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Drivers of soil fertility in smallholder banana systems in the African Great Lakes Region

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Si tu supportes la fumée, tu te réchaufferas avec la braise...

Proverbe africain

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Foreword

The chapters of this dissertation are structured as papers, in the hope of submission of some of them to peer review journals. I would like to apologize to the reader for the inconvenience caused by the redundancies among the chapters dictated by this kind of presentation.

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Summary

East African Highland banana (*Musa spp.* AAA-EA) is a crop of major importance in the African Great Lakes Region, because of the food and cash it provides to about 85 % of the population. Bananas are produced in low input smallholder farms. Low yields are mainly attributed to (1) poor soil fertility and limited input use, (2) drought or irregular rainfall, (3) pests and diseases and (4) inappropriate management practices. Most of the studies addressing these constraints are geographically limited, conducted under controlled conditions and mainly focused on pests since those are often perceived as most important constraints by farmers. Studies that cover larger geographical areas and make the effort to rank constraints and quantify associated yield losses are rare. Although low soil fertility is recognized as one of the problems, there is little understanding on the temporal and spatial variation of the different nutrient pools in the soil. Knowledge also lacks on the extent to which the limited reserves and maintenance of soil fertility relate to the mineralogical and organic components of the soil.

This study is largely based on observations on plants, crop management, pests and soils in four agro-ecoregions, three in Rwanda (Butare, Kibungo and Ruhengeri) and one in South-Western Uganda (Ntungamo). Soil data from an additional area in Central Burundi further contributes to capture the diversity of the East African Highland banana-based system.

To get a general overview of the constraints faced by smallholder banana producers a Boundary Line Analysis (BLA) is performed on the available plant, crop management, pest and soil data. The BLA shows that the gap between actual production and attainable yield may attain 70-96%. Ranking the constraints, BLA highlights that poor soil fertility is an overall problem in the region. The question of soil fertility and possible associated nutritional disorders is further investigated by relying on commonly used approaches to interpret tissue analyses (critical nutrient values and sufficiency ranges, Diagnosis and Recommendation Integrated System (DRIS) and Compositional Nutrient Diagnosis (CND)). Those approaches show that K deficiencies are an overall problem in Rwanda, followed by Mg. In Ntungamo (SW Uganda), yields are limited by P. Comparisons at various scales further indicate that banana production does not only vary at regional scale in function of soils and parent materials, but also changes at inter-regional or intra-farm level. Besides an assessment of the geographical spread of specific nutritional disorders, this study also contributes to future research and communication with farmers and extension officers, by providing new critical nutrient values, sufficiency ranges and norms against which to interpret plant foliar data.

The second part of this study focuses more in-depth on the soil characteristics and processes. Since no quantified data are available for organic matter amendments, soil phosphorus is used as tracer of human activities. Verifying a series of conditions when using the tracer, differences in total phosphorus contents or phosphorus fractions are interpreted in terms of intra-farm differential management of organic matter. Phosphorus hence seems to indicate the existence of management gradients in farms of Butare and Ntungamo, while practices seem more uniform in Kibungo and Ruhengeri. In order to evaluate the human imprint on soil fertility, organic matter and soil minerals are evaluated as nutrient providers and contributors to the cation exchange capacity of the soil. These analyses quantify soil mineral abundances and emphasize the key role of organic matter in maintaining soil fertility.

General introduction

General context and research needs

The East African Great Lakes Region includes Rwanda, Burundi, Uganda, the Kivu Provinces of Democratic Republic of Congo (DRC), Southwestern Kenya and Northwestern Tanzania. Agriculture is the backbone of the economy in the region insuring food and income of 81-89% of the populations (FAOstat online, estimates for 2010). In the last decades, demographic growth and the ensuing constraint on land availability increasingly led to occupation of marginal land, land fragmentation and intensification of agriculture (Clay et al., 1998). The average farm size is now usually less than 1 or 2 ha. The land of traditional farms is fragmented in different plots, with food and cash crops covering the major part of the surface. Farmers rely almost exclusively on traditional techniques (rudimentary tools, no machinery, no animal draft power, no or rare inorganic fertilizer) to manage their fields.

Amongst all the crops grown, the East African Highland Banana is of particular importance as a food and a cash crop. Despite the management efforts of smallholder farmers, reported on-farm banana yields are low (5-30 $t.ha^{-1}.year^{-1}$) and well below the potential yields obtained in research stations or plantations (40-70 $t.ha^{-1}.year^{-1}$) (Bekunda et al., 2004; van Asten et al., 2004). Low yields are mainly attributed to poor soil fertility and limited input use, drought or irregular rainfall, pests and diseases and inappropriate management practices. Most studies identifying these constraints suffer the disadvantages of (1) being geographically restricted, (2) conducted in research stations under artificially induced and controlled conditions, and (3) focused only on those single constraints that farmers perceive as most important. Comprehensive quantification and ranking of yield constraints are efforts only rarely undertaken (Wairegi et al., 2010).

Low inherent soil fertility and decline of soil fertility because of export of produce and transfers of biomass are cited amongst the banana yield constraints (Bekunda and Woomer, 1996; Ssali, 2001; Okech et al., 2004; Wairegi et al., 2010). It is widely accepted that old soils contain only small amounts of weatherable minerals, but studies focusing on soil mineralogy and the capacity of soils to supply plant nutrients are scarce or non-existent for the region. Studies in Kenya, Tanzania and Uganda, pinpoint the key role of soil organic matter in maintaining soil fertility. The existence of soil fertility gradients is recognized and attributed to differential management by farmers (e.g. Baijukya and De Steenhuysen Piters, 1998; De Jager et al., 1998; Van den Bosch et al., 1998; Wortmann and Kaizzi, 1998; Bekunda and Manzi, 2003). Nutrient fluxes and balances related to biomass transfers are often calculated at regional, intra-farm or plot scale. However, the impact of traditional soil management practices on soil fertility is largely lacking, particularly for Rwanda or Burundi. Also, current crop and soil management practices do not always take into account the soil gradients that resulted from the past management of these fields. A global understanding of the influence of past or present management on soil fertility and consequently crop production would be a step forward when addressing the question of how limited inputs should best be used in order to insure productivity and sustainability of these banana-based farming systems.

Main objectives and outline of the dissertation

This study is largely based on observations on plants, crop management, pests and soils in three agro-ecoregions in Rwanda (Butare, Kibungo and Ruhengeri, Figure A) and one in South-Western Uganda (Ntungamo, Figure A). These sites have been part of earlier research efforts in the framework of the project led by the Consortium for Improving Agriculture-based Livelihoods in Central Africa (CIALCA). This consortium brings together scientists and extension partners from these target countries, the International Institute of Tropical Agriculture (IITA) and the Université Catholique de Louvain (UCL), amongst others (see www.cialca.org). The sites differ in altitude, rainfall and their soils developed on contrasting parent materials. In addition to the sites in Rwanda and Uganda, some of the soil characterization work occurred in Gitega (Central Burundi, Figure A) where other CIALCA colleagues conducted some additional work (see Nibasumba, 2008; Gaidashova, 2009). Soil data for this additional area, known for its banana-based agriculture, thus further contributed to capture the diversity of the East African Highland banana-based system. The data collected over the various sites, although complementary, differed in nature (regional distribution of soil data, soil profiles, plant and management data). This explains that in the chapters of this dissertation, not all the data of all the sites will systematically be studied altogether.

Largely based on plant, crop management and soil data from these sites, this thesis tries to answer the following research questions:

1. What are the major constraints on banana yields in those regions? If constraints vary, are differences then caused by variations in agro-ecological conditions or management practices?

2. To what extent is soil fertility a production constraint and how do soil properties vary across the sites?

3. Do soil fertility differences appear at farm level? And if so, can they be related to farm management practices as has been shown in other smallholder farming systems in the region?

4. To what extent does soil organic matter content and management determine the fertility and productivity of these soils?

5. Can soil mineral abundances be assessed in order to evaluate plant nutrient reserves and nutrient release by weathering?

Chapter 1 is a literature overview on the banana-based system in the African Great Lakes Region, the constraints faced by farmers and the challenges to be met. In the first part of this study (**Chapters 2, 3 and 4**), banana-plants are used as indicators of the quality of the production environments. Using a Boundary Analysis including soil chemical characteristics, crop management practices and incidence of major pests, **Chapter 2** attempts to identify and rank the yield constraints in the various regions. Yield losses due to these different constraints are quantified. Comparisons at regional and intra-regional scale are made. The calculation of soil quality indices allows comparisons on an even smaller scale: at farm level. **Chapter 3** compares four approaches commonly used to interpret plant tissue analyses for their ease of use and their ability to identify nutrient imbalances. The approach recommended is then used in **Chapter 4** to identify possible nutrient deficiencies or imbalances at various scales. The second part of his study (**Chapters 5, 6, 7**) focuses more in-depth on the soil characteristics and processes. **Chapter 5** focuses on soil phosphorus and its geochemical (labile, moderately labile, and non-labile) fractions to trace the differential management so often invoked to explain fertility gradients in smallholder farms. In **Chapter 6**, we try to develop a tool to quantify soil mineral abundances and compare this tool to X-Ray Diffractometry commonly used to assess soil mineral stocks. In **Chapter 7** we then compare soil minerals and organic matter as sources of plant nutrients, by weathering or mineralization, and as contributors to the soil cation exchange capacity.

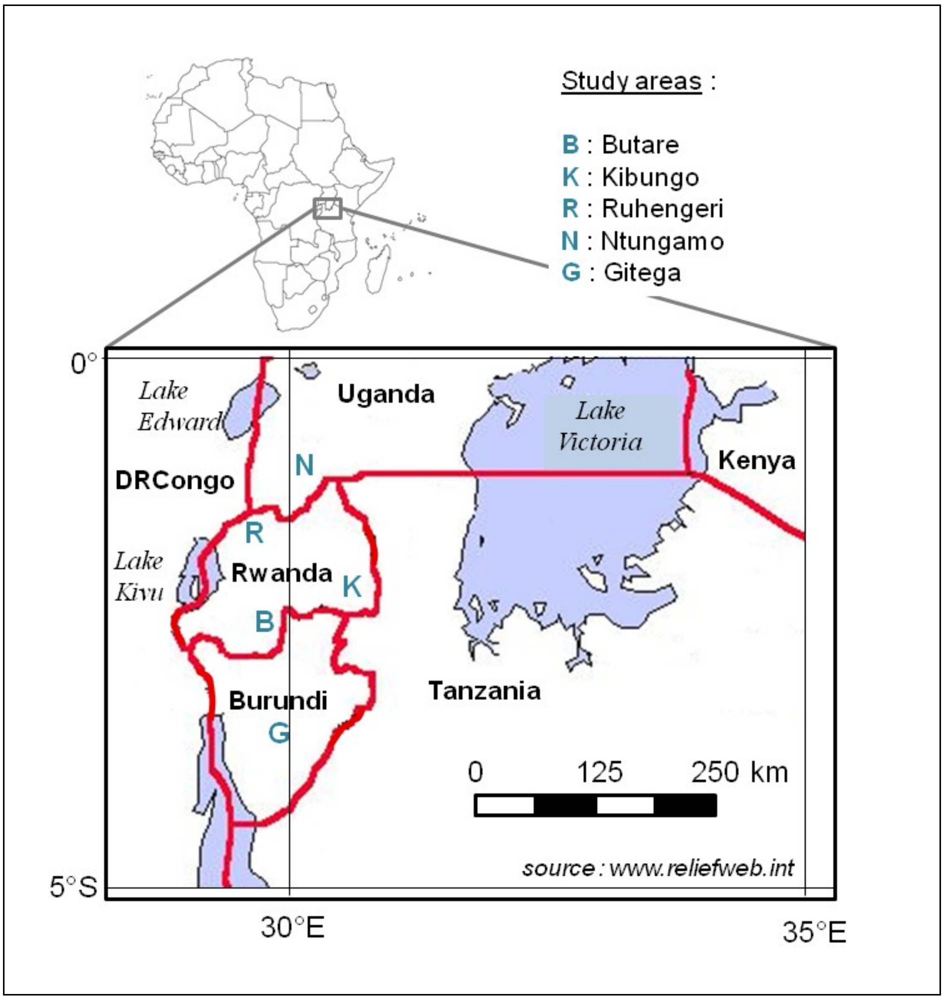

Figure A. Map situating the five regions of interest to this study: Butare, Kibungo, Ruhengeri in Rwanda, Ntungamo in the South-Western part of Uganda and Gitega in Central Burundi.

Introduction

Context of the study

Chapter 1. Introduction

1.1. Physical environment

The Great Lakes Region is a region the in central-eastern part of African, extending over Rwanda, Burundi, the Southern part of Uganda, the Eastern Province of the Democratic Republic of Congo, South-West of Kenya and Northern Tanzania. The great lakes referred to are Lake Edward, Lake Victoria, Lake Kivu and Lake Tanganyika (Figure 1.1). Plateaus, mountains, valleys, wide or narrow valley bottoms and a thousand hills constitute the landscape. Altitude stretches from 1200-2000 meters above sea-level (m*asl*) in the central plateaus to more than 3000 m*asl* in the mountain ranges of the Western Rift System (Figure 1.1.A; FAO, 2005a). The overall altitude over 1200 m*asl* justifies the common name of "African Highlands".

Climate changes slightly regionally, depending on altitude, wind-regimes and rainfall (Davies, 1995; Place et al., 2006). It is equatorial in Uganda, tropical in the West of Burundi near Lake Tanganyika, and moderate tropical in the highlands of Rwanda. Rain is distributed two periods, annual precipitation varying between 800-900 $mm.year^{-1}$ in Eastern parts of Rwanda and Burundi and 2000 $mm.year^{-1}$ in the high altitude region of Western Rwanda or around Lake Victoria. Mean annual temperatures are about 20°C (FAO, 2005a).

Proterozoic pelitic and quartzitic rocks metamorphosed in the greenschist or amphibolite facies, and granite or gneiss complexes, underlie most of the Region. Cenozoic volcanic rocks associated to Rift activities occur in the west of Uganda and Rwanda and in the Eastern Province of Congo. Tertiary to Recent sediments fill parts of the Rift system and major river beds

(Gérards and Ledent, 1970; Fernandez-Alonso et al., 1986; Baudet et al., 1988; Van Straaten, 2002; Schlüter, 2008). Except for soils developed on alluvium or forming from Cenozoic volcanic rocks, soils are old and highly weathered. Deeply weathered Ferralsols and Acrisols and also Nitisols are among the major soil types found in the Region (Figure 1.1.B; Eledu et al., 2004; Bouwmeester et al., 2009). They have low nutrient reserves and can show Al or Mn toxicities (Bationo et al., 2006).

Large parts of the land are permanent cultures and arable land: 32% for Uganda, 48% for Burundi and 60% for Rwanda (FAOstat online, data for 2007). Agricultural expansion to respond to population growth, takes toll on meadows, pasture and forests. In Uganda, water bodies and marshes occupy 18% of the total country area (FAOstat online: estimates and calculated data for 2007).

1.2. A young and growing population

According to the statistics provided online by the FAO, the African Great Lakes Region is presently home to 70 million people (FAOstat online, estimates for 2010). Populations are young (75% are younger than 30 (FAOstat online, data for 2004-2006)) and still growing, predicted to double by 2050 (FAOstat online). With respectively 390 ha/km² and 306 ha/km² (FAOstat online, data for 2010), Rwanda and Burundi are amongst the five most densely populated countries in the world (FAO, 2005a).

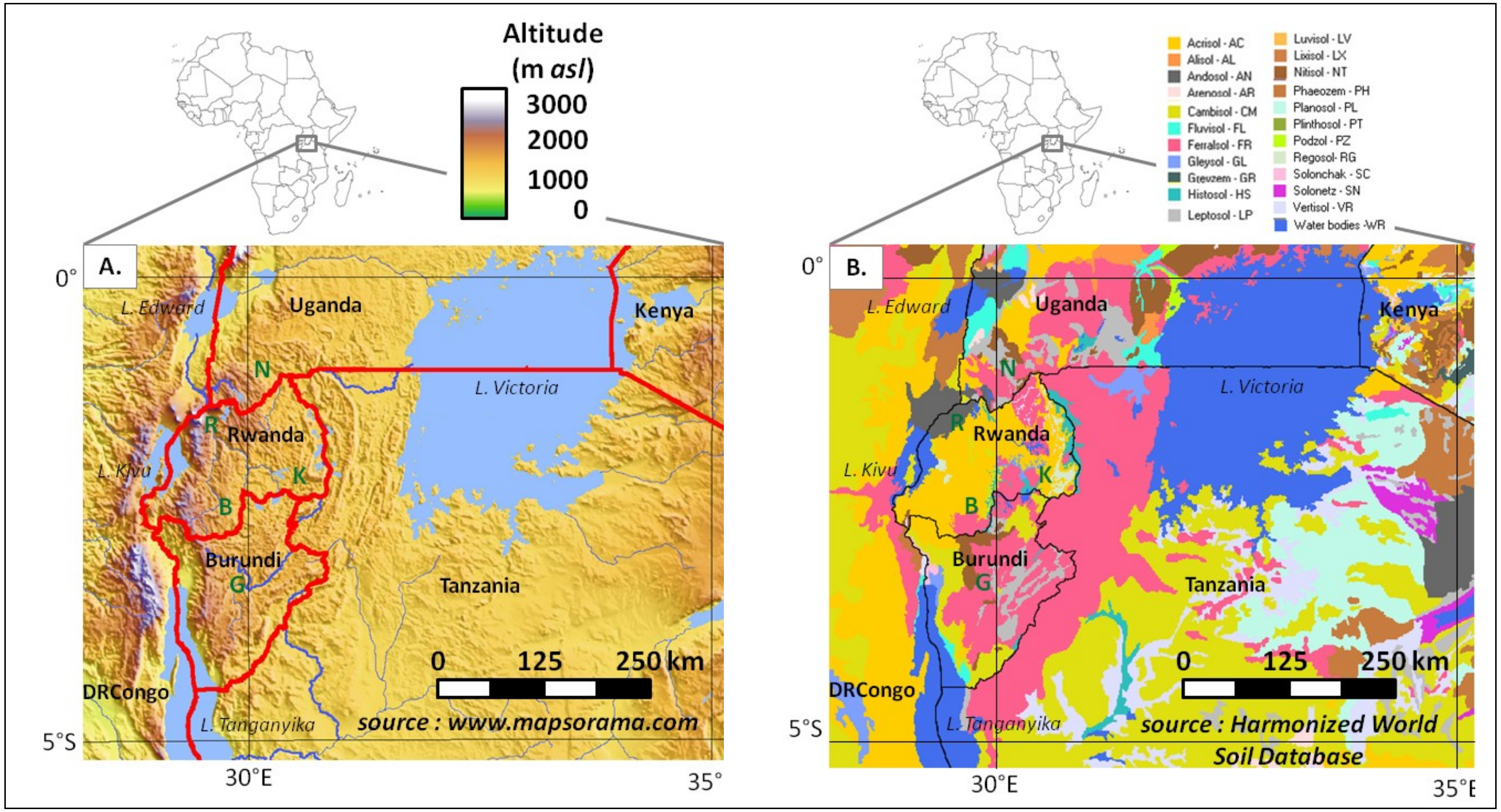

Figure 1.1. (A) Relief and (B) soil types in the African Great Lakes Region.

1.3. Agriculture, backbone of the economy in the Great Lakes Region

Agriculture insures food and income to 81-89% of the people in the African Great Lakes Region (FAOstat online, estimates for 2010). Most of them work and depend on small subsistence-oriented farms for their livelihood. The size of those smallholder exploitations has decreased due to the high population growth and ensuing constraint on land availability: their total land surface is now usually less than 1 or 2 ha (Ssali, 2001; Okech et al., 2005; Ansoms et al., 2008; National Institute of Statistics of Rwanda, 2010). The surface of the farm is fragmented in different plots, usually distributed around the houses, but sometimes situated further away. Food and cash crops cover the major part of the farm surface; the remaining land is allocated to forage, pasture, forest or is not cultivated (National Institute of Statistics of Rwanda, 2010). All crops are rain-fed and grown almost exclusively using traditional techniques (rudimentary tools, no machinery, no animal draft power, no or rare inorganic fertilizer) (Oduol and Aluma, 1990; Roose and Ndayizigiye, 1994; Wortmann and Kaizzi, 1998; Aniku et al., 2001; Clay et al., 2001; National Institute of Statistics of Rwanda, 2010). Banana, beans, cassava, potato, sweet potato and maize are the major food crops grown; coffee and tea are important cash crops (Raemaekers, 2001; FAO, 2005a; National Institute of Statistics of Rwanda, 2010). Production is mostly for home-consumption, but many households sell some of the farm produce on local or regional markets (Okech et al., 2005), or sell it directly from their home (Nyombi et al., 2006). Most farmers also possess a few animals (cattle, goats, sheep, pigs, rabbits, chickens or other poultry) (Bekunda and Woomer, 1996; Aniku et al., 2001; National Institute of Statistics of Rwanda, 2010), but these do not contribute much to daily human caloric intake (McIntyre et al., 2001; National Institute of Statistics of Rwanda, 2010).

