampala, 14-18 June 1993 (Kampala, Uganda: African Crop Science Society), pp. 177-182

Bashaasha, B. 2001. The evolution and characteristics of farming systems in Uganda. Policies for improved land management in Uganda. Eds Jagger, P. and J. Pender. EPTD (IFPRI) workshop summary paper No. 10. p. 24-26

Batiano, A. and Mokwunye, A. Y. 1991. Role of Manures and Crop residues in alleviating Soil fertility constraints on crop production fertilizer research. 29: pp.117-125

Bwamiki, D.P. 2004. Role of plant Nutrition of Growth parameters of Banana and Supression of Populations and Damage of *Radopholus Similis*. PhD thesis. Cornell University, United States Of America

Bekunda, M.1999. Farmers' responses to soil fertility decline in banana-based cropping systems of Uganda. Managing Africa's Soils No. 4. 26p

Bekunda, M.A. and Muzira, R. 2003. Utilising cattle manure and Napier grass to rehabilitate degraded banana fields. Proceedings of the 20th Conference of the Soil Science Society of East Africa. Mbale, Uganda. pp. 293-296

Bekunda, M. 1999. Farmers' responses to soil fertility decline in banana-based cropping systems of Uganda Managing Africa's Soils No. 4 February 1999. 26 pp

Bekunda, M. and Woomer, P.L. 1996. Organic Resource Management in Banana Based Cropping Systems of Lake Victoria Basin, Uganda. *Agric Ecosystem Environ* 59:171-180p

Blomme, G. 2000. The interdependence of root and shoot development in Banana (*Musa* spp.) under field conditions and the influence of different biophysical factors on this relationship. Dissertationes de Agriclutura No.421. Faculty of Agriculture and Applied Biological Sciences, Katholeike Universiteit, Leuven. 183pp

Bosch C., Lorkeers, A., Ndile, M.R. and Sentozi, E. 1996. Diagnostic survey: constraints to banana productivity in Bukoba and Muleba districts, Kagera region, Tanzania. Working paper no. 8. Tanzania/Netherlands Farming Systems Research Project, Lake Zone. Ari Muruku, Bukoba, Tanzania. 119pp

Bosch, C., Lorkeers, A., Ndile, M. R. and Sentozi, E. 1995. Diagnostic Survey: Constraints to banana productivity in Bukoba and Muleba Districts Kagera region

Tanzania.Tanzania/Netherlands farming systems research project, Lake zone. Ari Muruku, Bukoba, Tanzania. Working paper No. 8. 119pp

Bravo, F. P., Uribe, E.G. 1981. Temperature dependence of the concentration kinetics of absorption of phosphate and potassium in corn roots. *Plant Physiology* 67, 815–819

Bwamiki, D.P. 2004. Role of plant Nutrition of Growth parameters of Banana and Supression of Populations and Damage of *Radopholus Similis*. PhD Thesis, Cornell University, United States of America

Carlier, J., De Waele, D. and Escalant, J.V. 2002. Global Evaluation of *Musa* Germplasm for Resistance to Fusarium wilt *Mycosphaerella* Leaf Spot Diseases and Nematodes. In: Vezina and Picq, C. (Eds.) INIBAP Tech Guidelines 6. Montpellier, France: 68p

Crowley, E.L., 1997. Rapid Data Collection Using Wealth Ranking and Other techniques. International Centre for Research in Agroforestry (ICRAF), Nairobi, Kenya, p. 16.

Dahal, G., Hughes, J., d' A., Thottappilly, G. and Lockhart, B.E.L. 1998b. Status of banana streak disease in Africa: Problems and future needs. *Integrated Pest Management Reviews* 3, 16-21

De Sherbinin, A., VanWey, L., McSweeney, K., Aggarwal, R., Barbieri, A., Henry, S., Hunter, L., Twine, W. and Walker, R.2007. Rural Household Micro-Demographics, Livelihoods and the Environment. A working paper IBS Population Program POP. 3: 45 p

Dildine, J. P. 1999. Triangle Explorations Heron's Formula for Calculating the Area of a Triangle www.mste.uiuc.edu/dildine/heron/triarea.html

Ellis, F. 2000. *Rural Livelihoods and Diversity in Developing Countries*. Oxford University Press: Oxford

Engels, C., Münkle, L., Marschner, H. 1992. Effect of root zone temperature and shoot demand on uptake and xylem transport of macronutrients in maize (*Zea mays* L.) *Journal of Experimental Botany* 43, 537–547

FAO, 2005. Indian Agricultural annual production. FAOSTAT data Base. Eight steps to India 8 p

FAO. 2004. Faostat agricultural data. Internet: http://apps.fao.org

FAO.2002. Food and Agricultural Organisation-Production Yearbook.56, 256p

FAO. 2001. Banana and Plantain Production FAO, 1998. Agricultural Production Statistics Database (FAOSTAT). Food and Agricultural Organization of the United Nations Rome, Italy

FAO. 1993. Year Book for Agricultural production. Food and Agricultural Organization of the United Nations Rome, Italy

FEWSNET. 2004. FEWS Uganda Food Security Update November 08 December 2004. Increased movement hampers aid efforts

Filajdi'c, N. and Sutton, T.B. 1994. Optimum sampling size for determining different aspects of Alternaria blotch of apple caused by *Alternaria mali*. Plant Dis. 78:719-724

Frison, E., and Sharrock, S. 1999. The economic, socials and nutritional importance of banana in the world. In C. Picq, E. Foure' and E.A. Frison (Eds.). *Bananas and food scurity. Proceedings of an International Symposium,* Douala, Cameroon, 10-14 November,1998 (France, Montpelilier:INIBAP) .pp.21-35

Giarcia R., Guijarro R., Diaz B. Changes in the nutritional status of banana due to the effect of potassium, on red soil in Cuba; their relations with yield and with the control of fertilizing. Potash Rev. 1980; 10:1-7.

Gichure, E., and Ondieki, J.J. 1977. A survey of banana nematodes in Kenya. Zeitschrift für pflan-zenkrankheiten und Pflanzenschutz 84, 724-728

Gold, C.S., Kagezi, G. H., Night, G. and Ragama, P.E. 2004. The effects of banana weevil *Cosmopolites sordidus*, damage on highland banana growth, yield and stand duration in Uganda. *Ann. appl. Biol.*, 145, 263-269

Gold, C.S., Pena, J. E. and Karamura, K.B. 2003. Biology and integrated pest management for the banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidea). *Integrated Pest Management Reviews*, 6, 79-155

Gold, C.S., Pinese, E. and Pena, J. E. 2002. Tropical Fruit pests and pollinators. (Eds.) Pena, J. E., Sharp, J.L. and Wysoki, M. *CAB International* 2, 13-14

Gold, C.S., Pena, J.E. and Karamura, E.B. 2001. Biology and integrated pest management for the banana weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae).Integrated PestManagement Reviews 6: 79-155

Gold, C.S., Karamura, E.B., Kiggundu, A., Bagamba, F., Abera, A.M. 1999a. Geographical shift in the highland cooking banana (*Musa* spp., group AAA-EA) production in

Uganda. *International journal of Sustainable Development and World Ecology* 6, 45-59

Gold, C.S., Karamura, E.B., Kiggundu, A., Bagamba, F., Abera, A. M.1999c. Geographical shifts in the highland cooking banana (*Musa* spp., group AAA-EA) production in Uganda. *The International Journal of Sustainable Development and World Ecology* 6, 45-56