Banana (*Musa spp.*) is a crop of major importance for the rural people in the African Great Lakes Region and as such deserves to be considered in more detail in following sections.

1.4. Banana-based farming systems

Worldwide, bananas (*Musa spp.*) are the fourth most important food after rice, wheat and milk (Swennen and Vuylsteke, 2001). Populations of East and South Africa are the world's most important consumers of banana (Karamura et al., 1999). The crop is the most important staple for 50% of the population in the humid mid-altitude zones of the Great Lakes Region (Bekunda et al., 2003). Numerous varieties are grown: cooking bananas (AAA-EAHB), brewing bananas (AB, ABB) and dessert bananas (AB, AAA). Cooking bananas dominate in Uganda, beer bananas are more important in Rwanda and Burundi (Karamura et al., 1999). Cooking bananas are boiled, fried, roasted, steamed or transformed to flour and eaten. Brewing bananas are processed to give a kind of beer or wine, or are distilled in stronger alcohol. Dessert bananas are consumed fresh (Bekunda et al., 2003; Okech et al., 2005). Bananas and beer are home-consumed but also sold. Although higher prices are given for bunches of cooking bananas, beer bananas are considered most profitable by Rwandan farmers (Okech et al., 2005).

Bananas are grown on lower slopes, valleys and between-hill depressions. In Rwanda, Burundi and Eastern Democratic Republic of Congo bananas are also found on hilltops and plateaus if soil are deep enough (Gaidashova, 2009 *and references therein*). The most common system to grow bananas is the smallholder subsistence farm described above. The banana-grove is installed around the homestead (Kirkby and Ngendahayo, 1985; Karamura et al., 1999; Figure 1.2).

Figure 1.2. A smallholder subsistence farm in the banana-based agricultural system of Ntungamo, South-West Uganda. The farm buildings, where people and animals live, are surrounded by the banana-grove (photo by S. Delstanche, UCL).

Since farmers only have small surfaces of land to grow the food needed to satisfy their families, they intensify their production (Ansoms et al., 2008) by intercropping bananas and fruit trees, food (beans, cassava, sweet potatoe, maize) and cash crops (coffee) (Oduol and Aluma, 1990; Bekunda and Woomer, 1996; Kangasniemi, 1998; Wortmann and Kaizzi, 1998; Karamura et al., 1999; Bekunda et al., 2003, Esilaba et al., 2005; Ouma, 2009). Other management practices in the banana plot include fertilization with organic matter, mulching with grasses or banana and other crop residues, weeding, de-suckering and mat density management, pruning of leaves, de-budding, stalking of pseudostems carrying bunches to prevent toppling (Figure 1.3) (Lassoudière, 1989; Oduol and Aluma, 1990; Robinson, 1995). Banana-plants at all the stages of development can be found in a plantation. Bunches are harvested year-round.

Figure 1.3. Common management practices in banana-plots, Ntungamo, SW Uganda. Association of banana with fruit-trees, mulching with banana residues, control of weeds (not evenly effective everywhere), stalking of banana-plants carrying bunches (photo by P. Freymann, UCL).

1.5. Constraints on banana production

Despite the management attention brought to bananas in East-Africa, on-farm yields are low (5-30 $t.ha^{-1}.year^{-1}$) and well below the potential yields obtained in research stations or plantations (40-70 $t.ha^{-1}.year^{-1}$) (Bekunda et al., 2004; *references in* McIntyre et al., 2003; van Asten et al., 2004). Low and declining yields are attributed to (1) poor soil fertility and limited inputs, (2) inadequate soil moisture, (3) diseases and pests, (4) inappropriate farming practices, and (5) socio-economic constraints. The constraints faced when growing bananas are described below.

1.5.1. Poor soil fertility and limited inputs

Most soils in the African Great Lakes Region are old, highly weathered, and have low or limited soil fertility. As a consequence of demographic growth and land pressure, the traditional ways of soil fertility maintenance, as fallow or shifting cultivation, are no longer feasible (Wortmann et al., 1994a; Nyaki, 2001a+b). Farmers thus rely on mineral and organic amendments to manage soil fertility for continuous cropping.

Industrial fertilizers are little used by smallholder farmers, because of the high costs at purchase (low benefit/cost ratio) (Okech et al., 2004), their low availability and the lack of knowledge on how to use them (Sseguya et al., 1999; Kelly et al., 2001; Bationo et al., 2006; Mafongoya et al., 2006; Mowo et al., 2006). When used, industrial fertilizers are applied on cash crops (Bekunda et al., 2004; Nyombi et al., 2006; Vanlauwe and Giller, 2006) or annual crops (Sseguya et al., 1999). Agrominerals have been proposed as an alternative to industrial fertilizers (Van Straaten, 2002), but are poorly known to farmers, expensive (Nyombi et al., 2006) and their results are delayed in time (Vanlauwe and Giller, 2006).

Organic matters generated on-farm, grasses from communal lands or swamps and purchased organic matter, are the major sources of nutrients available to farmers to amend their soils. The quantities of organic matter available are usually small because (1) the numbers of animals and thus quantities of manure have decreased, (2) crop residues are insufficient, (3) there is a parallel need of organic matter for fuel, animal feed or as building material, (4) collection and transport of bulky organic matter require high labor costs (e.g. Bekunda and Woomer, 1996; Wortmann and Kaizzi, 1998; Quansah et al., 2001). Beside insufficient in quantities, the organic matter also cumulates the inconvenience of being often of low quality (inappropriate C/N ratio, lignin content) (Palm et al., 1997, 2001).

Nutrients are lost because of harvest (Figure 1.4) or transfers of organic matter between fields, especially from plots far from the homestead to fields around the house. Some of these nutrients are never replaced because of insufficient quantities of (low quality) organic matter and no/low use of inorganic fertilizers. In Africa, nutrient balances at the continental, national, regional, farm or plot level are often negative, indicating that farmers mine their soils (e.g. Stoorvogel et al., 1993 *cited in* Nandwa and Bekunda, 1998; Smaling et al., 1992 *cited in* Smaling and Fresco, 1993; Bekunda and Woomer, 1996; Aniku et al., 2001; Bekunda et al., 2004). Estimates in annual nutrient depletion in East Africa are 41 $kg.ha^{-1}.year^{-1}$ for N, 4 $kg.ha^{-1}.year^{-1}$ for P and 31 $kg.ha^{-1}.year^{-1}$ for K. These are the highest nutrient mining rates in Sub-Saharan Africa (Bekunda et al., 2004).

Banana plots are preferentially amended with kitchen ashes and/or organic matter (self-mulch, household wastes, sweepings, peelings, compost and farmyard manure, residues of annual crops transferred to banana plots) (Figures 1.3 and 1.5; Bekunda and Woomer, 1996; Baijukya and De Steenhuijsen Piters, 1998; Wortmann and Kaizzi, 1998; Aniku et al., 2001; Briggs and Twomlow, 2002; Nyombi et al., 2006). Thanks to these nutrient supplies, banana fields close to the homestead can have positive or near-neutral nutrient balances, but this is not always true. Possible good or not-too-bad balances of the banana plot are not necessarily a reason to be optimistic, since they are built at the expense of annual crop fields or fields further away from the house (Bekunda and Woomer, 1996; Wortmann and Kaizzi, 1998; Briggs and Twomlow, 2002). Despite the particular attention given by farmers to their bananas, plant nutrition is not optimal. Based on foliar data, Gaidashova et al. (2010) reported N-, P-, K- and Ca-deficiencies for plots distributed along a toposequence in a Rwandan site near Lake Kivu. Foliar analysis identifies K and Mg as constraints in Southern (Ssali et al., 2003), Southwestern (Smithson et al., 2001) and Central Uganda (Smithson et al., 2004). According to Wairegi et al. (2010), poor soil quality in South and Southwestern Uganda explains between 10% and 20% of banana yield losses.

Figure 1.4. A truck filled with banana bunches leaves the Southwestern part of Uganda, probably to the country's capital Kampala. Van Asten et al. (2004) evaluate that 100 trucks of banana bunches reach Kampala each day, depleting soils in rural areas of 1.5 million kg of K and 0.5 million kg of N annually (photo by P. Freymann, UCL).

Figure 1.5. Swamp grasses (A), banana leaves (A), banana peelings and peduncle (B) as mulch in banana plots (photos by P. Freymann, UCL).

For the African Great Lakes region, data on banana nutritional status considering sulfur or micronutrients are scarce. Zn-deficiencies in banana are reported by Janssen (1993, *cited in* Bekunda et al., 2003) working in North-West Tanzania. In their review paper on the banana system in Eastern Africa, Bekunda et al. (2003) state that Zn deficiencies often constrain banana production, while S, B and Cu deficiencies are of secondary importance. According to the pH-deficiencies relationships by Marchal and Martin-Prével (1971), Mn and Fe deficiencies are not expected in the globally acid soils of the Region. Mn toxicities could, on the contrary, not be excluded. A rapid screening on micronutrients contents in banana from Congo (Kivu), Rwanda, Burundi and Uganda, corroborated by data on other common plants, suggests that Se-availability is highly variable over short distances and that Mo and Co may be a problem in some areas (*information by* R. Graham, Lyons, R, University of Adelaide - School of agriculture, Food and Wine).

Researchers and farmers recognize soil fertility as a major and increasing constraint on agricultural production in smallholder farms in Africa (Sanchez et al., 1997; Nandwa and Bekunda, 1998; Ssali, 2001; Bouwmeester et al., 2009; Mugwe et al., 2009). A lot of research has been done on soil fertility, to trigger the alarm to the problem or to propose solutions. The better use of organic matter advocated by research is a mere extension of what is traditionally done by smallholder farmers. Research goes further by advising methods to improve use of neglected sources of organic matter (Smaling et al., 1996; Ssali, 2001; Briggs and Twomlow, 2002; Zingore et al., 2007), by combining it to inorganic fertilizers or agro-minerals (Van Straaten, 2002; Okalebo et al., 2006; Vanlauwe and Giller, 2006; Zingore et al., 2007), and by identifying the optimum quality, rates, placement and time of restitution of fertilizers (Nandwa and Bekunda, 1998; Palm et al., 2001; Zingore et al., 2007).

1.5.2. Inadequate moisture

Banana is a water-demanding crop, which extracts 60% of the water it needs from the top 30 cm of the soil and is not efficient at taking up water from drying soils (Landon, 1991). When total annual precipitation, rainfall distribution and water-holding capacities of soils are considered together, it seems that the water-availability in some banana-production areas in Uganda, Rwanda and Burundi is not adequate (Eledu et al., 2004). Banana yield losses in Southwestern Uganda are attributed for 5% to low rainfall (Wairegi et al., 2010). Okech et al. (2004) link strong temporal variations in yields in a fertilizer trial in South-West Uganda to fluctuations in rainfall. Irregular rainfall and insufficient water supply is also a problem in the banana production region of Kibungo, in the eastern part of Rwanda (Lassoudière, 1989). According to Van Asten et al. (2011) a decline of 100 mm rainfall on one year could reduce bunch weights by 9%. Areas with an annual rainfall inferior to 1100 mm could suffer yield losses between 20 and 65%. Mulching can affect soil water recharge significantly, because it induces an increase in total porosity (McIntyre et al., 2000), or a decrease of water run-off and evaporation (Ssali et al., 2003).

1.5.3. Diseases and pests

Diseases are often mentioned as constraints on production but are more rarely studied. Major diseases affecting banana in the Great Lakes Region are the Banana streak virus, Black Sigatoka, and, more recently, banana *Xanthomonas* wilt.

The Banana streak virus (BSV, family Caulimoviridae, genus *Badnavirus*) was first reported for “Poyo” in the Ivory Coast, but has since spread throughout Africa and abroad. Mealybugs act as vectors in spreading the disease (Jones and Lockhart, 1993). Yield losses of 7 to 82% have been attributed to BSV, due to smaller bunches or reduced size of fruit on infested plants (Dahal et al., 2000; Daniells et al., 2001) or due to delays in harvest (Daniells et al., 2001).

Caused by the fungus *Mycosphaerella fijiensis* Morelet, Black Sigatoka is considered the most important banana leaf spot disease (Tushemereirwe et al., 2004). Premature dying of the leaves leads to reduced yields and premature ripening of fruit (Mourichon et al., 1997). A yield loss assessment study conducted in Central Uganda reveals reduction in bunch weights of 37% (Tushemereirwe et al., 2000 *cited in* Tushemereirwe et al., 2004).

Banana *Xanthomonas* wilt (BXW, also named banana bacterial wilt BBW) is caused by the bacterium *Xanthomonas vasicola* pv. *musacearum*. It affects all banana types. The disease was first reported in Central Uganda in 2001 (Tushemereirwe et al., 2003a+b), and has since moved rapidly south- and westwards towards Rwanda, Kenya or Congo (Eden-Green, 2004). According to Karamura et al. (2006, *cited in* Biruma et al., 2007) banana yield losses due to BXW in Uganda are estimated between 30 and 52% for the time-span 2001-2004.

Major pests of banana in the Great Lakes Regions are the banana weevil (*Cosmopolites sordidus)* and the plant parasitic nematodes, *Pratylenchus goodeyi*, *Radopholus similis*, *Helicotylenchus multicinctus* and *Meloidogyne* spp*.*

The banana weevil *Cosmopolites sordidus* (Germar) is a free-living insect, most often found between leaf sheaths, in the soil at the base of the banana-plant or associated with moist crop residues. Females deposit their eggs in leaf sheaths or at the rhizome surface (Gold and Messiaen, 2000). Larvae hatch into the corm or pseudostem for food, hence weakening the stability of the plant and impeding nutrient uptake. Plant loss due to toppling or snapping, premature death of plants and lower bunch weights explain the observed reduced yields (Gold and Messiaen, 2000). Since the 1970s, the weevil contributes to the decline of the highland banana in Central Uganda (Gold et al., 1999). In an on-station trial in Central Uganda, Rukazambuga et al. (1998) observe between 0 and 72% of yield loss for highland cooking banana, depending on the degree of *C. sordidus* damage. Plant losses contribute more to global yield decreases than reduction in bunch weight (Rukazambuga et al., 1998; Gold et al., 2005).

Pratylenchus goodeyi, *Radopholus similis*, *Helicotylenchus multicinctus* and *Meloidogyne* spp. are nematode species often found in the Great Lakes Region. Their distribution is altitude-related. *P. goodeyi* is limited to higher elevation zones and only rarely encountered below 700 m*asl* (Bridge et al., 1997). *R. similis* is not found above 1400 m*asl* because of the prevailing cooler temperatures (Sarah et al., 1996). Populations of *Helicotylenchus multicinctus* and *Meloidogyne* spp. tend to be larger at lower altitudes (Speijer and Fogain, 1999). The nematodes feed on root and corm tissues, causing root lesions and necrosis. Reduction of the root system induces lessened anchorage, reduction in water and nutrient uptake, hindering plant growth and development (Sarah et al., 1996; Bridge et al., 1997; Mukasa et al., 2005). Yields decrease due to more frequent toppling, longer production cycle and reduced bunch weights (Sarah et al., 1996; Bridge et al., 1997; Speijer and Kajumba, 2000). In trials in Uganda, yield losses of 30-50% for highland banana cultivars have been attributed to mixtures of nematodes implying *R. similis, H. multicinctus* and/or *P. goodeyi* (*references in* Speijer and Fogain, 1999; Speijer et al., 1999; Speijer and Kajumba, 2000). Yield losses depend on altitude (higher temperatures promote root decay), banana genotype (*references in* Speijer and Fogain, 1999), nematode species involved (Barekye et al., 2000) and management. Hence, *R. similis* is more destructive than *P. goodeyi* (Talwana et al., 2003) or *H. multicinctus* (Barekye et al., 2000). Losses are particularly important on poor soils (Sarah et al., 1996; Bridge et al., 1997; McIntyre et al., 2000). Good management and, especially, mulching helps to mitigate the effects of nematodes when soils are less optimal for plant growth (Talwana et al., 2003; Gaidashova et al., 2010). Nematodes decrease production in mulched plots, but production is still higher than in bare non-mulched plots (Speijer et al., 1999; McIntyre et al., 2000).

1.5.4. Inappropriate farming practices

Management practices influence banana-plant growth and yield. Mulching, use of chemical fertilizer, control of intercrop, control of plant spacing, de-suckering, weeding, no or superficial tillage, de-budding, leaf pruning, use of clean planting material, use of disease- or drought-tolerant cultivars, all have, by one way or the other, positive influences on above-ground plant development, root growth and fruit production (Lassoudière, 1989; Robinson, 1995; Odeke et al., 1999; Speijer et al., 1999; Bananuka et al., 2000; Badgujar et al., 2003; Ssali et al., 2003; Talwana et al., 2003; Kagoda et al., 2005; Mukasa et al., 2005; Tinzaara et al., 2005; Dowiya et al., 2009). The positive influences are explained by the reduction of competition for water and nutrients, preservation of the root system, reduction of the damaging effects of pests, or slow-down of disease spread. Because of high costs, limited access to resources, information and labor, small-holder farmers do not or cannot always give these good practices the attention they disserve (Figure 1.5).

1.5.5. Socio-economic constraints

Marketing problems and poor supply of inputs (Kangasniemi, 1998; Nkonya et al., 2005; Okech et al., 2005), regulations and policies (Kangasniemi, 1998; Ansoms et al., 2008; Kyomugisha, 2008; Namazzi, 2008; Bayite-Kasule, 2009), land scarcity and poverty (Pender et al., 2004), constitute other, intertwined, constraints faced by farmers. Socio-economy is beyond the scope of this work, and is thus just noted here for the record.

Figure 1.5. Bananas intercropped with maize, in a badly weeded field near Gitega (Central Burundi) (photo by S. Delstanche, UCL).

1.5.6. To summarize: heterogeneity at different scales

As could be deduced from the descriptions and examples given above, management practices and banana production can vary spatially due to the numerous and complex interactions of environmental, biophysical and socio-economical factors. The present section re-arranges the information given previously to explain yield differences at different scales, from national to farm level.

At national or inter-regional levels, productivity varies as a function of biophysical parameters (climate, soil type and its inherent properties) but depends also on socio-economic factors. Population densities, access to markets and infrastructure, access to information and services, access to inputs, opportunities for off-farm income, access to credit, regulations and policies, land tenure, all determine land-use patterns and management practices (Nkonya, 2005; Tittonell et al., 2005a, 2007, 2010).

Production differences across a region are explained by (1) different location on a topographic slope, (2) resource endowment (whether it is in natural, physical, financial or human capital), (3) cultivation priorities and production strategies (subsistence- or market-oriented) and (4) differences in constraints faced (Bekunda and Woomer, 1996; Crowley and Carter, 2000; Wopereis et al., 2006; Tittonel et al., 2005a, 2010).

Production varies even at the farm-level because of the differential management practiced by farmers (e.g. Wortmann and Kaizzi, 1998; Mairura et al., 2007; Tittonell et al., 2005b, 2007). Good management and high organic inputs are provided to plots around the homestead (e.g. Briggs and Twomlow, 2002; Bekunda and Manzi, 2003), because they are most easily accessed and high-value produce cultivated there (banana) is less susceptible to theft (Giller et al., 2006). Differential management of organic matter concentrates nutrients in the small areas around the homestead at the expense of fields further away (e.g. Wortmann and Kaizzi, 1998; Briggs and Twomlow, 2002; Tittonell et al., 2005b). Management hence maintains the pre-existent soil fertility gradient that originated from biophysical discontinuities or past management (Tittonell et al., 2005b). Modeling soil fertility for soils on granite in Zimbabwe, Rowe et al. (2006) think 5 to 10 years to be sufficient to create soil fertility gradients under maize. Others observe that even after 20 years of differential management, soil organic matter and nutrient status do not show significant differences between poor and rich fields (Mtambanengwe and Mapfumo, 2005).

1.6. Limited adoption of the solutions promoted by research

Research shows that African farmers know their soils very well. Relying on crop yield and performance, presence of indicator plants, soil color, depth, structure and workability, they evaluate soil fertility and recognize differences (Osunade, 1988; Habarurema and Steiner, 1997; Nandwa and Bekunda, 1998; Quansah et al., 2001; Barrios et al., 2006; Mairura et al., 2007). Smallholder farmers are aware of the particular importance of soil organic matter (Quansah et al., 2001). They recognize soil fertility as a major constraint to crop production. Soil fertility management and choice of crops are decided in function of soil type (Habarurema and Steiner, 1997; Steiner, 1998). Aware of their environments and the constraints they have to cope with, farmers can move inside a range of soil fertility management strategies if conditions warrant (Bekunda and Woomer, 1996).

Considering smallholder farmers as oblivious to the soil fertility problem, and their management as an unworried mining of their soils, is a clear oversimplification (Bekunda and Woomer, 1996). Constrained by a variety of environmental, biophysical and socio-economic factors, people tend to satisfy the immediate needs of their families, instead of investing in the longer-term sustainability of their farm (Smaling et al., 1996; Haileslassie et al., 2007). In this context, limited adoption of the solutions promoted by research is not surprising. Indeed, these new technologies fail to take into account the needs and possibilities of the local farmers (Barrios et al., 2006; Vandeplas et al., 2010). In the end, production goals and market opportunities, availability of materials, land-, water-, cash- and labor-requirements determine whether proposed technologies are practically feasible to smallholder farmers (Palm et al., 2001; Barrios et al., 2006; Tittonell et al., 2010; Vandeplas et al., 2010). The solutions proposed by research, suffer another inconvenient. Established in research stations, or on-farm at plot or field scale, the technologies have been translated into blanket recommendations. These blanket recommendations are not appropriate, seen the heterogeneity of systems previously described (Mwijage et al., 2009). This last critic aims in particular at inorganic fertilizer application. Numerous studies underline the need of site- and crop-specific recommendations, to render inorganic fertilizer use efficient and economical (Nandwa and Bekunda, 1998; Kelly et al., 2001; Vanlauwe and Giller, 2006; Zingore et al., 2007).

1.7. The "Great Lakes" project within the CIALCA consortium

Agriculture is the backbone of the economy in the Region since it insures food and income to 81-89% of the people in the African Great Lakes Region (FAOstat online, estimates for 2010). In the last decades, demographic growth and the ensuing constraint on land availability, led to occupation of marginal land, land fragmentation and intensification of agriculture (Clay et al., 1998). Over-exploitation of old and nutrient-poor soils in these low-input systems threatens the long-term sustainability of the agriculture in the East African Highlands.

Growth of agricultural output stagnates since 25 years in Sub-Saharan Africa (Chikanda, 2009) and food production growth now lags behind population growth (Schweigman, 2008). In his report on food production and related problems, Alexandratos (2005) pinpoints Burundi and Uganda as already having problems of food insecurity. High levels of food insecurity also emerge from a field survey in the northern and central parts of Burundi, in South Kivu (DRC) and the southern part of Rwanda (Bouwmeester et al., 2009). Projections to 2050, predict that countries as those in the African Great Lakes Region, having an agriculture-based economy, with an increasing population pressure on the agricultural resources, will face food insecurity for decades ahead (Alexandratos, 2005).

The East African Highland banana (*Musa spp.* AAA-EA) is of major importance to the populations in the African Great Lakes Region, both as a food and a cash crop (FAOstat online, estimates for 2010). Increasing productivity of banana-based system would help to meet food security. In this context, IITA[1] and its partners (UCL, ISAR, IRAZ, ISABU, INERA)[2] initiated, in 2005, a multi-disciplinary project as part of a consortium named CIALCA[3]. The project is entitled “Sustainable and Profitable Banana-based Systems for the African Great Lakes Region” and aims to contribute to profitable and sustainable banana-based systems in the Great Lakes Region

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[1] IITA : International Institute of Tropical Agriculture, www.iita.org

[2] UCL : Université catholique de Louvain (Belgium), www.uclouvain.be
ISAR : Institut des Sciences Agronomiques du Rwanda (Rwanda), www.isar.rw
IRAZ : Institut de Recherche Agronomique et Zootechnique (Burundi)
ISABU : Institut des Sciences Agronomiques du Burundi (Burundi) : www.isabu-bdi.org
INERA : Institut National pour l’Etude et la Recherche Agronomiques (DRCongo) : www.inera-rdc.org

[3] CIALCA : Consortium for Improving Agriculture-based Livelihoods in Central Africa, www.cialca.org

by developing and disseminating integrated packages involving soil conservation, organic and inorganic inputs, improved germplasm, improved agronomic and integrated pest management, and post-harvest technologies. Through its analyses and findings, this dissertation contributes to the "Great Lakes" project…

PART 1

Plant Analysis

Chapter 2. The contribution of soil fertility to banana yield gaps in the African Great Lakes Region

Abstract

Banana is an important food crop for the populations in the African Great Lakes region. Despite the efforts of smallholder farmers, yields remain low. In order to improve production, the yield constraints need to be understood. We used Boundary Line Analysis (BLA) on soil, crop management, and pest data from four areas differing in agro-ecological and socio-economic characteristics. 223 soil and plant observations distributed over parts of Uganda (Ntungamo) and Rwanda (Butare, Kibungo, Ruhengeri) are considered. Yield losses are calculated from the BLA and expressed against the attainable yield in each region. In Butare, yield losses of 46-49% are attributed to poor soil fertility. In Ntungamo too, soil fertility is the most important constraint on banana (pH in 31% of the observations, cation deficiency and disequilibria in 13 to 33% of them). Soil fertility is the second most important constraint for plants on the more fertile soils of Kibungo and Ruhengeri, with management being the major one. Inappropriate plant spacing causes yield losses of 29% in Ruhengeri, 26% in Ntungamo, 25% in Kibungo and 22% in Butare. Insufficient mulching and weeding explain important yield losses in Butare (resp. 45 and 23%), Ruhengeri (resp. 30 and 27%) and Ntungamo (resp. 15 and 30%) but are not a problem in Kibungo (resp. 9 and 4%). Damages by pests influence yield in the altitudinal lower areas of Kibungo (root necrosis - 13%) and Ntungamo (root necrosis - 30%, weevil corm damage - 16%). Although our analysis reveals very clear regional differences in constraints and yield that can be

attributed to differences in geology and associated soil types, the soil's potential to sustain banana production also shows large intra-regional and intra-farm scale as shown by the computation of soil quality indices.

Keywords
East-Africa highland banana; Boundary Line Analysis; yield constraints; soil quality index

2.1. Introduction

The East African Highland banana (*Musa spp.* AAA-EA) is one of the major crops for the population in the African Great Lakes Region, because of the food and cash it provides to about 85% of the population (FAOstat, estimates for 2010). Despite the efforts of smallholder farmers, on-farm banana yields are low (5-30 $t.ha^{-1}.year^{-1}$) and well below the potential yields obtained in research stations or plantations (40-70 $t.ha^{-1}.year^{-1}$) (Bekunda et al., 2004; van Asten et al., 2004). Low and declining yields are mainly attributed to poor soil fertility and limited input use (Bekunda and Woomer, 1996; Ssali, 2001; Okech et al., 2004; Wairegi et al., 2010), drought or irregular rainfall (Okech et al., 2004; van Asten et al., 2011), pests as nematodes (Speijer et al., 1999; Speijer and Kajumba, 2000; McIntyre et al., 2000) or banana weevil (Rukazambuga et al., 1998; Gold et al., 1999, 2005) and diseases (Dahal et al., 2000a; Tushemereirwe et al., 2004; Biruma et al., 2007). As pinpointed by Wairegi et al. (2010) some of these studies suffer the disadvantages of (1) being geographically restricted, (2) conducted in research stations under artificially induced and controlled conditions, and (3) focused on single constraints as guided by what farmers perceive as most important. Comprehensive quantification and ranking of yield constraints are efforts only rarely undertaken. Yet, the knowledge of the relative effects of constraints on yield would allow development of targeted solutions to overcome these constraints (Shatar and McBratney, 1999).

Proposing efficient solutions arises thus from a quantitative assessment of yield constraints and the understanding of inter- and intra-regional differences.

The Boundary Line Analysis (BLA) is an alternative to traditional statistical methods to evaluate constraints on yield. The method constructs an envelope-line through the upper points of a scatterplot opposing yield (Y-axis) and the values of an independent biophysical factor (X-axis) (Waggoner and Norvell, 1979), hence the name "boundary line". The boundary line represents the maximum potential yield at each value of the independent test factor if no other factor imposes a limitation on the production (Webb, 1972). Based on Liebig's Law of the minimum (von Liebig, 1843 *cited in* Webb, 1972), the factor explaining the least amount of yield is the limiting factor (Webb, 1972). Compared to traditional multivariate statistical models, the BLA offers the possibilities to (1) isolate single-factor yield responses from datasets where multiple factors determine yield (Shatar and McBratney, 2004) and to (2) quantify identified and remaining yield gaps (Cassanova et al., 1999). Despite it being an oversimplification, ignoring interactions between factors (Shatar and McBratney, 2004) or its unclear meaning (Lark, 1997; Milne et al., 2006), the BLA already proved useful in studies on various crops. It allowed, for instance, the identification of site specific causes of yield variations and limitations of rice in Spain (Casanova et al., 1999) or Mauretania (van Asten et al., 2003), sorghum in Australia (Shatar and McBratney, 2004), cassava in Uganda and Western Kenya (Fermont et al., 2009) or banana in Uganda (Wairegi et al., 2010).

Within agro-ecoregions (i.e. altitude, climate and soil), differences due to management could be assessed by the calculation of a soil quality index (Karlen and Stott, 1994; Brejda et al., 2000; Liebig et al., 2001; Andrews et al., 2002, 2004; Mukashema, 2007; Karlen et al., 2008). Because of its dynamic nature implying numerous and interacting physical, chemical and biological factors, soil quality has been difficult to describe and quantify

(Doran and Parkin, 1994). As a consensus, a committee appointed by the Soil Science Society of America defined soil quality as "the fitness of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance environmental quality, and support human health and habitation" (Karlen et al., 1997). Soil quality cannot be measured directly but can be inferred by measuring biophysical factors that serve as indicators (Brejda et al., 2000). The information contained in these measurements can be grouped and summarized as a soil quality index. Calculation of a soil quality index allowed for instance the evaluation of the influence of management on vegetable (Andrews et al., 2002) or corn yield in the USA (Hussain et al., 1999; Liebig et al., 2001). Mukashema (2007) used soil quality indices to study human induced differences in soil fertility in the western part of Rwanda.

In this study, we apply the Boundary Line Analysis (BLA) to study the effects of biotic and abiotic factors on banana yield. The analysis identifies and ranks the constraints on banana yield in four agro-ecoregions in Rwanda and Uganda. Ranking is allowed by (1) the determination of the percentages of plants for which each factor is identified as limiting yield and by (2) the quantification of yield gaps attributed to these factors. The data used in the BLA are also used to calculate soil quality indices to identify differences within (1) regions and (2) within farms.

2.2. Materials and methods

2.2.1. Study area

The areas of interest in the present study are situated between the latitudes S 00°46' – S 2°17' and the longitudes E 29°38 – E 30°37'. More specifically, they are located near the towns of Butare, Kibungo and Ruhengeri in Rwanda, and Ntungamo in the south-western part of Uganda (Figure 2.1). The study areas represent different agro-ecoregions, varying in altitude, climate and soil type (Table 2.1). Altitude was about 1500-1600 meters above sea-level (m*asl)* in Kibungo and Ntungamo, and rises to about 1700 m*asl* in Ruhengeri and 1800 m*asl* in Butare. Mean annual temperature is about 19-20°C. The mean annual rainfall ranges from 820 to 1350 mm.year^{-1}; rainfall has a bimodal distribution with most of the precipitation falling in the periods March to May and September to December. Soils in the area around Ruhengeri are Andosols developed on Cenozoic volcanic ashes, while soils in the other regions are old and highly weathered Acrisols and Nitisols, developed on various parent materials (Table 2.1). Land is fragmented between the numerous smallholder farmers who grow their crops in intensively exploited banana-based systems. Farmers rely almost exclusively on traditional techniques (rudimentary tools, no machinery, no animal draft power, no or rare inorganic fertilizers) to manage their fields (Oduol and Aluma, 1990 ; Roose and Ndayizigiye, 1994 ; Wortmann and Kaizzi, 1998 ; Aniku et al., 2001 ; Clay et al., 2001 ; National Institute of Statistics of Rwanda, 2010). All crop-production is rain-fed.

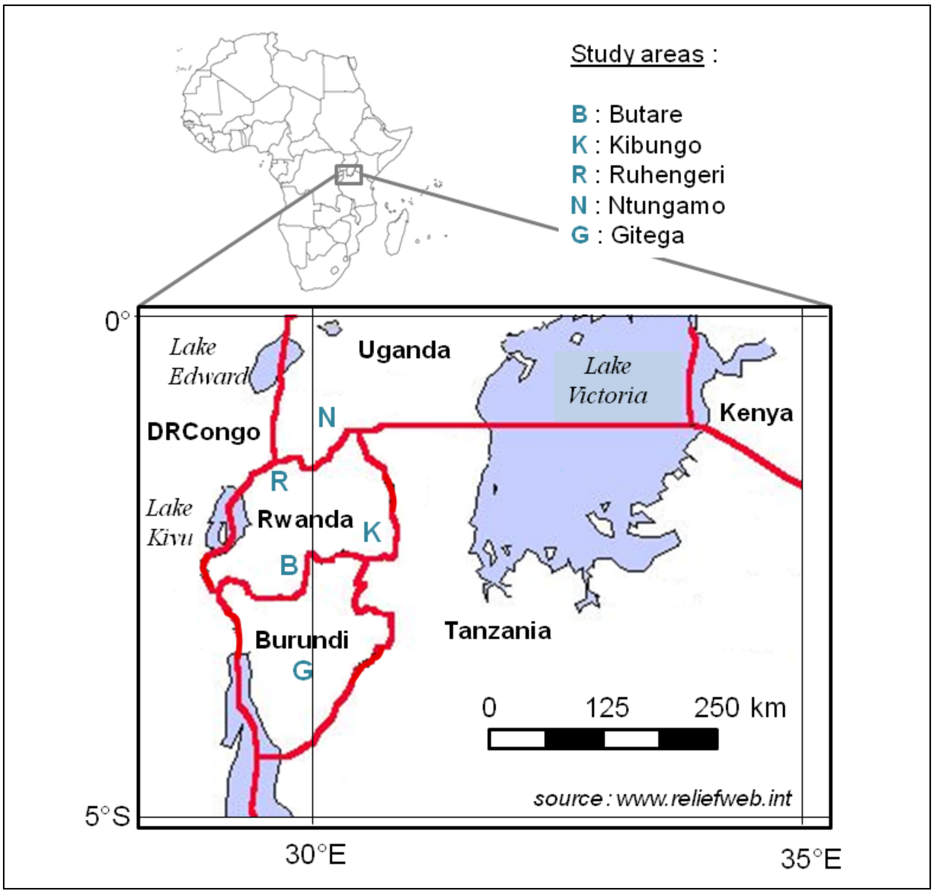

Figure 2.1. Map of the African Great Lakes Region, situating the four study areas.

Table 2.1. Characteristics of the studied agro-ecoregions.

Area	Altitude (m*asl*)	Mean annual rainfall (mm.year^{-1})	Mean annual temperature (°C)	Soil type (IUSS, 2006)
Rwanda				
Butare (S 2°17-27'/ E 29°45-47')	1675-1763	1150-1260 (*)	19.2 (**,°)	Acrisol, on granite
Kibungo (S 2°12-17'/ E 30°35-37')	1498-1623	900-980 (*)	19-20.6 (**,°)	Nitisol, on pelitic rocks
Ruhengeri (S 1°32'/ E 29°38')	1659-1692	1300-1350 (*)	19.6 (**,°)	Andosol, on mafic volcanic ash
Uganda				
Ntungamo (S 00°46-47'/ E 30°13-14')	1535-1611	1100-1200 (*) wide variability between years : 820-1300	19 (**)	Acrisol, on quartzite or micaschist
References: Location coordinates and altitudes were measured in the field (GPS). Soil type was ascribed in accordance with the FAO World Reference Base. Other data were found in literature: (*) Roark and Dickson, (1986, *cited in* Byers, 1990), Delepierre (1974, *cited in* Ndindahizi and Gwabije, 1991), Verdoodt and Van Ranst (2003), Smithson et al. (2004), FAO (2005b), Bouwmeester et al. (2009), Nyombi et al. (2009), Gaidashova et al. (2009), van Asten et al. (2011), ISAR online (http://www.isar.rw, accessed on October 12th 2010). (**) FAO (2005b), (°) Gaidashova et al. (2009). "m*asl*": meters above sea-level.				

2.2.2. Data collection

A. Diagnostic survey in Butare, Kibungo and Ruhengeri (Rwanda)

Selection of farms, plots and plants

The survey in Rwanda in the eco-regions of Butare, Kibungo, and Ruhengeri has earlier been described in Gaidashova et al. (2009). The survey was conducted in March and April 2006 and banana plant performance data was recorded for the common East Africa Highland cultivar *Intuntu* (AAA-EA). The restriction to only one cultivar minimized the effect of the genotype on the collected data. In the three eco-regions, respectively, 20, 20 and 22 farms were visited. A farm could consist of one or more banana fields. For each area, farms were selected for the survey if they responded simultaneously to two criteria. The selected farms needed to (1) have plots with variable plant vigor, and (2) have, in one plot, at least five flowering banana-plants at the stage of fully opened hands. Plant vigor was evaluated by (1) visual appraisal, and (2) measurement of growth- and yield-related components (height, girth at 1 m, number of functional leaves and number of fingers per bunch). Two plots were sampled per farm, one plot with relatively high vigor plants ("plots A"), and one where the plants looked relatively poor ("plots B"). The farms in the region of Butare were small and the contrasting plots (A and B) could belong to neighboring farmers. Described plots and selected plants were GPS-positioned.

Estimate of bunch weight

Bunches were not weighted directly, but their weights were estimated using the allometric relationship established by Gaidashova et al. (2007, [eq.1]) :

$$\mathrm{EBW} = (0.173\ \mathrm{x}\ \mathrm{girth_{1m}}) + (0.995\ \mathrm{x}\ \mathrm{NFL}) + (0.123\ \mathrm{x}\ \text{number of fingers per bunch}) - 16.1 \quad (\mathrm{R}^2 = 0.56) \qquad \text{[eq.1]}$$

where EBW stands for estimated bunch weight and NFL for number of functional leaves. $Girth_{1m}$ is the girth at 1m height.

Soil sampling and chemical analyses

A soil sample was taken at the base of each studied plant. It is a composite sample obtained by mixing thoroughly the soil withdrawn between 0 and 25 cm depth from three places at distances of 50 to 70 cm from the plant. The soil samples were air-dried, softly ground and sieved to pass a 2mm mesh. Soil chemical analyses have been performed at the UCL-laboratories (Michamps and Louvain-la-Neuve, Belgium).

Soil pH was measured in a 1 : 5 soil : water-suspension (5 g : 25 ml) after 3 to 4 hours. Total carbon and nitrogen contents were determined by dry combustion. Exchangeable K, Ca and Mg were extracted using a 1M ammonium acetate solution at pH 7 (Page et al., 1982), and the cation contents determined by atomic absorption spectrophotometry (AAS). The amount of ammonium retained by the soil, after washing it free of the excess of ammonium acetate by denatured ethanol, was considered to represent an estimate of the cation exchange capacity of the soil. The retained ammonium was released by leaching the soil with a 1M potassium chloride solution at pH 3. Ammonium contents in the leachates were determined by distillation. All data are expressed against dry soil weight (105°C). Total chemical analyses were performed by digesting finely ground powder (mineralized at 950°C for 72 h) in a mixture of lithium tetra- and metaborate at 950°C (Chao and Sanzolone, 1992). The cooled digestion beads were dissolved in hot (100°C) 2M nitric acid. Elemental (Al, Fe, Si, Ti, Ca, K, Mg, Mn and P) contents in 100 ml 2M HNO_3 were determined by inductively coupled plasma – atomic emission spectrometry (ICP-AES). Elemental contents were expressed as percentages of respective oxides. Total reserve in bases (TRB) was calculated as the sum of total contents of alkaline-earth and alkaline cations (Herbillon, 1986).

Crop management

The evaluation of crop management was performed as described in Gaidashova et al. (2009). The distances between the selected mat and the four nearest surrounding mats were measured to calculate average mat distance. "Mat" is a cluster of plants with interconnected living corms. A mat has only one mother plant, but one or more sucker plants. Visual appreciation, allowed ranking of the surface occupied by weeds or intercrops in a radius of 2 m around the selected banana plant, as none (<2%), very little (3-5%), little (6-10%), medium (11-25%), high (26-50%) or very high (>50%). Mulch thickness was measured at five random points around the studied plant and averaged.