Gold, C.S., Rukazambuga, N.D.T.M, Karamura, E. B., Nemeye, P., Night, G. 1999b. Recent advances in banana weevil biology, population dynamics and pest status with emphasis on East Africa. In Frisson, E., Gold, C.S., Karamura, E.B., Sikora, R.A (Eds.), Mobilizing IPM for sustainable banana production in Africa. *Proceedings of a workshop on banana IPM, Nelspruit*, South Africa, 23-28 Nov.1998.Montpellier, France. INIBAP. 33-50pp

Gold, C.S., Speijer, P.R., Karamura, E.B., Tushemereirwe, W.K. and Kashaija, I.N. 1994. Survey methodologies for banana weevil and nematode damage assessment in Uganda. *African Crop Sci. J.* 2: 309-321

Gold, C.S., Ogenga-Latigo, M.W., Tushemereirwe, W., Kashaija, I. and Nankinga, C. 1993. Farmer perceptions of banana pest constraints In Uganda: Results of A rapid rural appraisal: In Gold, C.S and Gemmill, B. (Eds.), Biological and integrated control of Highland banana and plantain Pests and diseases. *Proceedings of a research coordination meeting.* IITA, Ibadan

Gomez, K. A. and Gomez, A. A. 1984. Statistical Procedure for Agricultural Research. IRRI and John Wiley & Sons, New York

Gowen, S.R. and Quénéhervé , P. 1990. Nematode parasites of bananas, plantains and abaca. In M. Luc, R.A. Sikora and J. Bridge (Eds.). *Plant Parasitic Nematodes in Subtropical and Tropical Agriculture* (Wallingford, Oxon: CAB International), pp.431-460

Hartemink, A.E. 2003. Soil fertility decline in the tropics with case studies on plantations. 360 pp. ISRIC-CABI, Wallingford

Holderness, M., Tushemereirwe, W.K. and Gold, C.S. 1999. Cultural control and habitat management in integrated management of bananas leaf diseases. In: Mobilizing IPM for Sustainable Production in Africa: *Proceedings of a workshop on banana IPM* *held in Nelspruit*, South Africa held on 23-28 November 1998. Frison E.A., Gold, C.S., Karamura, E.B. and Sikora, R.A., (Ed.). 149-163. INIBAP, Montpellier, France

IITA. 2002. International Institute of Tropical Agriculture Biometric Unit: Statistical Computing and Data Analysis with SAS, Module 3. Regression-type and classification Analyses. pp 12-15

IITA Foodnet 2002. Evaluating the Marketing Opportunities for Bananas and its products in the principle banana growing countries of ASARECA. 60p

IPNI. 2008. International Plant Nutrition Institute-India Programme. Introduction to Magnesium (Mg). http://www.ipni.net/ppiweb/nwindia.nsf, retrieved on February 8, 2008

Jacome, L., Lepoivre, P., Marin, D. Ortiz, R., Romero, R. and Escalant, J.V. (Eds.). 2003. *Mycosphaerella* leaf spot diseases of bananas: present status and outlook. Proceedings of the 2nd international workshop on *Mycosphaerella* leaf spot diseases held in San José, Costa Rica, 20-23 May 2002. INIBAP, Montpellier, France. 318pp

Jones, D.R. (Ed.) 2000a. Diseases of Banana, Abacá and Enset. CABI Publishing. Wallingford, Oxon, UK. 544p

Jones B., Wolf, H., Mills, A. 1991. Plant analysis handbook, Micro-Macro Publishing, Inc., Athens, USA

Kangire, A., Karamura, E., Gold C. and Rutherford, M. 2000. *Fusarium* Wilt of Banana in Uganda, with special emphasis on Wilt-like Symptoms observed in East African Highland Cooking Cultivars *(Musas* AAA). In: *Proceedings of the First International Conference on Banana and Plantain for Africa, Uganda*

Kajumba, C., Gold, C.S., Speijer, Coyneand, P.R., Semana, D. A.K. 2002. Farmers' perceptions on the use of banana clean planting material for pest management in Uganda. Integrated pest management conference for Sub-Saharan Africa, 8-12 September 2002, Kampala, Uganda

Koppenhofer, A.M., Seshu Reddy, K.V., and Sikora, R.A. 1994. Reduction of banana weevil populations with pseudostem traps. *International journal of Pest Management*, 4, 300-304

Jones, T.M. 1986. Pests and Diseases of bananas and plantains of Trinidad and Tobago. *Journal of the Agricultural Society of Trinidad and Tobago*, 86: 18-33

Karamura, D.A., Karamura, E.B. and Gold, C.S. 1996. Cultivar distribution in major banana growing regions of Uganda. *Musa Africa*, 9, 3-5

Karamura,D.A. 1993. The strategic importance of bananas and plantains in Uganda. In C.S. Gold and B. Gemmill (Eds.). *Proceedings of a Research Coordination Meeting for Biological and Integrated Control of Highland and Plantain Pets and Diseases* Contou, Benin. 12-14 November 1991.pp. 384-397

Kashaija, I.N., McIntyre, B.D., Ssali, H. and Kizito, F. 2004. Spatial distribution of roots, nematode populations and root necrosis in highland banana in Uganda. *Nematology*, 6(1):7-12

Kashaija, I.N., Speijer, P.R., Gold, C.S. and Gowen, S.R. 1994. Occurrence, distribution and abundance of plant parasitic nematodes on bananas in Uganda. *African Crop Science Journal*, 2, 99-104

Kungu'u, J.N., Seif, A.A. and Waller, J.M. 1992. Black leaf steak and other foliage disease of bananas in Kenya. *Tropical Pest Management* 38, 359-361

Levene, H. 1960. Contributions to Probability and Statistics, pp.278–292. Stanford University Press, CA

Lahav, E., Bareicett, M. and Zamalek, P.1981. La adecuación del limbo, del nervio central y del pecíolo en la determinación nutritivos en la planta del plántano. *Fruits* 36(7-8) 417-420

Landon, J.R. 1991. Soil Suitability for Banana (*Musa Sp*). In: Brooker Tropical Soil Manual. J.R. Landon (ed.) Oxon UK: 292-293

Lufafa, A., Tenywa, M.M., Woomer, P.L., Manjaliwa, M.J.G. and Kizito, F. 2003. Towards a Decision Support System for smallholder banana management in Uganda: Modelling yield using GIS and an aggregated model. *Proceedings of the 20th Conference of the Soil Science Society of East Africa,* Mbale, Uganda. pp. 258-268

Martin-Prével P., Fisiología de la platanera, Colegio oficial de ingenieros agrónomos, Santa Cruz, Spain, 1979, 78 p

Marschner H., 1997. Mineral Nutrition of Higher Plants (2nd Edition). Academic Press Inc. Sandiego.