Root necrosis

As described by Gaidashova et al. (2009), roots were collected from an excavation of 20x20x20 cm extending outwards from the rhizome of each selected plant at flowering stage. The percentages of root necroses were assessed using five randomly selected functional primary roots as advocated in the reference methods by Speijer and Gold (1996) and Speijer and De Waele (1997).

B. Monitoring in Ntungamo (Uganda)

Selection of farms and plants

Ten farms located in a valley near Ntungamo were selected, representing the range of relative wealth status of the household and slope position of the farm. To capture intra-farm variability of plant performance and crop/soil management, 15 banana-plants were selected at varying distances (< 100 m) from the homestead. The distances between the kitchen's door and the selected banana-mats were measured. Five mats were located at relative distances "close" to the homestead, 5 at "intermediate" and 5 at "remote" relative distances from the kitchen. All the selected mats were of the highland banana variety *Enyeru* (AAA-EA), to avoid influence of genotype in the collected data. Described plots and selected plants were GPS-positioned. While in the Rwandan campaign high and low vigor plants were distinguished by visual appraisal, in Ntungamo this distinction was based on the measured bunch weights. Plants providing bunches which weights were superior to the median bunch weight of the farm, were considered high vigor plants (on "subplot A"). Other plants of the same farm were assumed to be low vigor plants (on "subplot B"). When comparing (paired sample *t*-test) subplots "A" and "B" of a same farm, the data for the different high ("A") or low vigor ("B") plants were averaged.

Bunch weight

For each selected mat, the plant growth for one follower ratoon was monitored monthly from sucker emergence to harvest. Plants were harvested when farmers considered bunches mature. Harvested bunches were weighted using a balance (±0.5 kg).

Soil chemical analyses

A composite soil sample was obtained at the base of each selected plant, by mixing three to five cores of soil taken around the banana-plant and covering the 0-30cm depth. The soil samples were air-dried, softly ground and sieved to pass a 2mm mesh. Soil chemical analyses were done in the soil science laboratories at Kawanda (Uganda) and UCL (Louvain-la-Neuve, Belgium). Soil pH was measured in a 1 : 2 soil : water-suspension according to Okalebo et al. (2002). Available P and exchangeable K, Ca and Mg were evaluated by the Mehlich 3-procedure (0.015M NH_4F + 0.25M NH_4NO_3 + 0.2M CH_3COOH + 0.013M HNO_3 + 0.001M EDTA) detailed in Okalebo et al. (2002). Total carbon and nitrogen contents were determined by dry combustion. Total chemical analyses on soil samples were performed as described above for the samples from Rwanda (section 2.2.2.A, “Soil sampling and chemical analyses”).

Crop management

Surfaces between plants, percentages of surface covered by weeds and average mulch thicknesses were evaluated using the same procedures as in the Rwandan survey.

Damages attributed to pests and records of diseases

As for the campaign in Rwanda, root necrosis was determined according to the guidelines of Speijer and De Waele (1997). Weevil (beetle) damage was estimated by the cross-section method of Gold et al. (1994). Two cross-sections were made, one at the junction between pseudostem and corm, the second 10 cm below this junction. For each cross-section, the weevil damage was assessed on both the central cylinder and cortex by estimating the proportion of corm tissue affected by galleries. The observations on the four sections (upper section inner cylinder, upper section outer section, lower section inner cylinder, lower section outer section) were averaged to generate a total cross-section damage estimate.

The severity of the banana streak virus infection was evaluated using the 0-3 symptom scale of Dahal et al. (1998, 2000b) where 0 represents the situations with no visible symptoms of the disease, 1 represents situations where less than 10% of the leaf area shows chlorotic streaks or flecks, 2 witnesses moderate severity (10-50%) and in 3 more than 50% of the leaf area is covered by chlorotic streaks or flecks. The number of the youngest spotted leaf was used as an index for black Sigatoka severity (Rubaihayo et al., 1994). Leaves were numbered downwards from the topmost (first) open leaf.

2.2.3. Data analysis

A. Boundary Line Analysis (BLA)

Data for 31 factors (soil chemical characteristics, crop management and pests) were available for the three regions in Rwanda. For the Ntungamo area (Uganda), additional data on diseases (Black Sigatoka and Banana Streak Virus severity) were available. The choice of the factors finally retained for the Boundary Line Analysis (BLA) relied on (1) expert knowledge and literature review and (2) a significant (P<0.10) correlation between the independent biophysical factor and banana yield. Since the data for the various factors did not have a normal distribution, correlation was verified using Spearman's rank correlation test for non-parametric data. The effectiveness of the relation announced by Spearman's test was verified by scatterplots. When different factors containing similar information showed significant correlations with yield (for instance, K_{exch}

($cmol_c.kg^{-1}$), $K_{exch}/(K+Ca+Mg)_{exch}$ ($cmol_c.kg^{-1}/cmol_c.kg^{-1}$), $K_{exch}/(Ca+Mg)_{exch}$ ($cmol_c.kg^{-1}/cmol_c.kg^{-1}$)), a principal component analysis (PCA) was performed on those factors. In order to avoid redundancy and to reduce the number of factors, only one of the variables grouping together in the correlation circle was retained as a representative for that group.

The boundary line bordering the scatterplots of bunch weights (Y-axis) against the selected biophysical factors (X-axis) was obtained using the BOLIDES-algorithm of Schnug et al. (1996), after elimination of outliers by the circle method of Schnug et al. (1996). The boundary lines were fitted through the boundary points generated by BOLIDES, using

- a logistic equation [eq.2] when there was a positive correlation between yield and the biophysical factor (Fermont et al., 2009; Wairegi et al., 2010)

$$\mathrm{Y(X)} = \frac{\mathrm{Y_{att,region}}}{1 + (\mathrm{K\,x\,exp}(-\mathrm{R\,x\,X}))} \qquad [\mathrm{eq.\,2}]$$

  where *Y(X)* is the boundary line, *X* are the observed values for the biophysical factor under consideration, $Y_{att,region}$ (where region = Butare, Kibungo, Ruhengeri, Ntungamo) is the maximum bunch weight observed in each region separately, K and R are constants.

- a second degree polynomial if the relation between yield and the biophysical factor was bell-shaped ($Ca_{exch}/(K+Ca+Mg)_{exch}$, $Mg_{exch}/(K+Ca+Mg)_{exch}$, K_{exch}/Ca_{exch} or $K_{exch}/(Ca+Mg)_{exch}$ ($cmol_c.kg^{-1}/cmol_c.kg^{-1}$)) (Lacoeuilhe and Martin-Prével, 1971a; Lahav and Turner, 1983; Martin-Prével, 1984; Wortmann et al., 1994a).

- a straight line with negative slope, when bunch weights and biophysical factor were negatively correlated and alternative fits (e.g. sigmoid curve) did not yield significantly better fits.

The equations for the boundary lines for each of the m individual factors are used to calculate, for each of the n plots, the bunch weights that would have been obtained if the test factor was the only variable limiting yield : $Y(X_{1,1})$, $Y(X_{2,1})$, …, $Y(X_{m,1})$, …, $Y(X_{1,n})$, $Y(X_{2,n})$, …, $Y(X_{m,n})$, where the first index refers to the 1 to m selected factors, and the second to the 1 to n plots. For each factor and each plot, the yield gap between the calculated bunch weight $Y(X_{i1,i2})$ (i1 = 1,..,m; i2 = 1,…,n) and the highest bunch weight observed in the farmer's field in the region of interest ($Y_{att,region}$) can be computed. The yield gap is expressed as a percentage of $Y_{att,region}$ to allow comparison amongst regions (Wairegi et al., 2010).

For each of the n plots, the minimum predicted yield considering all of the m factors, is identified [eq.3] :

$$\begin{aligned} &\text{For plot 1 in region A :} \quad && Y_{min,1} = \min\left(Y(X_{1,1}), Y(X_{2,1}), \ldots, Y(X_{m,1})\right) \\ &\qquad\vdots && \qquad\vdots \\ &\text{For plot n in region A :} \quad && Y_{min,n} = \min\left(Y(X_{1,n}), Y(X_{2,n}), \ldots, Y(X_{m,n})\right) \end{aligned} \qquad [\text{eq. } 3]$$

For each of the n plots of one region, the explained yield gap is the difference between the maximum yield observed in that region ($Y_{att,region}$) and the determined $Y_{min,i2}$ (i2 = 1,…,n). The unexplained yield gap is the difference between $Y_{min,i2}$ and the bunch weight effectively observed for that plot. The biophysical factor determining $Y_{min,i2}$ is the factor limiting the yield in the plot under consideration (Casanova et al., 1999).

B. Soil quality index (SQI)

Numerous variations in calculating the soil quality index exist, but all respect a common framework (Karlen and Stott, 1994; Andrews and Carroll, 2001; Arshad and Martin, 2002; Nortcliff, 2002; Karlen et al., 2003; Rezai et al., 2006). First, the management goals specific to the site of interest (economic goal, environmental risk, crop production,…) need to be identified (Andrews et al., 2002). Second, amongst all the data available, a representative minimum dataset of physical, chemical and biological properties is selected by using univariate and/or multivariate statistics (Brejda et al., 2000; Andrews and Carroll, 2001; Andrews et al., 2002; Rezai et al, 2006). Third, the variables of the minimum dataset are scored, using linear (Liebig et al., 2001; Andrews et al., 2002), non-linear (Karlen and Stott, 1994; Andrews et al., 2002, 2004) or class scoring techniques (Mukashema, 1997). The lowest scores are given to the values furthest away of the optimal conditions. Finally, the soil quality index is obtained by cumulating the individual scores by simple (Andrews and Carroll, 2001; Andrews et al., 2002) or weighted addition (Hussain et al., 1999; Andrews et al., 2002). Hence, the highest values for the soil quality index witness higher soil quality.

In this study the soil quality index is called upon to assess intra-regional differences in the soil's ability to sustain banana production. The representative minimum dataset considered for the index calculation was the same as that selected for the BLA, the selection criteria being (1) expert knowledge and literature review and (2) a significant relationship between yield and the biophysical factors under consideration.

The values measured for the different factors were scored using three scoring techniques:

- the class scoring technique used by Mukashema (2007). The values observed for a biophysical factor were compared to classes of values (Table 2.2). At each value is attributed the corresponding class number. The score is calculated by equation 4:

$$\text{score} = \left(\frac{1}{\substack{\text{total number of classes} \\ \text{for the considered factor}}} \right) \text{x class number} \qquad [\text{eq. } 4]$$

- the internal relative linear scoring of Liebig et al. (2001). The selected factors are distributed in two groups depending on a high value of the factor being considered "good" or "bad" for the banana production. For the factors where "more is better", scores are calculated as the measured values divided by the maximum value observed. For the factors where "less is better", scores are calculated as the division of the minimum value observed by the measured values. For a third group, observations are scored as "more is better" until reaching a threshold value and as "less is better" beyond it.

- the non-linear scoring technique advocated by Karlen and Stott (1994), Andrews and Caroll (2001) and Andrews et al. (2002). The scores were calculated by relying on the boundary lines (bell-shaped curves, sigmoid curves with an upper asymptote or straight lines with negative slope) established previously. The score attributed to a plot of one region for a biophysical factor was determined by dividing the bunch weight predicted by the boundary line for that factor for the plot under consideration ($Y(X_{i1,i2})$) by the maximum observed yield in the region ($Y_{att,region}$).

Table 2.2 (continued on following pages). Categories of values for various biophysical factors (pH in water; total nitrogen, phosphorous and calcium content; exchangeable potassium), as used by the class scoring technique.

Factor / Class number	pH_{H2O}	$\%N_{tot}$	$\%P_2O_{5,tot}$	$\%CaO_{tot}$	K_{exch} ($cmol_c.kg^{-1}$)
Reference or method, studied area	Mukashema (2007), Western Rwanda	Mukashema (2007), Western Rwanda	Analogy with Mehlich P-classes in Mukashema (2007) (*)	Analogy with Ca_{exch}-classes in Mukashema (2007) (*)	Mukashema (2007), Western Rwanda
5	[6.9, 7.6[	-	≥ 0.20	≥ 0.87	≥ 1.2
4	[7.6, 6.9[[6.2, 6.9[	-	[0.17, 0.20[	[0.50, 0.87[	[0.6, 1.2[
3	[5.2, 6.9[	≥ 0.125	[0.14, 0.17[	[0.28, 0.50[	[0.2, 0.6[
2	[4.2, 5.2[	[0.075, 0.125[	[0.12, 0.14[	[0.20, 0.28[	[0.1, 0.2[
1	[3.5, 4.2[	[0.000, 0.075[	[0.00, 0.12[	[0.00, 0.20[	[0.0, 0.1[

(*) The linear regression relationships (1) $\%P_2O_{5,tot}$ *vs.* Mehlich-P and (2) $\%CaO_{tot}$ *vs.* Ca_{exch} were considered. The limits of classes by Mukashema (2007) for Mehlich-P and $\%Ca_{exch}$ were "translated" to limits of classes for $\%P_2O_{5,tot}$ and $\%CaO_{tot}$ through those linear relationships.

Table 2.2 (continued). Categories of values for various biophysical factors (ratio between the exchangeable potassium, calcium and magnesium; surface between individual plants), as used by the class scoring technique.

Factor / Class number	$Ca_{exch}/(K+Ca+Mg)_{exch}$ ($cmol_c.kg^{-1}/cmol_c.kg^{-1}$)	$Mg_{exch}/(K+Ca+Mg)_{exch}$ ($cmol_c.kg^{-1}/cmol_c.kg^{-1}$)	K_{exch}/Ca_{exch} ($cmol_c.kg^{-1}/cmol_c.kg^{-1}$)	$K_{exch}/(Ca+Mg)_{exch}$ ($cmol_c.kg^{-1}/cmol_c.kg^{-1}$)	Surface between banana-plants (m^2)
Reference or method, studied area	Adapted boundary line procedure	Adapted boundary line procedure	Adapted boundary line procedure	Adapted boundary line procedure	
5	[0.55, 0.65[	-	[0.35, 0.45[	[0.25, 0.35[	-
4	[0.65, 0.75[[0.45, 0.55[	[0.275, 0.325[	[0.45, 0.55[[0.25, 0.35[	[0.35, 0.45[[0.15, 0.25[	-
3	[0.75, 0.85] [0.35, 0.45[	[0.325, 0.375[[0.225, 0.275[	[0.55, 0.65[[0.15, 0.25[	[0.45, 0.55[[0.05, 0.15[	≥ 10.0
2	[0.25, 0.35[	[0.375, 0.425[[0.175, 0.225[	[0.65, 0.75] [0.05, 0.15[	[0.55, 0.65] [0.00, 0.05[	[6.3, 10.0[
1	[0.00, 0.25[	[0.425, 0.475] [0.125, 0.175[	≥ 0.75 [0.00, 0.05[	≥ 0.65	[0.0, 6.3[

(°) Adapted boundary line procedure: determination of optimal conditions by the boundary line procedure of Quesnel et al. (2006), classes established to have an equal distribution.

Table 2.2 (continued). Categories of values for various biophysical factors (intercrop; weed cover, mulch thickness, root necrosis and corm damage), as used by the class scoring technique.

Factor / Class number	Intercrop (%)	Weed (%)	Mulch (cm)	root necrosis (%)	Corm damage (%)
Reference or method, studied area	Gaidashova et al. (2009), Rwanda	Gaidashova et al. (2009), Rwanda	Gaidashova (2009), Rwanda	Gaidashova et al. (2010), Rwanda	Rukazambuga et al. (1998), Uganda
5	-			-	[0, 5[
4	[0, 2[	[0, 2[	[5.0, 10.0[	[0, 2[	[5, 10[
3	[2, 20[	[2, 20[	[2.0, 5.0[	[2, 25[	[10, 15[
2	[20, 60[	[20, 60[	[0.1, 2.0[	[25, 50[	[15, 20[
1	[60, 100]	[60, 100]	[0.0, 0.1]	[50, 100]	[20, 100]

The global soil quality index was obtained by equation 5:

$$\text{soil quality index} = \frac{\sum \text{individual scores}}{\text{number of factors considered}} \text{ x } 100 \qquad [\text{eq. } 5]$$

C. Computer software

All calculations or statistical tests were carried out in *MATLAB 7.4.0 (R2007a)*. Graphs were drawn either in *Microsoft Excel 2007* or in *MATLAB*.

2.3. Results

2.3.1. Characteristics of the four regions of interest

Mean bunch weights was 10.4 kg in Butare, which was significantly ($P<0.05$) lower than the 15.9 kg observed in Kibungo, the 15.3 kg in Ruhengeri and the 14.8 kg in Ntungamo (Table 2.3). The highest bunch weights measured in Butare, Kibungo, Ruhengeri and Ntungamo were, respectively, 23.1, 27.4, 27.0 and 35.0 kg. A more conventional way of presenting yield, was by expressing it in terms of mass per surface area. Using average measured banana-mat distances, densities of 3058, 1711, 3746 and 2808 $mats.ha^{-1}$ were calculated for the regions of Butare, Kibungo, Ruhengeri and Ntungamo, respectively. This translated to mean yields of 34.5 $t.ha^{-1}.cycle^{-1}$ for Butare, 25.2 $t.ha^{-1}.cycle^{-1}$ for Kibungo, 54.7 $t.ha^{-1}.cycle^{-1}$ for Ruhengeri and 39.7 $t.ha^{-1}.cycle^{-1}$ for Ntungamo (Table 2.3).

Besides banana population densities and spacing between plants, other management differences existed between regions. Hence, the data of Table 2.3 confirmed the good management for which the farmers of Kibungo are reputed. With averages of 3.2 cm, mulch thicknesses were significantly ($P<0.05$) higher in Kibungo than in Butare, Ruhengeri or Ntungamo. In Kibungo, weeds covered only 3.2% of the surface, which was significantly lower ($P<0.05$) than the averages of 22.1 to 34.5% estimated for the other regions. The surface of the banana-plots covered by intercrops was about half in Kibungo (27.9%) or Ruhengeri (26.5%) of what it is in Butare (50.0%).

The soils of the regions of interest differed in age and parent materials. While soils in Ruhengeri were developed on Quaternary basaltic ashes, soils in Butare, Kibungo and Ntungamo were old and highly weathered soils formed on, respectively, granite, pelitic rocks, and quartzite or micaschist (Table 2.1). Soils of the Butare region were poor, with moderately acid to neutral pH (pH 5.2-7.4). They had the lowest mean values for different soil properties relating to soil fertility: total carbon, nitrogen or phosphorus content (resp. 1.80%C_{tot}, 0.14%N_{tot}, 0.15%$P_2O_{5,tot}$), cation exchange capacity (12.05 $cmol_c.kg^{-1}$), sum of exchangeable K, Ca and Mg (9.70 $cmol_c.kg^{-1}$) and total reserve in bases (TRB, 40.8 $cmol_c.kg^{-1}$). The differences with the more fertile soils of Kibungo or Ruhengeri were significant ($P<0.05$) (Table 2.3) for all mentioned factors except for TRB. The soils in Kibungo were characterized by a mean cation exchange capacity (31.00 $cmol_c.kg^{-1}$) and mean exchangeable Ca and Mg contents (resp., 18.68 $cmol_c.kg^{-1}$ and 7.39 $cmol_c.kg^{-1}$) that were significantly ($P<0.05$) higher than those measured in Butare or Ruhengeri (Table 2.3, no data available for Ntungamo or no direct comparison allowed). In Kibungo, exchangeable bases contributed for 33.9 to 59.2% (mean: 46.3%, $cmol_c.kg^{-1}/cmol_c.kg^{-1}$) to TRB.

In Ruhengeri, soils had a significantly higher total phosphorous content (in average 0.82%$P_2O_{5,tot}$, varying widely between 0.26 and 1.28%$P_2O_{5,tot}$) and total reserve in bases (382.5 $cmol_c.kg^{-1}$ in average, large range: 146.3-

610.0 $cmol_c.kg^{-1}$) than in Butare, Kibungo or Ntungamo. Exchangeable bases represented only a minor fraction of the total reserve in bases of the Ruhengeri soils (large range: 1.6-13.5%, mean 6.4%, $cmol_c.kg^{-1}/cmol_c.kg^{-1}$) (Table 2.3). The soil heterogeneity in Ntungamo was expressed by a high variability in all chemical properties (Table 2.3). pH_{H2O} ranged between 4.7 and 7.7. Mean total carbon (2.28%C_{tot}) was slightly higher than that in Butare, but absolute values varied between 0.99 and 6.70% C_{tot}. Mean Mehlich-3 extracted K, Ca and Mg were low, respectively, 0.92, 2.94 and 2.17 $cmol_c.kg^{-1}$. Total phosphorous contents varied between 0.09 and 0.92%$P_2O_{5,tot}$; total reserve in bases ranged between 23.2 and 128.4 $cmol_c.kg^{-1}$ (Table 2.3).