Masefield, G.B. 1949. The Uganda Farmer. London, Longmans. McIntyre, B.D., Speijer, P, R., Riha, S. J. and Kizito, F. 2000. Effects of mulching on biomass, nutrients, and soil water in banana inoculated with nematodes. *Agronomy Journal* 92: 1081 – 1085

cMaster, D.N. 1962. A Subsistence Crop Geography of Uganda. The world land use survey. Occasional papers No. 2. Geographical Publications Limited. Bude, Cornwall, England. 111pp

ARO. 2001. Multilocational Banana Germplasm Evaluation Trials: Third report. Unpublished Ndege, L. J., Ndile, M.R. and Bosch, C.H. 1995. Farmer's assessment of a weevil trapping trial in Ntoija village, Bukoba district. Lake Zone farming system project, Agricultural Research Institute, Makuru, Tanzania. Progress reports No.9.10pp

NARO. 1998. The Republic of Uganda: Banana Production Manual.18pp

N'gakanou, A. 1987. Etude des proprietes de charge de sols ferralliques riches en halloysite et caracterisation de leurs fractions argileuses. CNRS, CPB, Nancy Vandoeuvre, 32 pp

Ntungamo district Profile 2000.Retrieved December 10, 2006 from http://www.ugandadish.org/ntungamo.doc.

Ntungamo district Profile 2002. Retrieved March 6, 2008 from http:// www.foodnet.cgiar.org/

Nyakaana, J. and Katumwehe, A. 2005. Inception Report on the Selected Uranium Anomalies of Eastern Uganda. Geol. Surv. & Mines Dept. Entebbe, Uganda

Ministry of Agriculture Animal Industry and Fisheries (MAAIF). 2000. Plan for Modernisation of Agriculture- Eradicating Poverty in Uganda: Government Strategy and Operational Framework. MAAIF, Entebbe, Uganda

Murekezi, C. 2005. Effects of banana streak virus and crop management on the growth and yields of East African bananas (Musa spp., AAA-EA). PhD Thesis, The University of Reading, U.K. 194pp

Mutsaers, H.J.W., Weber, G. K., Walker, P. and N.M. Fisher P. 1997. A Field Guide for On-Farm Experimentation. IITA/CTA/ISNAR.pp235

Obiefuna, J.C. 1991. The effect of crop residue mulches on the yield and production of pattern of plantain (*Musa* AAB). *Biol. Agmric. Hor-tic*. 8: 77-80 alebo, J.R., Gathua, K.W., and Woomer, P.L. 2002. Laboratory Methods of Soil and Plant Analysis: A Working Manual, 2nd edition. Sacred African Publishers, Nairobi, Kenya

ech, S. H., Gold, C. S., Bagamba, F., Masanza, M., Tushemereirwe, W.K. and Ssennyonga, J. 2006. Cultural control of banana weevils in Ntungamo, southwestern Uganda. In: Blomme, G., Gold, C., Karamura, E. (Eds.). *Proceedings of the workshop on Farmer-participatory testing of IPM options for sustainable banana production in Eastern Africa*, Seeta, Uganda, 8 -9 December 2003. INIBAP: Kampala, Uganda

kech, S.H.O., Karamura, E.B., and Gold, C.S.1999. Banana IPM in Uganda. In: Frison, E.A., Gold, C.S., Karamura, E.B., and Sikora, R.A. (Eds.). *Mobilising IPM for sustainable banana production in East Africa. Proceedings of Workshop on banana IPM.* Nelspruit, South Africa, 23-28 November, 1998, pp: 225-236

)kech, S.H.O and Gold, C.S. 1996. Relationship of the banana weevil with its host plant and soil fertility; Literature review with emphasis on studies in eastern and central Africa. *The African Highland initiative Technical reports series no.2.* International Center for Research in Agroforestry. Uganda 22pp

Osiru, D.S.O. 2006. FAO Trans-boundary Agro-ecosystem Management Programme (TAMP). A report on crop/farming systems and PRA. Makerere University, Department of crop science

Okumu, M.O. 2007. On-farm interaction between soil fertility factors, farmer management, pests and diseases and their effect on banana (*Musa* species) yields in Maragua district Kenya. M.Sc. Thesis, Jomo Kenyatta University of Agriculture and Technology 91p

Pillai, O.A and Shanmugavelu, K.G.1987. Studies on the effect of the number of functional leaves on flower bud initiation in banana cultivar poovar. *Indian Journal of Horticulture* 34: 358-361

Pender, J., Place, F. and Ehui, S. 1999. Conceptual Framework and Hypotheses. 2: 31-52. www.ifpri.org/pubs/books/oc53/oc53ch02

PMA, 2000. Plan for modernisation of agriculture: Eradication of poverty in Uganda. Government of Uganda

PNB. 2007. Punjab National Bank and Agriculture Credit. Banana technical Website:

http://www.pnbkrishi.com/bananatech.htm accessed 24/01/2007

Price, N. 1995. Banana morphology - part 1: Roots and Rhizomes. In: Gowen, S.R. (Eds.). Bananas and Plantains. pp. 179-189. Chapman and Hall, London

Quénéhervé, P., Cadet, P., Mateille, T. and Topart, P. 1991. Population of nematodes in soils under banana, cv Poyo, in the Ivory Coast. 5. Screening of nematicides and horticultural results. *Revue de Nématologie*, 14, 231-249

Raghupathi, H.B., Reddy, Y.T.N., Kurian Reju, M., Bhargava, B.S. 2005. Diagnosis of Nutrient Imbalance in Mango by DRIS and PCA Approaches. *Journal of Plant Nutrition*, 27, 1131-1148

Reardon, T. and Vosti S. 1995. 'Links between rural poverty and the environment in developing countries: Asset categories and investment poverty'. *World Devt.* Vol.23, No.9, pp.1495-1506

Regional Land Management Unit (RELMA). 1999. Banana Production in Uganda: An essential food and cash Crop. RELMA Technical Handbook Series No. 18. Published by Sida's Regional Land Management Unit. 72 pp

Robinson, J.C. 1995. Systems of cultivation and management. p. 15–65. *In* S. Gowen (ed.) Bananas and plantains. Chapman and Hall, London, UK

Robinson, J.C. 1996. Bananas and plantains. CAB International, Wallingford, UK

Rubaihayo, P.R., Odongo, O.J.B. and Bananuka, J.A 1994. Some highland Banana production Constraints in Masaka District of Central Uganda. In African Crop Science Conference Proceedings; Vol.1 pp188-192. African Crop science Society, Uganda

Rufino, M. 2003. On Farm Analysis of Nematode Infestation and Soil Fertility as Constraints to the Productivity of Banana Based Production Systems in Uganda. MSc.Thesis Plant Science.Wageningen University, Netherlands. 91p

Rukazambuga, N.D.T.M., Gold, C.S. and Gowen, S.R. 1998. Yield loss in East African highland banana (*Musa* Spp., AAA-EA group) caused by banana weevil, *Cosmopolites sordidus* Germa.*Crop Protection* 17(7): 581-589

Rukazambuga, N.D.T.M., Gold, C.S. and Gowen, S.R. 2002. The influence of crop management on banana weevil, Cosmopolites sordidus Germar (Coleoptera: Curculionidae), populations and yield of highland cooking banana (cvAtwalira) in Uganda. Bulletin of entomology research: 92,413-421

Rishirumuhirwa T. 1997. Rôle du bananier dans le fonctionnement des exploitations agricoles sur les sauts plateaux de l'Afrique centrale. Thèse EPFL No. 1636. Lausanne. 321pp

SAS® 2003. Copy right © 2002 -2003 by SAS Institute Inc., cary, NC, USA. SAS® 9.1 (TSIMO)

Satyanarayana, M. 1986. Effects of the number of functional leaves on growth and yield of "Dwarf Cavendish" banana (AAA). Newsletter of the international group on horticultural physiology of banana, University of Western Australia 9: 34-36

Shahandeh, H., Hossner, L. R. and Turner, F. T. 2003. Phosphorus relationships to manganese and iron in rice soils. *Soil Science*168 (7):489-500

Ssali, H. 2006. Soil nutrient status in Uganda. A paper presented at a "Public seminar on organic Farming in Uganda; Merits and Demerits". 10th May 2006 Faculty of Agriculture, Makerere University, Kampala

Ssali, H., McIntyre, B.D., Gold, C.S., Kashaija, I.N. and Kizito, F. 2003. Effect of mulchand mineral fertilizers on crop, weevil and soil quality parameters in highland banana. *Nutrient cycling in Agroecosystems*, 65,141-150

Schnug, E., Heym, J. and Achwan, F. 1996. Establishing critical values for soil and plant analysis by means of boundary line development system (Bolides) *Commun Soil Sci. Plant Anal.*27:2739-2748

Schlecht, E. Buerkert, A., Tielkes, E. and Bationo, A. 2006. A critical analysis of challenges and opportunities for soil fertility restoration in Sudano-Sahelian West Africa. *Nutrient Cycling in Agroecosystems* 76:109–136

Seem, R. C. 1984. Disease incidence and severity relationships. *Annu. Rev. Phytopathol.* 22: 137-150

Sengooba, T. 1986. Survey of banana pest problem complex in Rakai and Masaka districts, August 1986: Preliminary trip report. Ministry of Agriculture, Namulonge Research Station, Uganda Unpublished, 10 pp

Sikora, R.A., Bafokuzara, N.D., Mbwana, A.S.S., Oloo, G.W., Uronum, B. and Seshu Reddy, K.V. 1989. Interrelationship between banana weevil, root lesion nematode and agronomic practices and their importance for banana decline in the united Republic of Tanzania. FAO *Plant Protection bulletin* 37, 151-157 ıli, H., McIntyre, B.D., Gold, C.S., Kashaija, I.N., and F. Kizito. 2003. Effects of mulch and mineral fertiliser on crop, weevil and soil quality parameters in highland banana. *Nutrient Cycling in Agroecosystems,* 65, 141-150

ıli, H. 2006. Soil nutrient status in Uganda. A paper presented at a "Public seminar on organic Farming in Uganda; Merits and Demerits". 10th May 2006 Faculty of Agriculture, Makerere University, Kampala

ewen, C.H. (undated). Soil Fertility Basics-Chapter 9. pg.56

over, R.H. and Simmonds, N.W. 1987. *Bananas.* Tropical Agricultural series, Scientific and technical, U.K, pp. 47

naling, E.M.A. 1993. Soil nutrient depletion in sub-Saharan Africa. Pp 53-57. In: Van Reuler, H. and Pins, W.H. (Eds.). The Role of Plant Nutrients for Sustainable Food Crop Production in Sub-Saharan Africa.). Dutch Association of Fertilizer Producers (VKP), Leidschendam, Netherlands

mithson, P.C., McIntyre, B. D, Gold, C. S., Ssali, H. and Kashaija I.N. 2001. Nitrogen and Potassiun Fertilizers Vs .Nemetode and Weevil Effects on Yield and Foliar Nutrient Status of Banana in Uganda. *Nutr. Cycl. Agroecosyst* 59:293-250

Smithson, P.C. and Giller, K.E. 2002. Appropriate farm management practices for alleviating N and P deficiencies in low-nutrient soils of the tropics. *Plant and Soil* 245:169-180

Smithson, P.C., McIntyre, B.D., Gold, C.S., Night, G. and S.OKech, S.O. 2004. Potassium and magnesium fertilizer on Banana in Uganda: Yields Weevil damage, foliar nutrient status and DRIS analysis. *Nutrient cycling in Agro ecosystems.* In Press

Smithson, P.C., McIntyre, B.D. Gold, C.S., Ssali, H., Night, G. and Okech, S. 2004. Potassium and magnesium fertilizers on banana in Uganda: y 69:43-49

Speijer, P.R. and De waela, D. 1997. Screening M*usa* Germplasm for Resistance and Tolerance to Nematodes, INBAP techn. Guidelines 1. INBAP, Montpellier, France. 44p

Speijer, P.R., Mudiope, J., Ssango, F. and Adipala, E. 1998. Nematode damage and densities at different plant growth stages of East African highland bananas (*Musa* AAA) cv. Mbwazirume. African Plant Protection, 4, 19-25

Speijer,P.R and Ssango,F. 1999. Evaluation of Musa host plant response Using Nematode densities and damage indices. *Nematropic*a, 29 185-192 eijer, P.R. and Kajumba, C. 2000. Yield Loss from Plant Parasitic Nematodes in East African Highland Banana (*Musa* Spp. AAA). In: Craenen, K, Ortiz, R., Karamura, E.B. and Vuyllsteke. (Eds.). Proc. Int. Symp. on Banana and Plantain for Africa. Acta Hort. (ISHS) 540: 453-459

eijer, P.R. and Dirk, D.E Waele 2001. Nematodes associated with East African Highland cooking bananas and cv. Pisang Awak (*Musa* spp.) in Central Uganda. *Nematology,* 3(6):535 -541

eguya, H., Bekunda, M.A., and Semana, A.R. 1999. Soil fertility management in banana based agriculture of Mukono district, Uganda: Farmer practices, constraints and opinions. *African Crop Sci. J.* 7(4): 1-10

even, F.J. 1991. Organic matter-micronutrient reactions in soil. In: Mortvedt, J.J., Cox, F.R., Shumen, L.M., Welch, R.M. (Eds.). Micronutrients in Agriculture, SSSA Book Series, 4, Madison. pp. 427-476

evenson, F.J. 1986. Cycles of the Soil: Carbon, Nitrogen, Phosphorus, Sulfur, Micronutrients. John Wiley and Sons. p. 110

ower, R.H. 1971. A proposed international scale for estimating intensity of banana leaf spot. *Tropical Agriculture,* Trinidad 48: 185-186

ower, R.H. and Simmonds, N.W. 1987. *Bananas*. Tropical Agricultural series, Scientific and technical, U.K, pp. 47

lwana, H.L., Spejier, P.R., Gold, C.S., Swennen, R.L., De Waele, D. 2003. A comparison of the effects of the nematodes *Radopholus similis and Pratylenchus goodeyi on growth, root heath and yield of East African highland bananas (Musa* AAA-group)

lwana, H. L. 2002. Spatial Distribution and Effect of Plant Parasitic Nematodes on Root Systems and Plant Nutritional Status of Bananas in Uganda. PhD Thesis 512. Faculty of Agriculture and Applied biological Sciences. Katholieke Universiteit Leuven, Belgium.133p

ulya, G. 2004. Topsoil depth-banana yield relationships on a chromic luvisol in a Lake Victoria basin micro-catchment. MSc thesis. Makerere University, Uganda. 72pp

dale, S.L., Werner, L.N., Beaton, J.D. 1990. (Ed.). Soil Fertility and Fertilizers 4th edition. Maxwell Macmillan Publishing Company New York.

onell, P., Vanlauwe, B., Leffelaar, P.A., Shepherd, K.D., Giller, K.E. 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya.