Data on damages by pests show that percentages in root necroses were significantly lower in Ntungamo (33.2%) than in Butare (43.7%) or Kibungo (47.9%). In Ruhengeri, average percentage of root necrosis was intermediate (36.1%, Table 2.3). Corm damage by weevil was only quantified for the plants studied in Ntungamo. Weevil damages varied widely, ranging from inexistent (0.0%) to very heavy (66.5%, Table 2.3). Concerning the diseases evaluated in Ntungamo, Black Sigatoka turned out to be minor problem since the youngest leaf showing at least 10 specks with a necrotic center was equal or superior to 5 (Rubaihayo et al., 1994). The severity of Banana Streak Virus (BSV) was assessed using the symptomatic scale of Dahal et al. (1998, 2000b). On the 77 plants for which BSV-severity was recorded, the majority (62 plants, 81%) was seriously affected, 14 others (18%) were moderately and 1 (1%) slightly affected.

Table 2.3 (continued on following pages). Range and means for selected production, management, pests and soil data.

Region	Butare		Kibungo		Ruhengeri		Ntungamo, all ten farms	
Descriptive statistics	Mean(±SD)	Range	Mean(±SD)	Range	Mean(±SD)	Range	Mean(±SD)	Range
Production	***N = 30***		***N = 38***		***N = 40***		***N = 117***	
Bunch weight (kg)	10.4(±5.2) (a)	2.0-23.1	15.9 (±6.1) (b)	4.7-27.4	15.3 (±4.4) (b)	8.2-27.0	14.8 (±7.1) (b)	1.5-35.0
Yield ($t.ha^{-1}.cycle^{-1}$)	34.5(±26.2) (a,b)	3.4-107.6	25.2 (±8.3) (a)	9.8-47.6	54.7 (±16.1) (c)	25.6-90.4	39.7 (±21.6) (b)	3.6-126.4
Management	***N = 30***		***N = 38***		***N = 40***		***N = 117***	
Surface for individual mats (m^2)	4.0(±1.9) (ln-transf : b)	1.8-8.5	6.4 (±2.0) (ln transf : c)	3.3-11.5	2.9 (±0.9) (ln transf : a)	1.4-5.5	4.2 (±1.7) (ln transf : b)	1.6-9.3
Population density ($plants.ha^{-1}$)	3058(±1306) (b)	1171-5646	1711(±508) (a)	873-3073	3746(±1158) (c)	1822-7182	2808(±1115) (b)	1074-6173
Intercrop (%)	50.0(±40.3) (b)	0.0-100.0	27.9(±30.9) (a)	0.0-100.0	26.5 (±30.5) (a)	0.0-100.0	ND	ND
Weed cover (%)	22.1(±20.9) (b)	0.0-75.0	3.2(±8.8) (a)	0.0-43.3	34.5(±18.1) (b)	0.0-75.0	31.0(±27.7) (b)	0.0-92.0
Mulch thickness (cm)	1.4(±1.4) (a)	0.0-4.7	3.2(±0.8) (b)	1.3-4.6	1.5(±1.1) (a)	0.1-5.3	1.7(±0.5) (a)	0.4 – 2.8

Legend : ND = no data ; SD = standard deviation. (a),(b),(c) = horizontal comparison between means - means followed by the same letter are not significantly different ($P<0.05$) ; ln-transf = normality of data only insured after natural log-transformation, statistical comparison is performed on the transformed data.

Table 2.3 (continued). Range and means for selected production, management, pests and soil data.

Region	Butare		Kibungo		Ruhengeri		Ntungamo, all ten farms	
Descriptive statistics	Mean(±SD)	Range	Mean(±SD)	Range	Mean(±SD)	Range	Mean(±SD)	Range
Pests	***N = 30***		***N = 38***		***N = 40***		***N = 117, for root necrosis: N = 68***	
Root necrosis (%)	43.7(±9.9) (b)	25.2-66.0	47.9(±11.3) (b)	26.4-70.6	36.1(±8.8) (a,b)	18.4-53.8	33.2(±21.1) (a)	6.0-83.0
Corm damage (%)	ND	ND	ND	ND	ND	ND	8.0(±10.7)	0.0-66.5
Soil data	***N = 30***		***N = 38***		***N = 40***		***N = 150***	
pH_{H2O}	6.1(±0.5) (a)	5.2-7.4	7.2(±0.5) (b)	6.4-8.2	7.0(±0.4) (b)	6.1-7.9	6.2(±0.8) (a)	4.7-7.7
Cation exchange capacity (CEC, $cmol_c.kg^{-1}$)	12.05(±2.87) (a)	6.20-18.30	31.00(±3.21) (c)	24.20-38.10	23.75(±10.11) (b)	9.10-40.90	ND	ND
Total carbon content ($\%C_{tot}$)	1.80(±0.59) (a)	0.80-3.14	4.63(±0.44) (b)	3.69-5.63	4.06(±1.67) (b)	1.54-7.33	2.28(±1.29) (a)	0.99-6.70
Total nitrogen content ($\%N_{tot}$)	0.14(±0.04) (a)	0.07-0.24	0.33(±0.03) (c)	0.26-0.39	0.35(±0.15) (c)	0.14-0.64	0.21(±0.11) (b)	0.08-0.58

Legend : ND = no data ; SD = standard deviation. (a),(b),(c) = horizontal comparison between means - means followed by the same letter are not significantly different (P<0.05) ; ln-transf = normality of data only insured after natural log-transformation, statistical comparison is performed on the transformed data.

Table 2.3 (continued). Range and means for selected production, management, pests and soil data.

Region	Butare		Kibungo		Ruhengeri		Ntungamo, all ten farms	
Descriptive statistics	Mean(±SD)	Range	Mean(±SD)	Range	Mean(±SD)	Range	Mean(±SD)	Range
Soil data (continued)	***N = 30***		***N = 38***		***N = 40***		***N = 150***	
Total phosphorous content (%$P_2O_{5,tot}$)	0.15(±0.06) (ln-transf : a)	0.07-0.33	0.26(±0.08) (ln-transf : b)	0.12-0.49	0.82(±0.24) (ln-transf : c)	0.26-1.28	0.20(±0.15) (ln-transf : a,b)	0.09-0.92
Exchangeable K (K_{exch}, $cmol_c.kg^{-1}$)	1.74(±0.83) (a)	0.61-3.80	3.21(±1.45) (b)	1.04-6.22	3.18(±1.54) (b)	1.09-6.43	0.92(±0.50) (not comp.)	0.18-2.83
Exchangeable Ca (Ca_{exch}, $cmol_c.kg^{-1}$)	5.82(±3.07) (a)	1.75-14.02	18.68(±4.06) (c)	10.43-29.74	14.32(±5.94) (b)	5.36-24.20	2.94(±2.63) (not comp.)	0.11-11.70
Exchangeable Mg (Mg_{exch}, $cmol_c.kg^{-1}$)	2.14(±0.93) (a)	0.72-4.12	7.39(±1.42) (c)	4.12-9.80	3.93(±1.54) (b)	1.63-6.89	2.17(±2.01) (not comp.)	0.06-8.35
$(K+Ca+Mg)_{exch}$ ($cmol_c.kg^{-1}$)	9.70(±4.36) (a)	3.67-20.83	29.29(±5.44) (c)	16.69-43.45	21.44(±8.57) (b)	8.94-37.00	6.03(±4.73) (not comp.)	0.72-20.27
Total Reserve in Bases (TRB, $cmol_c.kg^{-1}$)	40.8(±17.7) (a)	23. 7-104.1	63.8(±12.3) (a)	38.2-91.9	382.5(±93.6) (b)	146.3-610.0	60.9(±27.4) (a)	23.2-128.4
$(K+Ca+Mg)_{exch}$/TRB ($cmol_c.kg^{-1}/cmol_c.kg^{-1}$)	25.2(±10.3) (b)	9.0-46.3	46.3(±6.1) (c)	33.9-59.2	6.4(±3.6) (b)	1.6-13.5	9.2(±5.9) (not comp.)	1.5-48.4

Legend : ND = no data ; SD = standard deviation. (a),(b),(c) = horizontal comparison between means - means followed by the same letter are not significantly different ($P<0.05$) ; ln-transf = normality of data only insured after natural log-transformation, statistical comparison is performed on the transformed data.

2.3.2. Boundary Line Analysis (BLA)

About thirty variables were available for the BLA: pH_{H2O}, total nitrogen content ($\%N_{tot}$), total carbon content ($\%C_{tot}$),$\%C_{tot}/\%N_{tot}$, cation exchange capacity (CEC), exchangeable potassium, calcium and magnesium (K_{exch}, Ca_{exch}, Mg_{exch}), sum of exchangeable cations and ratios between them ($(K+Ca+Mg)_{exch}$, $K_{exch}/(K+Ca+Mg)_{exch}$, $Mg_{exch}/(K+Ca+Mg)_{exch}$, $Ca_{exch}/(K+Ca+Mg)_{exch}$, $K_{exch}/(Ca+Mg)_{exch}$, K_{exch}/Ca_{exch}, K_{exch}/Mg_{exch}, ratios expressed as $cmol_c.kg^{-1}/cmol_c.kg^{-1}$), total reserve in bases (TRB), $(K+Ca+Mg)_{exch}/TRB$ ($cmol_c.kg^{-1}/cmol_c.kg^{-1}$), total elemental analysis ($\%Al_2O_3$,$\%Fe_2O_3$,$\%SiO_2$,$\%TiO_2$,$\%CaO$,$\%K_2O$,$\%MgO$,$\%MnO_2$,$\%Na_2O$,$\%P_2O_5$), distances between banana-plants, weed cover, mulch thickness, root necrosis, intercrop (for Butare, Kibungo and Ruhengeri). For Ntungamo, data on corm damage were also available.

The following factors were finally retained for the BLA based on (1) Spearman's rank correlation test, (2) refinement by PCA, (3) expert's advice and literature reviews. For the Butare region, the analysis was performed on$\%N_{tot}$, K_{exch}, $Ca_{exch}/(K+Ca+Mg)_{exch}$, $K_{exch}/(Ca+Mg)_{exch}$, intercrop, weed cover and mulch thickness. $Mg_{exch}/(K+Ca+Mg)_{exch}$, $K_{exch}/(Ca+Mg)_{exch}$, surface between banana-plants, weed cover, mulch thickness and root necrosis were considered in the BLA in the Kibungo area. Four factors were included in the BLA for Ruhengeri: $K_{exch}/(Ca+Mg)_{exch}$, surface between banana-plants, weed cover, mulch thickness. For Ntungamo, pH_{H2O},$\%P_2O_{5,tot}$,$\%CaO_{tot}$, $Ca_{exch}/(K+Ca+Mg)_{exch}$, K_{exch}/Ca_{exch}, surfaces between banana-plants, weed cover, mulch thickness, root necrosis and corm damage were retained for further analysis. For each region separately, boundary lines were established for each factor individually (Figure 2.2). Note that ratios between cations or TRB ar eall expressed as $cmol_c.kg^{-1}/cmol_c.kg^{-1}$. The attempt to draw a boundary line over the categorical data for Banana Streak Virus gathered at Ntungamo, remained inconclusive because of an over-representation of one category compared to the two others.

The barplot (Figure 2.3) summarizes the biophysical factors identified as limiting by the BLA. Banana yield was limited primarily by factors related to soil fertility in the case of Butare (70%) and Ntungamo (50%). In Kibungo (52%) and Ruhengeri (73%), crop management limited yields most.

In more detail, total nitrogen content and a cationic desequilibrium reflected by K_{exch}, $Ca_{exch}/(K+Ca+Mg)_{exch}$ and $K_{exch}/(Ca+Mg)_{exch}$ (ratios as $cmol_c.kg^{-1}/cmol_c.kg^{-1}$) limited yield in Butare in respectively 13% and 57% of the plants. The remaining 30% of plants were limited by insufficient management practices (mulch thickness 17%; weed cover 13%). In Ntungamo, soil acidity, total phosphorous content and cationic desequilibrium ($\%CaO_{tot}$, $Ca_{exch}/(K+Ca+Mg)_{exch}$ and K_{exch}/Ca_{exch}, ratios as $cmol_c.kg^{-1}/cmol_c.kg^{-1}$) limited bunch weights for respectively 23%, 15% and 12% of the studied plants. Management factors limited yield in 25% of the cases (18% weed cover, 5% distance between plants, 2% mulch cover). Damages attributed to pests limited yield in another 25% (17% corm damage, 8% root necrosis). Management limited the bunch weights of 52% of the banana-plants studied in Kibungo: wide spacing between the plants was the major factor being incriminated (34%). Other management factors (weed cover 13%; mulch thickness 5%) were less limiting in Kibungo than in the other regions. Cationic desequilibrium ($Mg_{exch}/(K+Ca+Mg)_{exch}$ and $K_{exch}/(Ca+Mg)_{exch}$, ratios as $cmol_c.kg^{-1}/cmol_c.kg^{-1}$) and root necrosis limited yield in 37% and 11% of plants. In Ruhengeri, inadequate management limited bunch weights of 73% of the analyzed plants (38% distance between plants, 20% weed cover, 15% mulch thickness). The remaining 27% of plants saw their yield constrained by soil fertility, more precisely: $K_{exch}/(Ca+Mg)_{exch}$.

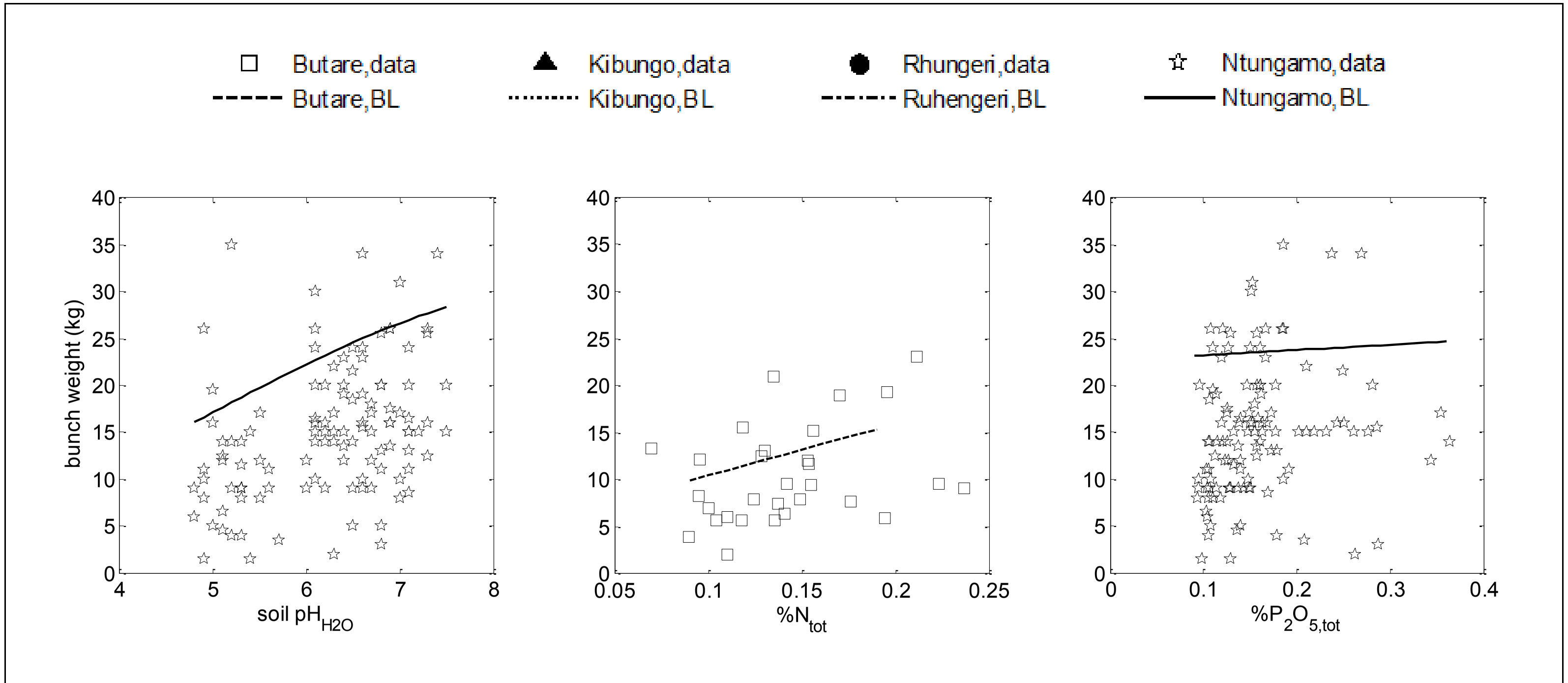

Figure 2.2 (continued on following pages). Boundary lines (BL) relating bunch weights to the values measured for the biophysical factors retained for further analysis.

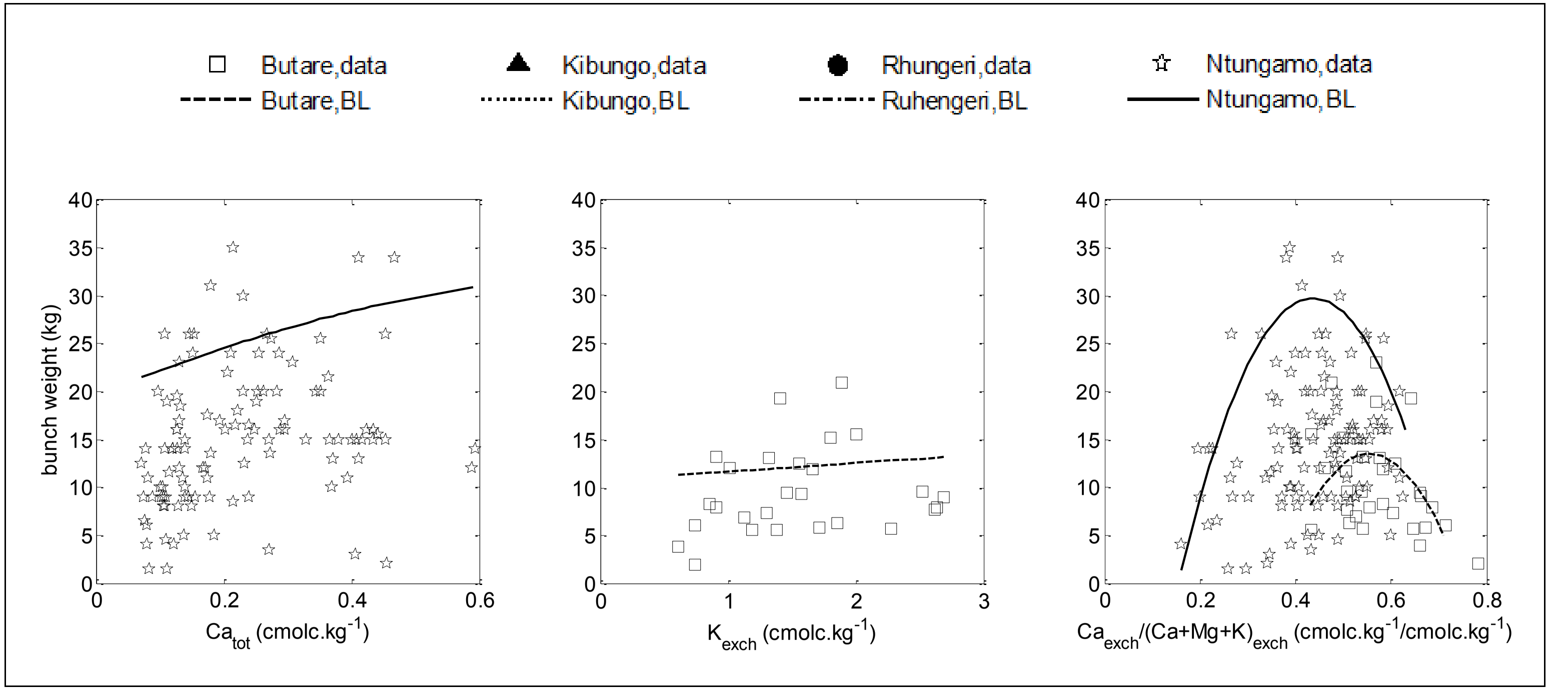

Figure 2.2 (continued). Boundary lines (BL) relating bunch weights to the values measured for the biophysical factors retained for further analysis.