Within-farm variability in resource allocation, nutrient flows and soil fertility status Agriculture, *Ecosystems and Environment* 110: 166–184

othill, J.D. 1940. Agriculture in Uganda, Oxford University Press, Oxford, U.K.

orquebiau, E. and Akyeampong, E. 1994. Mieux comprendre l'effets de l'ombre –ses effets sur le haricot,le mais et la banane. *L'Agroforesterie Aujourdhui* 6(4): 17-19

urner, D.W., and Barkus, B. 1977. A comparison of leaf sampling methods in bananas. *Fruits* 32 (12) 711-721

ushemereirwe W.K.1996. Factors influencing the expression of Leafspot diseases of highland bananas in Uganda. PhD Thesis, The University of reading 197p.

ushemereirwe W.K., Karamura, E.B. and Karyeija, R. 1996. Banana strike virus (BSV) and associated filamentous virus (unidentified) disease complex of highland bananas in Uganda. *Infomusa* 5, 9-12

reverrow, N., Peasley, D. and Ireland, G. 1992. Banana weevil borer: A pest management handbook for banana growers. Banana Industry Committee. NSW Agriculture. 28 pp

BS, 2005. Uganda Bureau of Standards. Banana Production and area harvested for the period 1961-2002, in Uganda. Data compiled by Uganda Bureau of Statistics and Ministry of Agriculture, Animal Industry and Fisheries for 2005 Uganda Bureau of Standards (Uganda Bureau of Statistics and Ministry of Agriculture, Animal Industry and Fisheries) (2005), added estimates for 2003 and projections for 2004

an Asten, P.J.A., Gold, C.S.; Okech, S.H., Gaidashova, S.V., Tushemereirwe, W.K. and De Waele, D. 2004. Soil quality problems in East African banana systems and their relation with other yield loss factors. *The International Journal on Banana and Plantain* 13 (2): 20-24

anlauwe, B., Tittonel, P. and Mukalama, J. 2006. Within-farm soil fertility gradients affect response of maize to fertilizer application in western Kenya. *Nutrient Cycling in Agroecosystems* 76:171–182

on Liebig, J. 1863. The Natural Laws of Husbandry. London. Walton and Maberly. In: Shatar, T.M., McBratney, A. B.2004. Boundary-line analysis of field-scale yield response to soil properties. *Journal of Agricultural Sciences*, 142, 553-560

Wairegi, L.W.I., Van Asten, P.J.A., Kiwanuka, C., Tenywa, M. and Bekunda, M. (unpublished). Assessment of soil management practices in East African Highland cooking banana (*Musa* spp. AAA-EA) systems in Uganda. A paper presented at the

AfNet symposium: Innovations as a key to the Green revolution in Africa: Exploring the Scientific Facts, Arusha, Tanzania, September 2007

llace, C.R. 1938. Effect of cultivation on suitability of bananas to beetles borers. *The Journal of the Australian Institute of Agricultural Sciences* 4: 220-225

ller, J.M. and Eden-Green, S.G. 1998. Crop protection in food security crops: examples and lessons from developing countries. In: E.A. Frison, C.S. Gold, E.B. Karamura and R.A. Sikora (Eds.). Mobilizing IPM for sustainable banana production in Africa. *Proceedings of a workshop on banana IPM*, Nelspruit, South Africa, November 23-28. pp. 23-30

bster, R. and Oliver, M.A. 1990. Statistical Methods in Soil and Land Resource Survey.

Oxford University Press, New York

omer, P.L., Mukhwana, E.J. and Lynnam, J.K. 2002. On-farm research and operational strategies in soil fertility management. In: Vanalauwe, B., Diels, J., Sanginga, N. and Merckx R. (Eds.) Intergarted Plant Nutrient Management in Sub-Saharan Africa

ortmann, C. S. and Kaizzi, C.K. 1998. Nutrient Balances and Expected Effects of Alternative Practices in Farming Systems of Uganda. *Agric.Ecosyst Environ* 71:115-129

ke, J.Y.K., Bwamiki, D.P. and Nkwine, C. 2000. Soil Management Requirements for Banana Production on the Heavy Soils around Lake Victoria in Uganda. In: Craenen, K, Ortiz, R., Karamura, E.B. and Vuyllsteke. (Eds.). *Proc. Int. Symp. on Banana and Plantain for Africa. Acta Hort. (ISHS)* 540: 285-292

ke, J.Y.K., Nkwine, C. and Magunda, M. K. 1999. Uganda. In: Integrated Management of Sustainable Agriculture and Food Security in Southern and East Africa: Proc. of the Expert Consultation

ke, J.Y.K. 1993. Tillage Systems and Soil Properties in East Africa. Tillage Research, 27 (1993) pp. 95-104

APPENDICES

dix-1. Selected farms for monitoring study representing the biophysical variability in the study area

ID in and (No. monitoring	Farmer's name/identity and wealth class†	Slope position and class*)	Slope description (%)	Mean % Clay and (Silt)	Surface course fragments (%)	Erosion and features
12 (1)	[2]Rushaija Yowasi	Crest (*Upper*)	66.7	67.0 (23.0)	>15 (many)	Moderate (small gully)
27 (2)	[1]Byarugaba Sebastiano	Lower slope (*Lower*)	85.7	25.2 (12.4)	2 - 5 (few)	Some (rill)
19 (3)	[2]Mahatane David	Middle slope (*Middle*)	81.8	22.3 (13.6)	>15 (many)	Moderate (small gully)
30 (4)	[1]Kabegambire Jackson	Upper slope (*Upper*)	81.8	24.1 (13.7)	5 – 15‡ (common)	Moderate (small gully
3 (5)	[3]Kagaba Amburozi	Lower slope (*Middle*)	85.7	21.6 (12.6)	5 – 15‡ (common)	Moderate (small gully
53 (6)	[2]Binabaabo Fred	Middle slope (*Middle*)	85.7	20.2 (9.5)	5 – 15 (common)	Moderate (small gully
48 (7)	[2]Bankiniika Edward	Valley bottom (*Lower*)	100	20.7 (9.9)	2 (none)	Some (rill)
56 (8)	[2]Bitwiire Saphat	Upper slope (*Upper*)	81.8	28.6 (11.5)	5 – 15 (common)	Moderate (small gully
46 (9)	[2]Rwabukwiire Florence	Lower slope (*Lower*)	85.7	22.4 (7.1)	5 – 15 (common)	Moderate (small gully
42 (10)	[3]Tumushangye Dismas	Lower slope (*Middle*)	85.7	24.9 (10.2)	2 (none	Some (rill)

veyed farms (n = 50) were later grouped into three slope positions* (in italics) and three wealth classes† ([1]Poor, [2]medium and [3]rich).
rage range from observations made on plots only for farms which had 2 different plots in terms of surface fragments and erosion tures

ndix -2. ANOVA for Table 12. Pest pressure within farms as defined by relative distance to homesteads
P value > 0.05

		Sum of Squares	df	Mean Square	F	Sig.
NT_NEC	Between Groups	7.995	2	3.998	.756	.475
	Within Groups	237.979	45	5.288		
	Total	245.975	47			
EIEVIL	Between Groups	40.977	2	20.489	.837	.439
	Within Groups	1100.973	45	24.466		
	Total	1141.950	47			
NT_DDR	Between Groups	54.003	2	27.001	.402	.672
	Within Groups	3024.764	45	67.217		
	Total	3078.767	47			

pendix-3. Regression of nematode root necrosis on soil fertility factors:
L OUTPUTS EXTRACTED FROM SPSS WINDOW

ANOVA for Table 13
te P = 0.000

ANOVA(b)

del	Sum of Squares	Df	Mean Square	F	Sig.
Regression	140.757	8	17.595	4.580	.000(a)
Residual	195.923	51	3.842		
Total	336.680	59			

redictors: (Constant), DIST_KIT, EXCH_K, SOIL_PH, SILT_PCT, AVAIL_P, TTL_NITR, EXCH_CA, SOC
ependent Variable: PCNT_NEC

Multiple Regressions

Coefficients(a)

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
del	B	Std. Error	Beta		
(Constant)	6.562	4.242		1.547	.128
SOIL_PH	.216	.619	.059	.348	.729
SOC	-.249	.584	-.216	-.427	.671
TTL_NITR	12.362	9.200	.498	1.344	.185
AVAIL_P	1.072E-02	.007	.489	1.627	.110
EXCH_K	.112	.417	.040	.269	.789
EXCH_CA	-1.319	.453	-1.321	-2.911	.005
SILT_PCT	5.307E-02	.118	.103	.451	.654
DIST_KIT	-8.169E-03	.016	-.063	-.504	.617

pendent Variable: PCNT_NEC

Stepwise regressions

Model Summary

del	R	R Square	Adjusted R Square	Std. Error of the Estimate
	.557(a)	.310	.298	2.00164
	.612(b)	.375	.353	1.92128

ctors: (Constant), EXCH_CA
ctors: (Constant), EXCH_CA, TTL_NITR

Excluded Variables(c)					
	Beta In	t	Sig.	Partial Correlation	Collinearity Statistics
Model					Tolerance
SOIL_PH	-.180(a)	-1.454	.151	-.189	.766
SOC	.460(a)	1.798	.077	.232	.175
TTL_NITR	.501(a)	2.440	.018	.308	.260
AVAIL_P	.568(a)	2.250	.028	.286	.175
EXCH_K	.137(a)	1.220	.228	.159	.941
SILT_PCT	.140(a)	.904	.370	.119	.495
DIST_KIT	-.149(a)	-1.277	.207	-.167	.871
SOIL_PH	-.025(b)	-.170	.865	-.023	.528
SOC	-.001(b)	-.004	.997	.000	7.528E-02
AVAIL_P	.443(b)	1.741	.087	.227	.164
EXCH_K	.064(b)	.564	.575	.075	.858
SILT_PCT	.036(b)	.231	.818	.031	.452
DIST_KIT	-.086(b)	-.738	.464	-.098	.817

a Predictors in the Model: (Constant), EXCH_CA
b Predictors in the Model: (Constant), EXCH_CA, TTL_NITR
c Dependent Variable: PCNT_NEC

Appendix I Appendix-4. Yields from different wealth classes of farms and relative distances

```
Analysis of Variance
  The GLM Procedure
    Class Level Information

Class              Levels    Values

Wlth_class              3    1 2 3

Rel_Dist                3    1 2 3

                Number of Observations Read          48

Data for Analysis of Bunch_mass, Cluster_num Finger_num Abve_Grndbiom,
Finger_bunch    Harvest_ndex

                Number of Observations Used          47

Data for Analysis of Hght_cm, Girth_B_ and Girth_1
                Number of Observations Used          48
NOTE: Variables in each group are consistent with respect to the presence or absence of
missing values.

          General Linear Models Procedure
         Analysis of Variance
       IML OUTPUT EXTRACTED FROM THE SAS LOG
```

Appendix-4A. Factorial ANOVA and LSD Fisher's test for the Hypothesis of: no differences in yields/growth within farms from different wealth Classes

```
       H = Type III SS for farm (BLOCK) E = Error SS for Wealth Class*relative distance

NOTE: t test controls the Type I comparison wise error rate, not the experiment wise error
rate.
        Alpha                           0.05
        Error Degrees of Freedom        38

4A (i) Dependent Variable: Bunch_mass   Bunch_mass
                                         Sum of
Source                    DF        Squares    Mean Square    F Value    Pr > F
Model                      8     59.9594639      7.4949330       0.40    0.9140
Error                     38    713.5462128     18.7775319
Corrected Total           46    773.5056767

                    R-Square     Coeff Var      Root MSE    Bunch_mass Mean
                    0.077517      31.95084      4.333305           13.56241

Source                    DF    Type III SS    Mean Square    F Value    Pr > F
Wlth_class                 2     2.52555036     1.26277518       0.07    0.9351
Rel_Dist                   2    38.11022581    19.05511290       1.01    0.3721
Wlth_class*Rel_Dist        4    23.28312827     5.82078207       0.31    0.8695

                   t Tests (LSD) for Bunch_mass
```

Error Mean Square 18.77753
Critical Value of t 2.02439
Comparisons significant at the 0.05 level are indicated by ***.

Wlth_class Comparison	Difference Between Means	95% Confidence Limits	
3 - 2	0.3501	-2.7738	3.4739
3 - 1	0.6458	-2.9355	4.2271
2 - 3	-0.3501	-3.4739	2.7738
2 - 1	0.2958	-2.8281	3.4196
1 - 3	-0.6458	-4.2271	2.9355
1 - 2	-0.2958	-3.4196	2.8281

4A (ii) Dependent Variable: Cluster_number

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	3.81195911	0.47649489	0.65	0.7321
Error	38	27.91834821	0.73469337		
Corrected Total	46	31.73030733			

R-Square	Coeff Var	Root MSE	Cluster_num Mean
0.120136	11.59301	0.857143	7.393617

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Rel_Dist	2	2.77879548	1.38939774	1.89	0.1648
Wlth_class	2	0.05940803	0.02970402	0.04	0.9604
Wlth_class*Rel_Dist	4	1.48467683	0.37116921	0.51	0.7321

t Tests (LSD) for Cluster_number
Error Mean Square 0.734693
Critical Value of t 2.02439
Comparisons significant at the 0.05 level are indicated by ***.

Wlth_class Comparison	Difference Between Means	95% Confidence Limits	
3 - 2	0.03539	-0.58253	0.65330
3 - 1	0.09861	-0.60978	0.80700
2 - 3	-0.03539	-0.65330	0.58253
2 - 1	0.06322	-0.55469	0.68114
1 - 3	-0.09861	-0.80700	0.60978
1 - 2	-0.06322	-0.68114	0.55469

4A (iii) Dependent Variable: Finger_number

Source	DF	Squares	Sum of Mean Square	F Value	Pr > F
Model	8	3954.50768	494.31346	1.01	0.4430
Error	38	18548.06784	488.10705		
Corrected Total	46	22502.57552			

R-Square	Coeff Var	Root MSE	Finger_num Mean
0.175736	20.62463	22.09314	107.1202

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Rel_Dist	2	3014.991734	1507.495867	3.09	0.0572
Wlth_class	2	46.795072	23.397536	0.05	0.9533
Wlth_class*Rel_Dist	4	1188.637398	297.159349	0.61	0.6588

t Tests (LSD) for Finger_num
Error Mean Square 488.107
Critical Value of t 2.02439
Comparisons significant at the 0.05 level are indicated by ***.