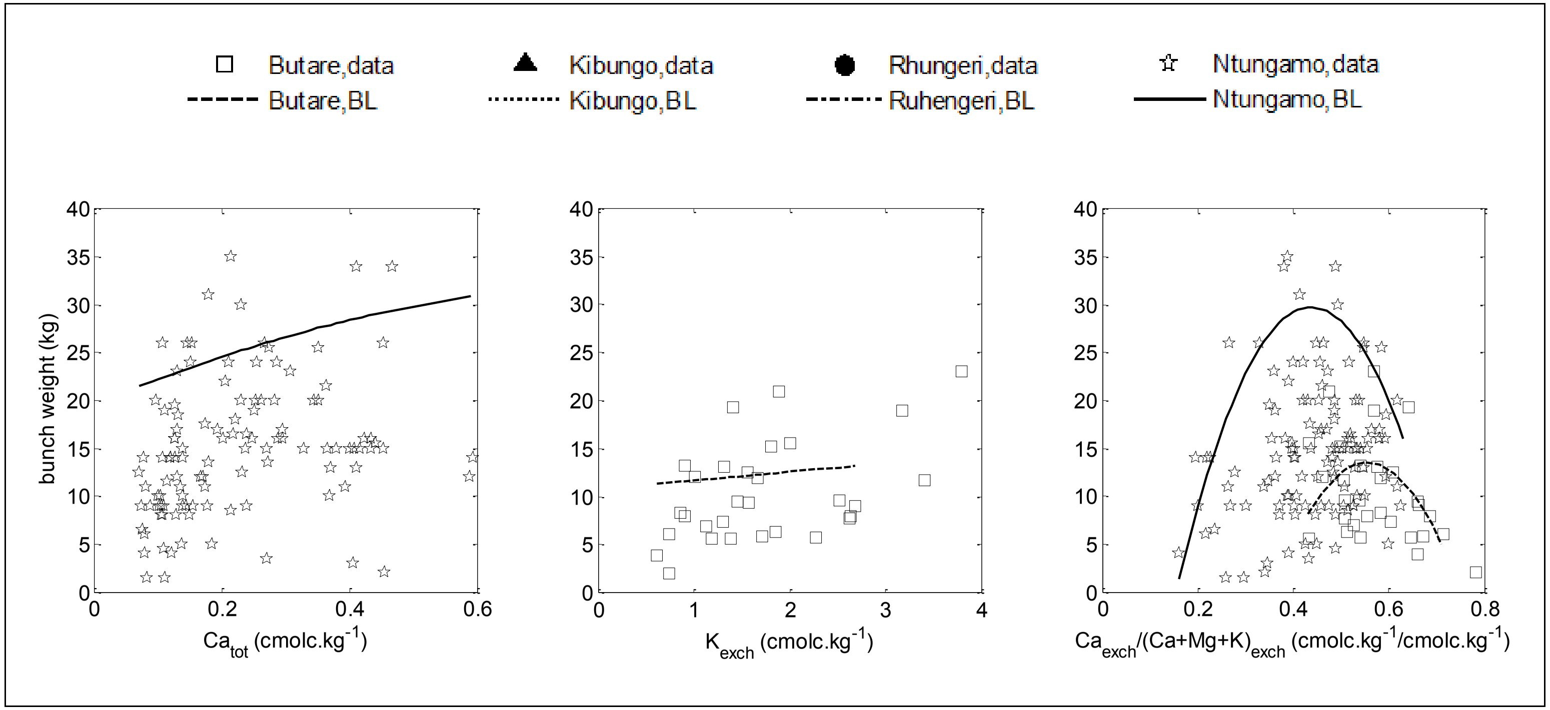

Figure 2.2 (continued). Boundary lines (BL) relating bunch weights to the values measured for the biophysical factors retained for further analysis.

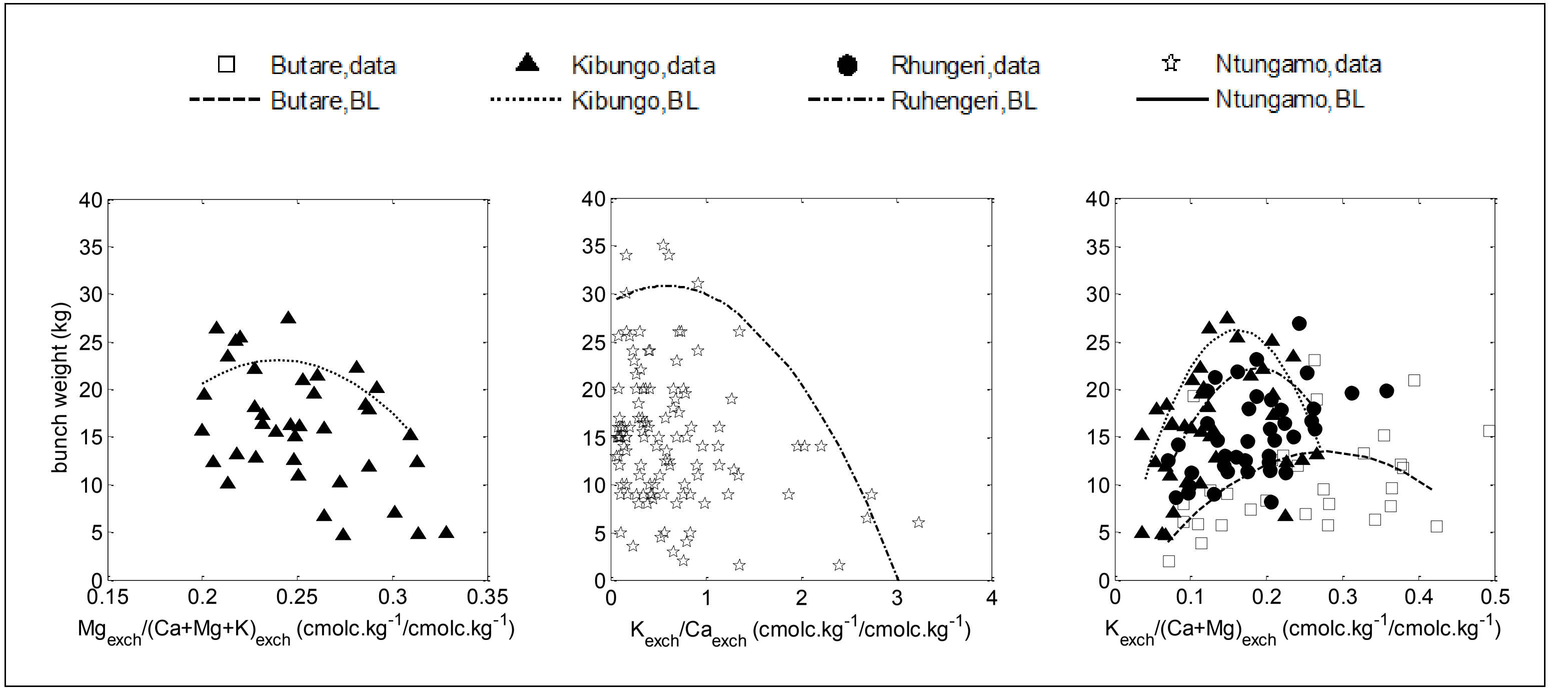

Figure 2.2 (continued). Boundary lines (BL) relating bunch weights to the values measured for the biophysical factors retained for further analysis.

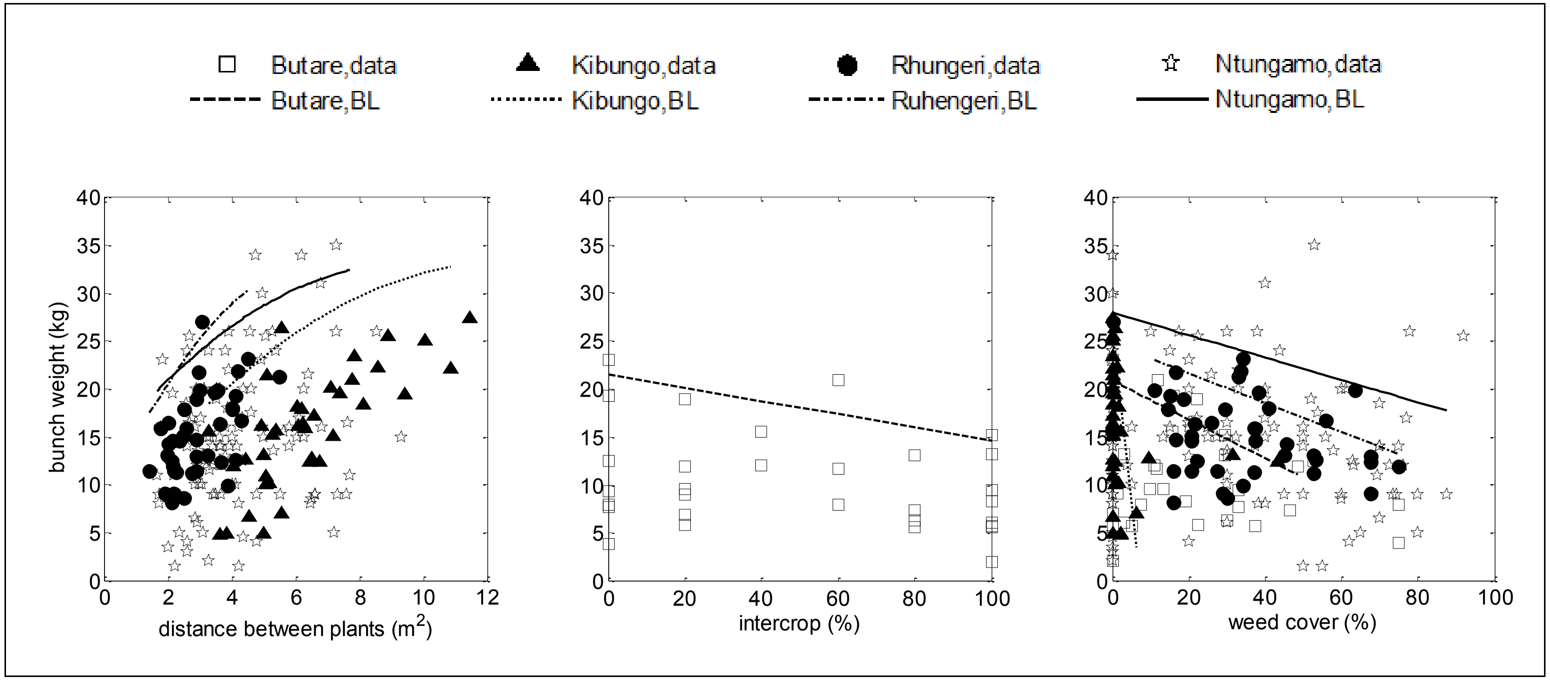

Figure 2.2 (continued). Boundary lines (BL) relating bunch weights to the values measured for the biophysical factors retained for further analysis.

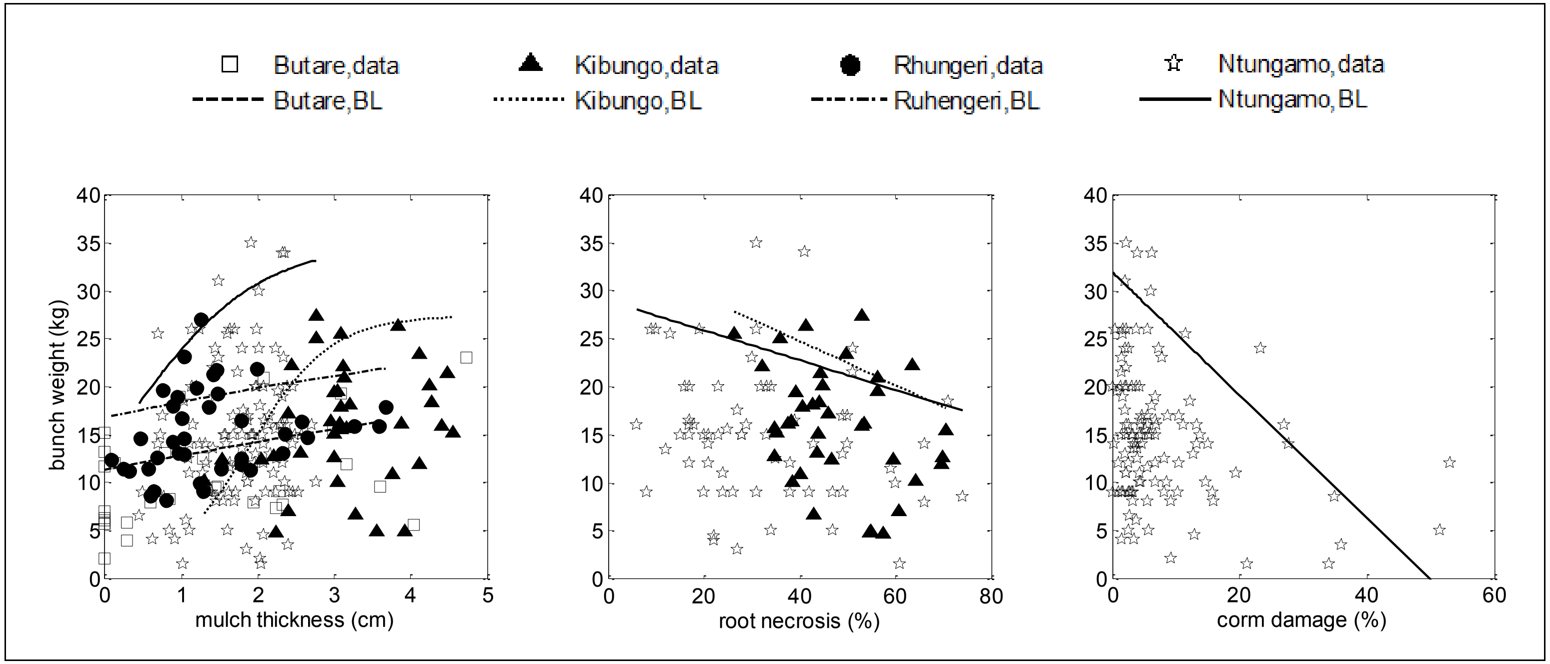

Figure 2.2 (continued). Boundary lines (BL) relating bunch weights to the values measured for the biophysical factors retained for further analysis.

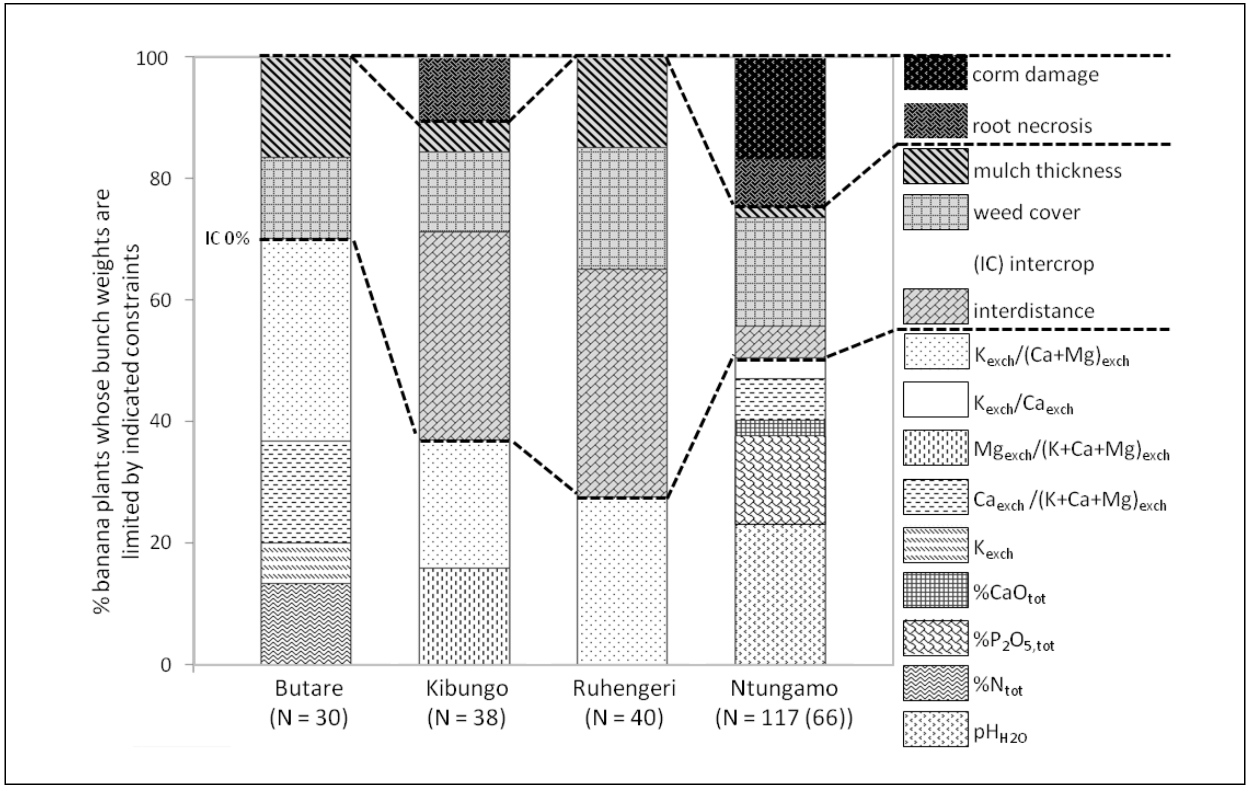

Figure 2.3. Graphic representation of the proportion of banana plants whose bunch weights were limited by different factors (soil chemical characteristics, management practices, damages due to pests) according the Boundary Line Analysis. From left to right: data for Butare, Kibungo, Ruhengeri and Ntungamo.

The relationship between minimum predicted bunch weights by BLA ($Y_{min,i2}$ [eq.2]) and measured bunch weights is represented in Figure 2.4. Points plotting close to the 1:1-line represent plants whose bunch weights were supposedly limited by the biophysical variable identified as the limiting factor. Points plotting "far" above the 1:1-line represent plants for which the yield was limited, (1) partly by the factor identified as limiting, (2) partly by one or more unidentified factors and (3) partly by interacting limiting factors. Points plotting "far" below the 1:1-line, are plants which have been discarded as outliers during the BLA. Since the outliers were not considered during the establishment of the boundary lines, the related equations did not really account for those data. This explained, for the outliers, the low minimum predicted bunch weights relatively to the corresponding observed yields. Amongst the outlying plants were some bananas for which a negative yield was calculated when using the equations of the boundary lines. These negative values were put equal to zero in Figure 2.4.

For Butare, Kibungo, Ruhengeri and Ntungamo, the coefficients of determination R-squared between the minimum predicted bunch weights and the observed yields, were, respectively, 0.19, 0.44, 0.34, 0.17 when the points recognized as outliers in the BLA were discarded. The mean explained yield gap was 13.5 kg for Butare, 11.9 kg for Kibungo, 10.9 kg for Ruhengeri and 8.8 kg for the region of Ntungamo. These explained gaps amounted to respectively 58, 43, 40 and 25% of the maximum yield ($Y_{att,region}$) measured in each region separately. The mean unexplained yield gap was 0.7 kg in Butare, 0.0 kg in Kibungo, 1.8 kg in Ruhengeri and 4.4 kg in Ntungamo; the minimum predicted bunch weights calculated for the outliers of the BLA were not considered in the calculation of these means.

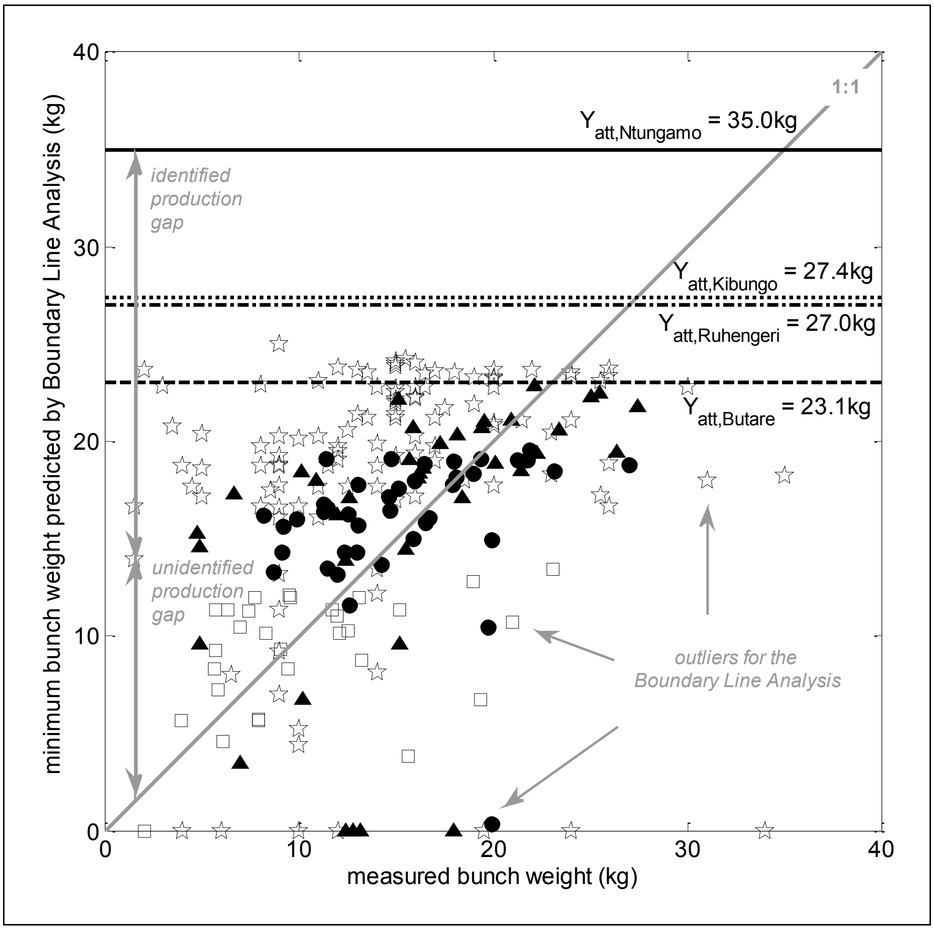

Figure 2.4. Comparison of measured bunch weights and the minimum bunch weights predicted by Boundary Line Analysis, for the Butare (squares), Kibungo (triangles), Ruhengeri (filled circles) and Ntungamo (stars) regions. The horizontal lines between 23.06 and 35.0kg represent the highest yield attained ($Y_{att,region}$) in the regions of interest.