Wlth_class Comparison	Difference Between Means	95% Confidence Limits	
2 - 3	1.756	-14.171	17.683
2 - 1	2.203	-13.724	18.130
3 - 2	-1.756	-17.683	14.171
3 - 1	0.447	-17.812	18.706
1 - 2	-2.203	-18.130	13.724
1 - 3	-0.447	-18.706	17.812

4A (iv) Dependent Variable: Above-Ground biomass

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	58.2723568	7.2840446	0.77	0.6328
Error	38	360.4768544	9.4862330		
Corrected Total	46	418.7492112			

R-Square	Coeff Var	Root MSE	Abve_Grndbiom Mean
0.139158	36.26691	3.079973	8.492516

rce	DF	Type III SS	Mean Square	F Value	Pr > F
_Dist	2	12.53828043	6.26914022	0.66	0.5222
h_class	2	30.66631913	15.33315956	1.62	0.2120
h_class*Rel_Dist	4	20.33448475	5.08362119	0.54	0.7102

t Tests (LSD) for Abve_Grndbiom
Error Mean Square 9.486233
Critical Value of t 2.02439
Comparisons significant at the 0.05 level are indicated by ***.

Wlth_class Comparison	Difference Between Means	95% Confidence Limits	
3 - 1	0.7055	-1.8400	3.2509
3 - 2	1.8718	-0.3486	4.0921
1 - 3	-0.7055	-3.2509	1.8400
1 - 2	1.1663	-1.0541	3.3866
2 - 3	-1.8718	-4.0921	0.3486
2 - 1	-1.1663	-3.3866	1.0541

(v) Dependent Variable: Finger_bunch ratio

rce	DF	Sum of Squares	Mean Square	F Value	Pr > F
el	8	0.01423226	0.00177903	0.67	0.7137
or	38	0.10078740	0.00265230		
rected Total	46	0.11501967			

R-Square	Coeff Var	Root MSE	Finger_bunch Mean
0.123738	5.703962	0.051500	0.902890

rce	DF	Type III SS	Mean Square	F Value	Pr > F
_Dist	2	0.00393953	0.00196976	0.74	0.4826
h_class	2	0.00388064	0.00194032	0.73	0.4878
h_class*Rel_Dist	4	0.00459733	0.00114933	0.43	0.7837

t Tests (LSD) for Finger_bunch
Error Mean Square 0.002652
Critical Value of t 2.02439
Comparisons significant at the 0.05 level are indicated by ***.

Wlth_class Comparison	Difference Between Means	95% Confidence Limits	
1 - 3	0.00158	-0.04098	0.04415
1 - 2	0.01788	-0.01924	0.05501
3 - 1	-0.00158	-0.04415	0.04098
3 - 2	0.01630	-0.02082	0.05343
2 - 1	-0.01788	-0.05501	0.01924
2 - 3	-0.01630	-0.05343	0.02082

(vi) Dependent Variable: Harvest_index

rce	DF	Sum of Squares	Mean Square	F Value	Pr > F
el	8	0.01774810	0.00221851	0.54	0.8226
or	38	0.15756740	0.00414651		
rected Total	46	0.17531550			

R-Square	Coeff Var	Root MSE	Harvest_ndex Mean
0.101235	16.42938	0.064393	0.391941

rce	DF	Type III SS	Mean Square	F Value	Pr > F
_Dist	2	0.00454383	0.00227191	0.55	0.5827
_class	2	0.00530353	0.00265177	0.64	0.5331
_class*Rel_Dist	4	0.00668337	0.00167084	0.40	0.8053

t Tests (LSD) for Harvest_ndex
Error Mean Square 0.004147
Critical Value of t 2.02439
Comparisons significant at the 0.05 level are indicated by ***.

Wlth_class Comparison	Difference Between Means	95% Confidence Limits	
1 - 2	0.01309	-0.03333	0.05951
1 - 3	0.02966	-0.02356	0.08288
2 - 1	-0.01309	-0.05951	0.03333
2 - 3	0.01657	-0.02985	0.06299
3 - 1	-0.02966	-0.08288	0.02356

(vii) Dependent Variable: Height_cm

urce	DF	Sum of Squares	Mean Square	F Value	Pr > F
del	8	6873.65914	859.20739	1.11	0.3774
or	39	30170.73438	773.60857		
rected Total	47	37044.39352			

R-Square	Coeff Var	Root MSE	Hght_cm Mean
0.185552	7.622545	27.81382	364.8889

rce	DF	Type III SS	Mean Square	F Value	Pr > F
_Dist	2	5660.852894	2830.426447	3.66	0.0350
_class	2	39.086806	19.543403	0.03	0.9751
_class*Rel_Dist	4	991.806424	247.951606	0.32	0.8625

t Tests (LSD) for Hght_cm

Error Degrees of Freedom	39
Error Mean Square	773.6086
Critical Value of t	2.02269

Comparisons significant at the 0.05 level are indicated by ***.

Wlth_class Comparison	Difference Between Means	95% Confidence Limits	
2 - 1	0.215	-19.675	20.106
2 - 3	2.146	-17.745	22.036
1 - 2	-0.215	-20.106	19.675
1 - 3	1.931	-21.037	24.898
3 - 2	-2.146	-22.036	17.745
3 - 1	-1.931	-24.898	21.037

Means with the same letter are not significantly different.

t Grouping		Mean	N	Rel_Dist
	A	379.016	16	1
	A			
B	A	363.563	16	2
B				
B		352.089	16	3

(viii) Dependent Variable: Girth_Base

ce	DF	Sum of Squares	Mean Square	F Value	Pr > F
l	8	592.594213	74.074277	1.27	0.2848
r	39	2267.045764	58.129379		
ected Total	47	2859.639977			

R-Square	Coeff Var	Root MSE	Girth_B_ Mean
0.207227	9.927335	7.624262	76.80069

ce	DF	Type III SS	Mean Square	F Value	Pr > F
Dist	2	377.3527824	188.6763912	3.25	0.0497
_class	2	154.0396528	77.0198264	1.32	0.2775
_class*Rel_Dist	4	43.7006597	10.9251649	0.19	0.9433

t Tests (LSD) for Girth_B_

Error Degrees of Freedom	39
Error Mean Square	58.12938
Critical Value of t	2.02269

Comparisons significant at the 0.05 level are indicated by ***.

Wlth_class Comparison	Difference Between Means	95% Confidence Limits	
2 - 3	2.310	-3.143	7.762
2 - 1	4.287	-1.165	9.740
3 - 2	-2.310	-7.762	3.143
3 - 1	1.978	-4.318	8.274
1 - 2	-4.287	-9.740	1.165
1 - 3	-1.978	-8.274	4.318

s with the same letter are not significantly different.

t Grouping		Mean	N	Rel_Dist
	A	80.450	16	1
	A			
B	A	76.509	16	2
B				
B		73.443	16	3

(ix) Dependent Variable: Girth_1m

rce	DF	Sum of Squares	Mean Square	F Value	Pr > F
el	8	280.143744	35.017968	0.85	0.5687
or	39	1614.156806	41.388636		
rected Total	47	1894.300550			

R-Square	Coeff Var	Root MSE	Girth_1 Mean
0.147888	11.87880	6.433400	54.15868

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Dist	2	171.7956991	85.8978495	2.08	0.1391
Class	2	75.7133507	37.8566753	0.91	0.4091
Class*Rel_Dist	4	29.1258681	7.2814670	0.18	0.9495

t Tests (LSD) for Girth_1

Error Degrees of Freedom 39

Error Mean Square 41.38864

Critical Value of t 2.02269

Wlth_class Comparison	Difference Between Means	95% Confidence Limits	
2 - 3	2.212	-2.388	6.813
2 - 1	2.753	-1.848	7.353
3 - 2	-2.212	-6.813	2.388
3 - 1	0.540	-4.772	5.853
1 - 2	-2.753	-7.353	1.848
1 - 3	-0.540	-5.853	4.772

Error Mean Square 773.6086

Critical Value of t 2.02269

Least Significant Difference 19.89

Means with the same letter are not significantly different.

t Grouping		Mean	N	Rel_Dist
	A	56.366	16	1
	A			
B	A	54.406	16	2
B				
B		51.704	16	3

Error Mean Square 41.38864

Critical Value of t 2.02269

Least Significant Difference 4.6007

Appendix 4B: t Tests (LSD) for yield (dependent Variable) variability within farms

Error Degrees of Freedom 38

Alpha 0.05

Comparisons significant at the 0.05 level are indicated by ***.