Yield gaps were calculated for each factor selected for the BLA in each of the four regions. The gaps were expressed as percentages of the maximum yield actually measured in each area ($Y_{att,region}$), to allow a comparison between regions. The distribution of the calculated yield gaps was not normal, so medians (instead of means) were compared using the Kruskal-Wallis nonparametric one-way analysis of variance (instead of the classical ANOVA). Results are represented by boxplots in Figure 2.5. In Butare, production gap medians were, in decreasing order: $K_{exch}/(Ca+Mg)_{exch}$ (49%), K_{exch} (47%),%N_{tot} (46%), $Ca_{exch}/(K+Ca+Mg)_{exch}$ (46%), mulch thickness (45%), surface between plants (32%), weed cover (23%) and intercrop (22%). In Kibungo, the large distances between mats contributed most to the yield gap median (25%). They were followed by $Mg_{exch}/(K+Ca+Mg)_{exch}$ (19%), $K_{exch}/(Ca+Mg)_{exch}$ (19%), root necrosis (13%), mulch thickness (9%) and weed cover (4%). In Ruhengeri, mulch thickness had the largest yield gap median (30%) followed by distance (29%), weed cover (27%) and $K_{exch}/(Ca+Mg)_{exch}$ (23%). In Ntungamo, yield gap medians were, in decreasing order:%$P_2O_{5,tot}$ (33%), pH_{H2O} (31%), root necrosis (30%), weed cover (30%),%CaO_{tot} (29%), surface between plants (26%), $Ca_{exch}/(K+Ca+Mg)_{exch}$ 20%), corm damage (16%), mulch thickness (15%) and K_{exch}/Ca_{exch} (13%).

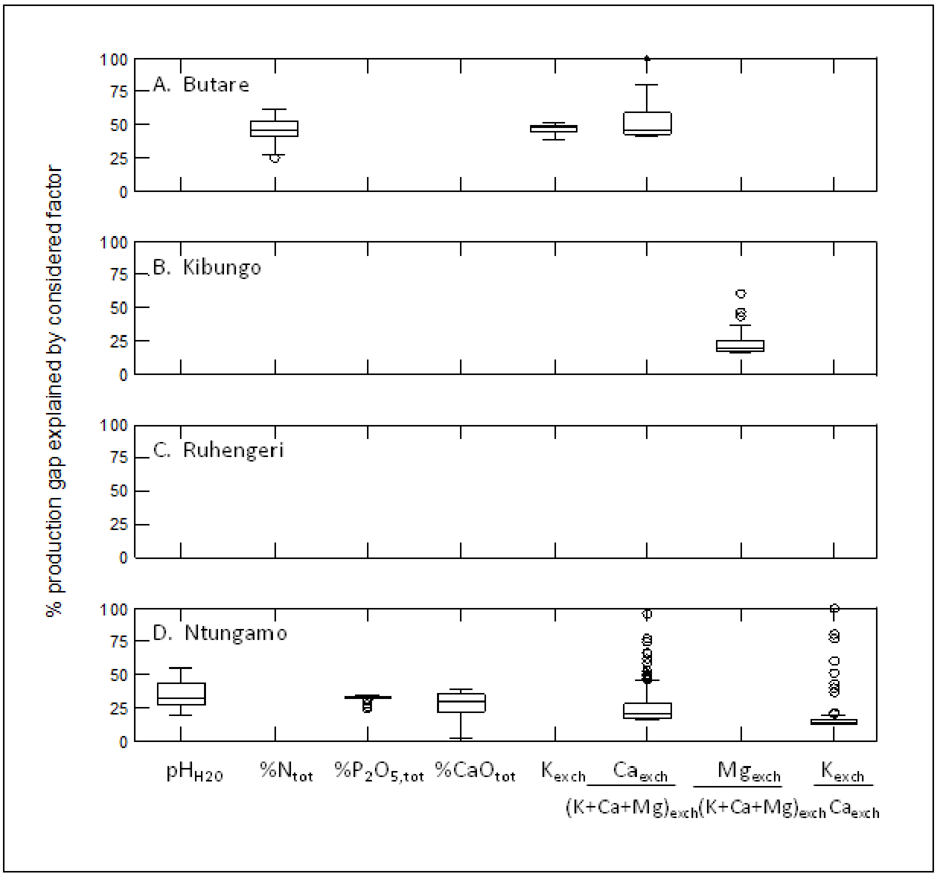

Figure 2.5 (continued on next page). The yield gaps explained by the biophysical factors considered in the Boundary Line Analysis, for (A) Butare, (B) Kibungo, (C) Ruhengeri and (D) Ntungamo. From base to summit, the horizontal lines of each box represent the lower quartile, the median and upper quartile values. Whiskers extend from each end of the box to represent the values within 1.5 times the interquartile range from the ends of the box. The circles beyond the ends of the whiskers are outliers.

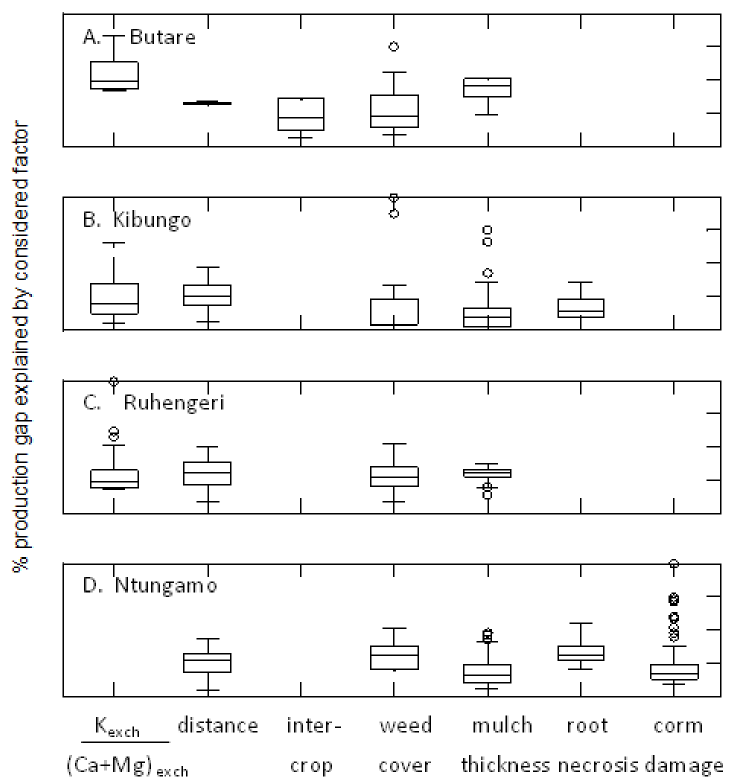

Figure 2.5 (continued). The yield gaps explained by the biophysical factors considered in the Boundary Line Analysis, for (A) Butare, (B) Kibungo, (C) Ruhengeri and (D) Ntungamo. From base to summit, the horizontal lines of each box represent the lower quartile, the median and upper quartile values. Whiskers extend from each end of the box to represent the values within 1.5 times the interquartile range from the ends of the box. The circles beyond the ends of the whiskers are outliers.

2.3.3. Soil quality index (SQI)

The calculated soil quality indices spreads were similar for the three scoring methods. All regions together, indices ranged from 32 to 96 when using the class scoring technique, from 19 to 88 with the linear scoring technique and from 53 to 99 for the non-linear scoring technique. The plots collecting the highest soil quality indices were those having the best soil quality in terms of banana yield.

Table 2.4 represents the linear relationships between bunch weights and the soil quality indices, calculated by three different techniques of scoring. Except for the linear scoring technique on the data for Butare (P=0.12) or Ntungamo (P=0.08), all relationships are significant at the 95% level of significance with coefficients of determination R-squared varying between 0.14 and 0.44. Bunch weights (BW, Y-axis) and soil quality indices (SQI, X-axis), were consistently positively correlated for all the methods used. However, the non-linear scoring technique generates the highest slopes and generates the best fits (R^2), with the exception of the Ruhengeri site where linear scoring performed better. The graphs in Figure 2.6 represent the bunch weights against the soil quality indices (non-linear scoring technique) for the four regions. Intra-regional differences indicate that in Butare, Kibungo and Ruhengeri, the low vigor plants have lower soil quality indices than soils under high vigor plants. A paired sample *t*-test confirmed that in all the regions (Butare P=0.10; Kibungo P=0.04; Ruhengeri P=0.05) except for Ntungamo (P=0.27) soil quality indices were higher in A-plots/subplots (high vigor plants) than in B-plots/subplots (low vigor plants).

Table 2.4. Linear relationship between bunch weights (BW) and the soil quality indices (SQI), calculated by class, linear or non-linear scoring.

Scoring method / Region	Class scoring (CSQI)	Linear scoring (LSQI)	Non-linear scoring (NSQI)
Butare (N=30)	BW = (0.30*SQI) - 11.72 R^2 = 0.28 ; p-value = 0.00	BW = (0.11*SQI) + 6.12 R^2 = 0.08 ; p-value = 0.12	BW = (0.33*SQI) - 15.99 R^2 = 0.31 ; p-value = 0.00
Kibungo (N=38)	BW = (0.59*SQI) - 23.26 R^2 = 0.35 ; p-value = 0.00	BW = (0.24*SQI) + 1.04 R^2 = 0.31 ; p-value = 0.00	BW = (0.39*SQI) - 16.49 R^2 = 0.43 ; p-value = 0.00
Ruhengeri (N=40)	BW = (0.26*SQI) + 1.06 R^2 = 0.19 ; p-value = 0.00	BW = (0.39*SQI) + 3.32 R^2 = 0.44 ; p-value = 0.00	BW = (0.31*SQI) - 9.98 R^2 = 0.19 ; p-value = 0.01
Ntungamo (N=66)	BW = (0.24*SQI) + 0.86 R^2 = 0.14 ; p-value = 0.00	BW = (0.18*SQI) + 8.24 R^2 = 0.05 ; p-value = 0.08	BW = (0.49*SQI) - 26.06 R^2 = 0.22 ; p-value = 0.00

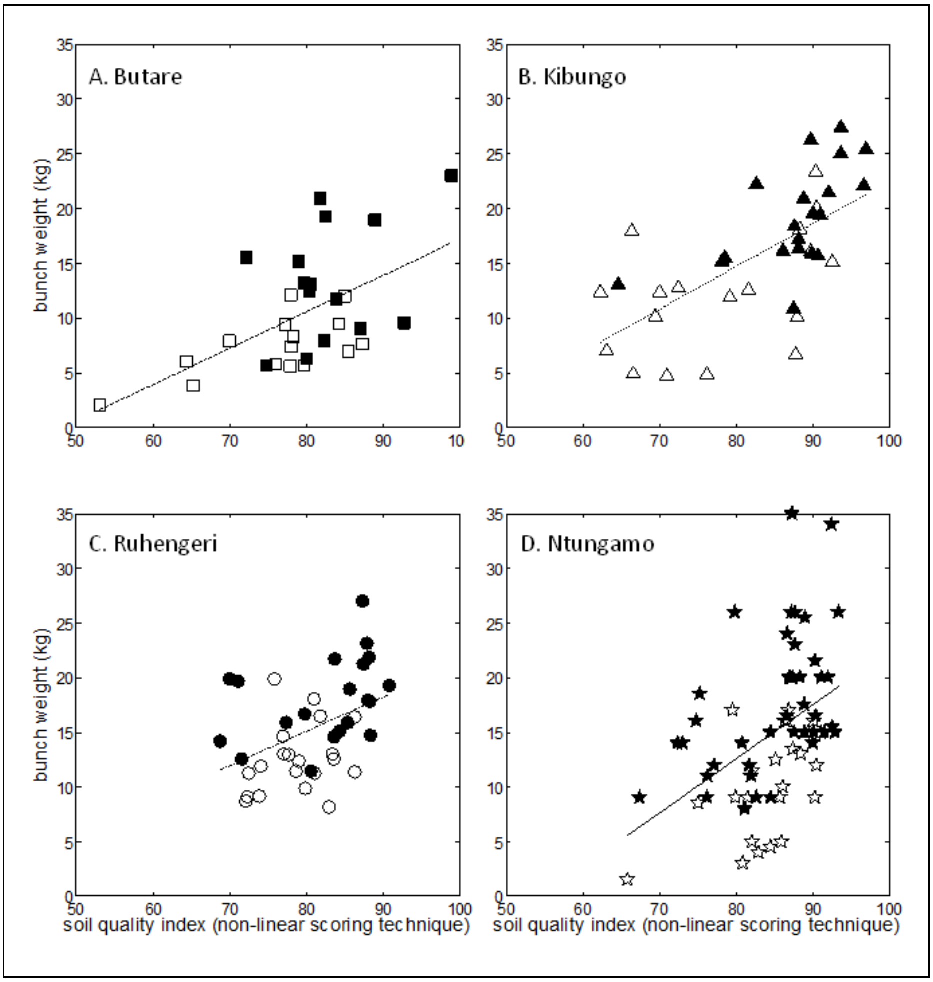

Figure 2.6. Graphs highlighting the intra-regional variability of plant production and soil quality indices. Full squares (graph A, Butare), triangles (graph B, Kibungo), circles (graph C, Ruhengeri) or stars (graph D, Ntungamo) represent the A-plots/subplots sustaining high vigor plant. The open symbols represent the B-plots/subplots on which grow low vigor plants.

2.4. Discussion

2.4.1. Banana yield

The highest yields are observed for Ruhengeri (54.7 t.ha^{-1}.cycle^{-1}) because of a combination of high bunch weights and high mat densities. Despite high bunch weights, yields calculated for Kibungo (25.2 t.ha^{-1}.cycle^{-1}) are significantly lower than in Ruhengeri or Ntungamo because of its significantly lower plant-population density. Lower bunch weights are reported for Ntungamo and, even more so, for Butare. By multiplying these lower bunch weights with intermediate values of plant densities, intermediate yields are calculated (39.7 and 34.5 t.ha^{-1}.cycle^{-1} in Ntungamo and Butare, respectively) (Table 2.3). These yields in tons per hectare should be considered rough estimates because, except for Ntungamo, bunch weights are not actually measured but estimated by an allometric equation. Secondly, differential management is customary in smallholder farms of the Great Lakes Region (Bekunda and Woomer, 1996; Wortmann and Kaizzi, 1998; Baijukya et de Steenhuijsen Piters 1998; Tittonnell et al 2005a; Giller et al, 2006; Zingore et al 2007; Okumu et al 2011). The well amended high-producing subplot, usually close to the homestead, is restricted in size compared to the less well managed banana grove possibly leading to an overestimation of yields at the regional level. Wairegi et al. (2010) report yields of 20 t.ha^{-1}.year^{-1} for the south-western part of Uganda, while our data suggest yields between 26.5 t.ha^{-1}.year^{-1} (if the crop cycle duration is 1.5 years) and 39.7 t.ha^{-1}.year^{-1} (if the crop cycle duration is 1.0 year) for the same area. Lassoudière (1989) estimates the average yield in the Kibungo area at 6.4 t.ha^{-1}.year^{-1}; Bouwmeester et al. (2009) publish yields of 25.1 t.ha^{-1}.year^{-1} for the Kigali-Kibungo axis and 20.2 t.ha^{-1}.year^{-1} for Gitarama, a little North to Butare. Adopting cycle durations of 1 or 1.5 years, the estimated yields from our data are 25.2 to 16.8 t.ha^{-1}.year^{-1} for Kibungo and 34.5 to 23.0 t.ha^{-1}.year^{-1} for Butare.

2.4.2. Banana yield constraints on banana production in four different agro-ecoregions

Soil fertility is a key constraint as illustrated by the fact that soil chemical factors are amongst the most limiting parameters (Figure 2.3) and that large production reductions are associated to these factors (13-49%, Figure 2.5). Soil fertility is the dominant yield constraint on the poor soils in Butare and heterogeneous soils in Ntungamo. Despite soils being more fertile in Kibungo and Ruhengeri (Table 2.3), soil fertility still features in second position behind suboptimal crop management as a yield constraint. Cation imbalances are a key problem in all regions. In Butare and Kibungo, the contribution of exchangeable K to $(K+Ca+Mg)_{exch}$ is low, while in Ruhengeri we also observe low exchangeable Mg. Low exchangeable Ca is found in Ntungamo, where soil acidity and low total phosphorus pose a problem. In Ntungamo, the 17 plants limited by low total soil P are located on the upper slope where TRB and pH are significantly ($P<0.05$) higher. In these cases, total and non-available P are significantly related to total and non-exchangeable Ca contents (R-squared $R^2 > 0.72$). The association of calcium and phosphorus could be explained by the possible precipitation of calcium phosphates at higher pHs (up to pH7.5) observed (Bougnom et al., 2009). The limitation by total phosphorous is thus interpreted through its association with an excess of calcium on the exchange complex and induced nutritional disorders. K deficiencies are reported by Lassoudière (1989) in the Kibungo area and by Okech et al. (2000) for bananas in Ntungamo (South-Western Uganda). Banana yield increases after K-fertilizer applications in station (Okech et al., 2004; Nyombi et al., 2010) and on-farm trials (Smithson et al., 2004) in South-West Uganda confirm a K deficiency in that region. Present study is limited to the nutrients N, P, K, Ca and Mg, while micronutrients may be a problem too. Deficiencies in Zn are reported for banana in North-West Tanzania (Bekunda et al., 2003). A rapid screening of micronutrient nutritional status in banana, beans and sweet potato in the Kivu-provinces of the Democratic Republic of Congo, in Rwanda, Burundi and Uganda indicates possible deficiencies in Co and Mo (*comm. by* R. Graham, G. Lyons, University of Adelaide - School of Agriculture, food and wine). Se levels are low in the Great Lakes Region and its availability varies over short distances (*comm. by* R. Graham, G. Lyons, University of Adelaide - School of Agriculture, food and wine). Mn toxicities could be a problem on acid soils.

Suboptimal crop management is the most important yield constraint in Kibungo and Ruhengeri (Figures 2.3 and 2.5). In Kibungo, the distance between mats is the most limiting factor. Lower bunch weights are observed when spacing is reduced. The observed reduction in bunch weights is mostly related to competition for water (van Asten et al., 2011). Hydric stress, because of the low annual rainfall (900-980 $mm.year^{-1}$, Table 2.1) and the existence of a dry season, is indeed often mentioned as limiting the banana-production in this eastern part of Rwanda (Lassoudière, 1989; Verdoodt and Van Ranst, 2003; Eledu et al., 2004; Okech et al., 2005; van Asten et al., 2011). Other management practices, such as insufficient weeding or mulching, do not limit production in the area of Kibungo (Figures 2.3 and 2.5), where farmers are reputed for the good management of their fields (Lassoudière, 1989; Okech et al., 2005). In the present study, the highest yields are found in the volcanic region of Ruhengeri, because climate (temperature and rainfall), topography (absence of steep slopes) and good soil fertility (high pH, high total carbon, nitrogen and phosphorus content, high TRB) combine optimally (Gaidashova et al., 2009). The BLA shows nevertheless that banana production is limited because of suboptimal management practices, as too close planting, insufficient weeding and mulching (Figs.2.3 and 2.5). It is known for long (Ndindabahizi and Gwabije, 1991) that because of the good inherent fertility of these young volcanic soils, farmers pay little attention to replenishing their soils by mulch or manure. Suboptimal management is the second most important constraint in Butare and Ntungamo. Competition of weeds for nutrients and water is a constraint to banana production in both regions. Butare also cumulates the limitations imposed by insufficient mulching of the already poor soils. The data detailed here confirm the habitual picture of the banana-system in Butare, as drawn by the preliminary results of Lassoudière (1989).