Bunch_mass

Error Mean Square 18.77753

Critical Value of t 2.02439

Rel_Dist Comparison	Difference Between Means	95% Confidence Limits	
1 - 2	0.372	-2.781	3.525
1 - 3	1.951	-1.150	5.053
2 - 1	-0.372	-3.525	2.781
2 - 3	1.579	-1.574	4.732
3 - 1	-1.951	-5.053	1.150
3 - 2	-1.579	-4.732	1.574

ii) Cluster_number

Error Mean Square 0.734693

Critical Value of t 2.02439

Rel_Dist Comparison	Difference Between Means	95% Confidence Limits	
1 - 2	0.2367	-0.3870	0.8603
1 - 3	0.5312	-0.0822	1.1447
2 - 1	-0.2367	-0.8603	0.3870
2 - 3	0.2946	-0.3290	0.9182
3 - 1	-0.5312	-1.1447	0.0822
3 - 2	-0.2946	-0.9182	0.3290

iii) Finger_number

Error Mean Square 488.107

Critical Value of t 2.02439

Rel_Dist Comparison	Difference Between Means	95% Confidence Limits		
1 - 2	3.773	-12.301	19.847	
1 - 3	17.526	1.713	33.339	***
2 - 1	-3.773	-19.847	12.301	

2 - 3	13.753	-2.321	29.827	
3 - 1	-17.526	-33.339	-1.713	***
3 - 2	-13.753	-29.827	2.321	

Above_Groundbiomass

Error Mean Square 9.486233
Critical Value of t 2.02439

Rel_Dist Comparison	Difference Between Means	95% Confidence Limits	
2 - 1	0.487	-1.754	2.728
2 - 3	1.053	-1.188	3.294
1 - 2	-0.487	-2.728	1.754
1 - 3	0.566	-1.638	2.771
3 - 2	-1.053	-3.294	1.188
3 - 1	-0.566	-2.771	1.638

inger_bunch ratio

Error Mean Square 0.002652
Critical Value of t 2.02439

Rel_Dist Comparison	Difference Between Means	95% Confidence Limits	
1 - 3	0.01339	-0.02348	0.05025
1 - 2	0.02769	-0.00978	0.06516
3 - 1	-0.01339	-0.05025	0.02348
3 - 2	0.01431	-0.02316	0.05177
2 - 1	-0.02769	-0.06516	0.00978
2 - 3	-0.01431	-0.05177	0.02316

Harvest_index

Error Mean Square 0.004147
Critical Value of t 2.02439

Rel_Dist Comparison	Difference Between Means	95% Confidence Limits	
1 - 2	0.01575	-0.03110	0.06260
1 - 3	0.02668	-0.01941	0.07277
2 - 1	-0.01575	-0.06260	0.03110
2 - 3	0.01092	-0.03593	0.05777
3 - 1	-0.02668	-0.07277	0.01941
3 - 2	-0.01092	-0.05777	0.03593

...dix-4C. Variation in banana yields within-farms of different resource endowments (wealth classes):

General Linear Model Procedure
The ANOVA Procedure (Factorial ANOVA)

Levene's Test for Homogeneity of yields for the Hypothesis of no equal variability within farms of different wealth classes
ANOVA of Squared Deviations From Group Means

H = Type III SS for Wealth Class E= wealth Class and relative distance

...: The within-farm variability in a dependent variable or yield is the one compared ...een groups
...: 1, 2 and 3 stand for poor, medium and rich wealth classes

...nch_mass Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Wlth_class	2	700.5	350.3	1.53	0.2274
Error	44	10058.5	228.6		

Level of Wlth_class	N	Mean	Std Dev
	-----------Bunch_mass--------		
1	12	13.2527778	4.59109581
2	23	13.5485507	4.37420891
3	12	13.8986111	3.27793132

Cluster_number Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Wlth_class	2	4.5335	2.2667	3.52	0.0383
Error	44	28.3704	0.6448		

Level of Wlth_class	N (Cluster_number)	Mean	Std Dev
1	12	7.33750000	1.12515150
2	23	7.40072464	0.79882297
3	12	7.43611111	0.58039665

Finger_number Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Wlth_class	2	1992506	996253	2.75	0.0747
Error	44	15918636	361787		

l of _class	N (Finger_num)	Mean	Std Dev
1	12	105.927778	25.6151947
2	23	108.131159	24.9763476
3	12	106.375000	11.7311842

Above_Ground biomass Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Wlth_class	2	682.6	341.3	2.68	0.0796
Error	44	5600.6	127.3		

el of th_class	N (Above_Ground biomass)	Mean	Std Dev
1	12	8.88313001	4.01134649
2	23	7.71684000	2.45218249
3	12	9.58861469	2.68619876

Finger_bunch ratio Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Wlth_class	2	682.6	341.3	2.68	0.0796
Error	44	5600.6	127.3		

el of _class	N (Finger_bunch ratio)	Mean	Std Dev
1	12	0.91204538	0.02184100
2	23	0.89416137	0.06239681
3	12	0.91046322	0.04335052

Harvest_index Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Wlth_class	2	0.000547	0.000273	1.77	0.1824
Error	44	0.00680	0.000155		

el of h_class	N (Harvest_index)	Mean	Std Dev
1	12	0.40592011	0.10149224
2	23	0.39282869	0.04091603
3	12	0.37625885	0.04249399

vii. Height_cm Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Wlth_class	2	2047222	1023611	1.04	0.3623
Error	45	44352465	985610		

Level of Wlth_class	N (Hght_cm)	Mean	Std Dev
1	12	365.263889	6.06481338
2	24	365.479167	7.36212398
3	12	363.333333	3.90064826

viii. Girth_Base

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Wlth_class	2	30919.0	15459.5	2.44	0.0985
Error	45	284910	6331.3		

Level of Width_class	---------Girth_Base-------- N	Mean	Std Dev
1	12	74.1625000	6.55201459
2	24	78.4500000	9.20184292
3	12	76.1402778	5.09797176

Girth_1m

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Wlth_class	2	11827.5	5913.7	2.68	0.0797
Error	45	99404.6	2209.0		

Level of Width_class	----------Girth_1--------- N	Mean	Std Dev
1	12	52.6472222	6.06481338
2	24	55.4000000	7.36212398
3	12	53.1875000	3.90064826