In the regions of Kibungo and Ntungamo, damages commonly attributed to pests appear as a third constraint, next to soil fertility problems and inadequate management. Root necroses are primarily caused by plant parasitic nematodes (Speijer et al., 1994). The percentage of root necrosis is related to the numbers of nematodes (Gaidashova et al., 2009, 2010) and yield decreases due to more frequent toppling, longer production cycles or reduced bunch weights (Sarah et al., 1996; Bridge et al., 1997; Speijer et al., 1999; Speijer and Fogain, 1999). Corms are damaged by weevil larvae that feed on the corm and weaken the stability of the plant and impede nutrient uptake. Plant loss due to toppling or snapping, premature death of plants and lower bunch weights explain the observed reduced yields (Gold and Messiaen, 2000).

Root necrosis is limiting production of about 10% of the plants of Kibungo (East Rwanda) and Ntungamo (South-West Uganda) (Figure 2.3). The relatively limited impact of nematodes on plant performance in Rwanda and South-West Uganda is in line with the conclusions by others (Okech et al., 2000; Smithson et al., 2001; Gaidashova et al., 2009). In the highlands of Rwanda and South-Western Uganda, the nematode *Pratylenchus goodeyi* dominates the nematode population (Speijer et al., 1998; Gaidashova et al., 2009). The absence of significant production losses because of nematode infestation in both the Rwandan highlands (Gaidashova et al., 2009) and South-West Uganda (Smithson et al., 2001) can be explained by different reasons: (1) the altitude/temperature-related absence of the more destructive nematode *Radopholus similis* (Kashaija et al., 1994; Talwana et al., 2003), (2) the lower pathogenicity of the rwandan races of *P. goodeyi* (Gaidashova et al., 2010), (3) the effects of the nematodes being masked by the management practices (plant density, mulching) (Gaidashova et al., 2009).

Damages by weevil larvae limit production in 17% of the plants studied in Ntungamo. A median value of 16% of yield reduction is ascribed to corm damages. The limited impact of weevil in South-West Uganda corresponds to the observations of Wairegi et al. (2010). As for nematode damages, weevil tunneling seems altitude-related. Speijer et al. (1994) describe weevil damage as severe up to 1400 m*asl*, but as negligible or inexistent above this altitude. At the lower altitudes of Central Uganda, weevil contributes, since the 1970, to the decline of the highland banana (Gold et al., 1999).

2.4.3. The unexplained yield gap

The relationships between the minimum predicted bunch weights by BLA and the bunch weights actually measured, are significant but rather low for Butare ($R^2 = 0.19$) and Ntungamo ($R^2 = 0.17$), but better for Kibungo ($R^2 = 0.44$) and Ruhengeri ($R^2 = 0.34$) and comparable to R-squares (R^2) obtained in similar studies on banana or other crops (Casanova et al., 1999; Fermont et al., 2009; Wairegi et al., 2010). Expressed against the maximum production observed in each region, the explained production gap is 58, 43, 40 and 25% for the regions of Butare, Kibungo, Ruhengeri and Ntungamo, respectively. The weak to moderate correlations and the existence of unexplained gaps indicate that some major limiting factors have not been included in the present BLA or that there are interactions between biophysical factors that are not taken into account by the BLA (Wairegi et al., 2010).

Hydric stress is one constraint not considered in this study because of lack of data. The problem of drought is mentioned above for Kibungo, but could apply to the other regions also. Indeed, with an annual rainfall between 900 and 1350 mm.year^{-1} (Table 2.1), precipitations for all the regions fall below the optimal conditions for banana growth as estimated by Sys et al. (1993) or Lassoudière (2007) (1500 to 2500 mm.year^{-1}). Van Asten et al.

(2011) establish gradients of yield losses in function of rainfall in the 12 months before harvest. Every 100 mm decline in rainfall causes yield losses of 9-10% in unfertilized plots in Uganda. Considering 1500 $mm.year^{-1}$ as a minimum to avoid hydric stresses (*deduced from* Wairegi et al., 2010; van Asten et al., 2011), the regions of Butare, Kibungo, Ruhengeri and Ntungamo could suffer, respectively, 30%, 50%, 15% or 35% relative yield losses because of drought.

Also, interactions between physical factors (climate, geology, topography) or management are not taken into account by BLA. Field observations in Butare indicate that topography, water availability, possible runoff on steep slopes, and management all vary together on small scales. Gaidashova et al. (2009), for instance, show that management varies with distance to homestead. Despite their close planting and the competition for water and light that induces, bananas in the garden around the homestead perform better than plants further away and this thanks to higher mulching (Gaidashova et al., 2009). In Ntungamo also, interaction between physical factors is observed. Hence, geological strata are subvertical with their direction parallel to the valley (field observation; Geological Survey of Uganda, 1961). Topography and water availability, geology and associated soil quality thus all vary together.

Diseases are mentioned as major constraints to the banana production (Dahal et al., 2000a; Harper et al., 2002, 2004; Tushemereirwe et al., 2004; Biruma et al., 2007). As in Wairegi et al. (2010), diseases are not an important constraint in the fields considered in this study. During the Rwandan survey, the survey team did not observe high disease pressure. For Ntungamo, Black Sigatoka affection and Banana Streak Virus (BSV) severity were recorded. Black Sigatoka was discarded from the BLA, since plants were not severely attacked. Data for BSV could not be used in BLA because of their categorical nature. Working on-station and in farmer's field in Uganda, Murekezi (2005) shows nevertheless that relative yield losses because of BSV are moderate, especially in well managed plots. Yield losses decrease from 30% to 10% by mulching and fertilizing. Karamura et al. (2006, *cited in* Biruma et al., 2007) attribute high yield losses in Uganda to Banana Xanthomonas Wilt. The disease spreads through Uganda since its appearance in 2001 and transgressed already the Ugandan border. The presence of the disease is mentioned in South-West Uganda (Kalyebara et al., 2006; Tushemereirwe and Opolot, 2005 *cited in* Abele and Pillay, 2007; Tripathi et al., 2009), in Ruhengeri (Biruma et al., 2007; Reeder et al., 2007; Tripathi et al., 2009) and Kibungo (Tripathi et al., 2009). The disease was not observed in this study, neither during the Rwandan campaign (in 2006) neither during the Ntungamo monitoring (between 2005 and 2007).

As a final remark, it is worth mentioning that despite the weakness of the relationship between minimum predicted bunch weights by BLA and measured bunch weights because of (1) the omission of factors or (2) the inherent limitation of the method, field observation concord with the results of the BLA as summarized in Figure 2.3.

2.4.4. Intra-regional and intra-farm variability

The soil quality index proves to be a useful tool to highlight intra-regional and intra-farm differences in the potential of soils to sustain banana production. Soil quality indexes vary within a region and even within a same farm (Figure 2.6). Differences in production between farms of as same region have been reported elsewhere and attributed to differences in resource endowment (Crowley and Carter, 2000; Tittonnell et al. 2005b, 2007, 2010; Wopereis et al., 2006; Mwijage et al., 2009) or different position on the topographic slope (Mowo et al., 2006). Intra-farm variability is usually explained by distribution of plots on the slope (Okech et al., 2004; Gaidashova et al., 2010) or by differential management of organic matter. Indeed, plots close to the homestead receive more organic amendments (plant residues, manure, household and kitchen wastes) and are globally better managed than fields further away (Bekunda and Woomer, 1996; Wortmann and Kaizzi, 1998; Baijukya et de Steenhuijsen Piters, 1998; Tittonnell et al., 2005b; Giller et al, 2006; Zingore et al., 2007; Okumu et al., 2011).

Three scoring methods are compared when calculating the soil quality indices: class, linear and non-linear scoring (here-after abbreviated respectively as CSQI, LSQI and NSQI). Although the linear scores (LSQI) are most easily computed, the linear scoring technique proved relatively insensitive as shown by the lack of significant relationships between bunch weights and LSQI. Despite their more difficult calculations and the necessary knowledge of the factor's behavior within the system (Andrews et al., 2002), non-linear scores are preferred over the class scoring technique. The higher coefficients of determination and slopes of the relationships between bunch weight and NSQI, compared to those for CSQI, explain this preference.

2.5. Conclusions

Smallholder banana yields are far from potential and the gap between the attainable yield and the actual average yield is large (up to 91%, 83%, 70%, 96% in Butare, Kibungo, Ruhengeri and Ntungamo). Factors that lead to these large yield gaps vary strongly between regions. However, soil fertility is a key production constraint across all regions, but is particularly dominant on the poor Acrisols in this region (e.g. Butare and Ntungamo). In areas with better soils such as Kibungo and Ruhengeri, farmers can improve yields by focusing on improving their crop management through improved plant spacing, weeding, and sometimes mulch practices. Pests and diseases are not yet a major crop constraint in the high altitude (> 1500 m*asl*) areas, but outbreaks of BXW and other diseases can possibly cause much damage when not controlled. Analytical tools such as boundary line analysis and soil quality indexing proof very useful and complementary, but the weaknesses of these tools have to be well understood and we do not recommend that scientists adopt a uniform approach across sites and surveys. Significant differences between the soil quality indices of the high and the low producing banana-plants within regions, recall that the potential to sustain bananas is not uniform within the region. Possible significant relationships linking the soil quality indices and distances to the homestead witness variations of production potential within a same farm. Differences at all scales need to be considered in order to provide smallholder farmers with feasible and economically viable solutions to increase their yields. All solutions should necessarily address the problem of poor soil fertility, a major constraint all over the Great Lakes Region.

Chapter 3. Nutrient diagnosis in the East African Highland banana (Musa spp. AAA-EA): relationship between critical nutrient values and DRIS- and CND-approaches

Abstract

Plant tissue analysis is considered a practical method for evaluating nutritional disorders and formulating fertilizer recommendations. Between the various existing approaches to interpret tissue analyses, it is important to identify the method that seems most appropriate to diagnose nutrient imbalances from what is already known in literature and additional observations. This study compares four commonly used approaches for their ease of use and their final conclusions. The four approaches are: (1) Critical Nutrient Values and Sufficiency Ranges (CNV/SR), (2) conventional Diagnosis and Recommendation Integrated System (conv.DRIS), (3) DRIS including a filling value (DRIS-Rd) and (4) Compositional Nutrient Diagnosis (CND). The data analyzed are foliar nitrogen, phosphorus, potassium, calcium and magnesium concentrations and plant performance for 221 East African Highland banana-plants (Musa spp. AAA-EA, varieties *Intuntu* and *Enyeru*) grown in three agro-ecoregions in Rwanda and one in South-West Uganda. Despite its numerous drawbacks, the CNV/SR-approach is appreciated because its ease of use and accessibility. New critical nutrient values (2.33%N, 0.15%P, 3.25%K, 0.54%Ca and 0.30%Mg) and sufficiency ranges (2.35-2.81%N, 0.13-0.18%P, 3.23-4.12%K, 0.49-0.80%Ca, 0.32-0.45%Mg, K/(K+Ca+Mg)=0.56-0.69, Ca/(K+Ca+Mg)=0.18-0.26, Mg(K+Ca+Mg)=0.18-0.24, ratios expressed as $cmol_c.kg^{-1}/cmol_c.kg^{-1}$) are proposed to substantiate the still scarce data for

Musa AAA-EA. As diagnostic tools, the multi-nutrient procedures as conventional DRIS, DRIS-Rd and CND are considered superior to the CNV/SR-approach. The dataset does not permit to disregard one of these three multi-nutrient methods. Because of the easy computation of CND compared to the complicated conventional DRIS or DRIS-Rd, CND should be recommended.

Keywords
Banana (*Musa spp.* AAA-EA); CND; critical values; DRIS; East African Highlands

3.1. Introduction

The East African Highland banana (*Musa spp.* AAA-EA) is one of the major crops for the population in the African Great Lakes Region, because of the food and cash it provides to about 85% of the people (FAOstat online, estimates for 2010). Despite the efforts of small-holder farmers, on-farm banana yields are low (5-30 $t.ha^{-1}.year^{-1}$) and well below the potential yields obtained in research stations or plantations (40-70 $t.ha^{-1}.year^{-1}$) (Bekunda et al., 2004; van Asten et al., 2004). Poor soil fertility is recognized, by scientists and farmers, as a major constraint on agricultural production (Sanchez et al., 1997; Nandwa and Bekunda, 1998; Ssali, 2001; Bouwmeester et al., 2009; Mugwe et al., 2009).

The soil nutrient status can be assessed by various methods. Amongst those methods, plant tissue analysis combines the advantages of its long-time use as a diagnostic tool and its convenience (Memon et al., 2001). The plant tissue analysis allows an evaluation of the soil nutrient status, through the determination of nutrient contents in whole plants or in diagnostic subsamples. The method is based on the premises that the determined nutrient contents are (1) directly related to the nutrient status of the soil and hence (2) verify the soil's ability to supply nutrients to the plant (Black, 1993).

Critical nutrient values / sufficiency ranges (CNV/SR) (1), Diagnosis and Recommendation Integrated System (DRIS) (2) and Compositional Nutrient Diagnosis (CND) (3), are three approaches commonly used to interpret plant nutrient contents in terms of nutritional sufficiency or, on the contrary, deficiency or excess.

The approach here-after referred to as critical nutrient values / sufficiency ranges-approach (CNV/SR) is based on the general relationship between essential nutrient concentrations and plant yield (or plant growth). A downward "C"-shaped curve, represents plant yield (or plant growth) versus the essential nutrient concentrations (Bates, 1971; Dow and Roberts, 1982; Havlin et al., 2004; Memon et al., 2005). The upper point or plateau-like part of the curve corresponds to the concentration or range of concentrations for which yields are the highest and is known as the "sufficiency, optimal or luxury values/ranges". The down-going left arm of the "C"-shaped curve at the lowest nutrient concentrations crosses the concentration or concentration range known as critical nutrient value or range. Critical nutrient values or ranges are defined as "the nutrient concentrations at a specified growth stage above which there is reasonable confidence that the crop is amply supplied and below which there is reasonable confidence that the crop is deficient" (Dow and Roberts, 1982). The down-going branch of the curve at the highest nutrient concentrations is explained either by toxicity or, indirectly, by reduction of other nutrients below their critical values (Havlin et al., 2004; Memon et al., 2005). The "C"-shaped curve and its constituting domains are established by considering the relationship between yield and nutrient content (Wortmann et al., 1994a), or by agronomic experimentation and fertilizer trials (Martin-Prével, 1984; *references in* the review by Angeles et al., 1993). The CNV/SR-approach that compares nutrient data to established concentrations or concentration ranges, is repeatedly criticized. Indeed, the method fails to recognize the interaction between nutrients and the use of concentrations or ranges is restricted to the conditions under which they are established (choice of tissue sample, age of plant at sampling, plant variety, soil and climatic conditions) (Escano et al., 1981a; Martin-Prével, 1984; Walworth and Sumner, 1987; Turner et al., 1989; Angeles et al., 1993; Wortmann et al., 1994a).

In an attempt to cope with the dynamic nature of plant tissue composition, multi-nutrient procedures are developed as an alternative to the CNV/SR-approach. Hence, DRIS evaluates the adequacy of each nutrient in relation to the other nutrients included in the analysis, by using ratios between pairs of nutrients (Walworth and Sumner, 1987; Wortmann et al., 1994a). CND considers multi-nutrient ratios instead of dual ratios (Parent and Dafir, 1992; Parent et al., 1994). In both DRIS- and CND-procedures, indices of nutrients are determined by standardizing the calculated nutrient ratios against the mean and the standard deviation ("norms") of the corresponding ratios for a reference population (Walworth and Sumner, 1987; Parent and Dafir, 1992; Khiari et al., 2001a) or against published norms (Escano et al., 1981b). DRIS-norms, when established for one crop, could, in theory, be used in all situations for that crop, but give probably the best diagnosis when used for plants growing in the same environmental conditions as those under which the norms were established (Escano et al., 1981b; Walworth and Sumner, 1987; Wortmann et al., 1994a).

Many experiments have been conducted on various banana cultivars, in different countries, with diverse ecological conditions, to establish critical nutrient values and sufficiency ranges for banana. The critical values determined by Lahav and Turner (1983, *cited in* Martin-Prével, 1984) or the means of critical values published by Angeles et al. (1993) are the most often cited references in scientific literature about banana. To our knowledge, only Wortmann et al. (1994a) proposes critical nutrient values for the East African Highland banana specifically. DRIS-norms are calculated by Angeles et al. (1993) from data compiled from 26 published and unpublished studies all over the world; data relate mostly to *Cavendish* cultivars. Another set of DRIS-norms is provided by Teixeira et al. (2007) for *Cavendish* in plantations in Brazil. Wortmann et al. (1994a) derive DRIS-norms for *Musa* AAA-EA in North-West Tanzania. Wairegi (2010) considers different agro-ecoregions all over Uganda when computing her DRIS- and CND-norms and hence expects the possibility to use these norms for other East African Highland Banana production systems.

The objectives of this study are
(1) to calculate DRIS- and CND-norms for East African Highland bananas grown in South-West Uganda and in three agro-ecoregions of Rwanda, in order to substantiate the still scarce data in the Great Lakes Region;
(2) to compare the established norms to published DRIS- and CND-norms;
(3) to compare and discuss the conclusions drawn from three commonly used approaches when interpreting plant nutrient contents (critical nutrient values / sufficiency ranges (CNV/SR), DRIS and CND);
(4) to revise and complete the critical nutrient values and ranges for the East African Highland banana, by (a) a boundary-line procedure, and by (b) the innovating method of according conclusions by the CNV/SR-approach to those derived from CND.

3.2. Material and methods

3.2.1. Study areas and data collection

The study data analyzed in this study come from four different areas, three in Rwanda and one in South-West Uganda.

The Rwandan sites were near Kibungo in the East of the country, Butare in the southern part and Ruhengeri in the western volcanic area. As detailed in Gaidashova et al. (2009) these areas were chosen as they encompass different agro-ecoregions, allowing variations in altitude (1500-1760 meters avove sea-level), rainfall (900-1300mm.year^{-1}) and soil type (Nitisol on pelitic rocks, Acrisol on granite and Andosol on mafic volcanic ash). Mean annual air temperature varied between 19 and 20°C. Between March and April 2006, 20 smallholder farms were visited in each of the areas. The farms showed variability in plant potential. One or two plots per farm were selected for further description and analyses. Each plot needed to have at least five flowering banana-plants at the stage of fully opened hands. Only plants of the common East African Highland cultivar *Intuntu* were considered. Bunch weights (kg) of the five selected plants were estimated through the allometric relationship established by Gaidashova et al. (2007). In agreement with the international reference method for banana (Martin-Prével, 1980, 1984), a composite sample of the inner laminas of third leaves of the five plants was constituted. Composite foliar samples were oven-dried at 60°C for two days and then finely ground. Analysis was performed in the laboratory of UCL (Michamps, Belgium). Total N contents in the foliar samples were determined by the Kjeldahl titration. To assess their total P-, K-, Ca- and Mg-contents, the foliar samples were dry ashed at 450°C for at least 12 hours. The ashes were then digested in hot concentrated nitric acid (Novozamsky et al., 1986). K-, Ca- and Mg-concentrations in the digest were determined using an atomic absorption spectrophotometer (AAS); P-concentrations were determined by colorimetry. Nutrient concentrations are expressed as weight percentages.

The site in South-West Uganda was located near the town of Ntungamo. The biophysical characteristics of the area were described by Newton (2009). The average altitude was about 1550m*asl*, the rainfall ranged between 820 and 1300mm.year^{-1}, mean annual temperature is about 19°C. The soils were Acrisols, developed on quartzite or micaschist. Ten farms located in a same valley near Ntungamo were selected based on relative wealth status of the household and slope position of the farm. Per farm 15 banana-plants of the *Enyeru* cultivar (AAA-EA) were selected along the topographic slope, at varying distances from the homestead. The plants were followed for two years (March 2005 to April 2007) for what their production and biomass development were considered. Bunches of first ratoons were weighted with a balance having a precision of 0.5kg. In accordance with the international reference for sampling banana tissue (Martin-Prével, 1980, 1984), the inner laminas of their third leaves were sampled in the 14 days following flowering. Foliar samples were oven-dried at 60°C for 2 to 4 days, and then grounded to pass a 2mm-mesh sieve. Chemical analysis of the samples was done at the laboratory in Kawanda, Uganda, by standard methods (Okalebo et al., 2002). The dried samples were digested by a mixture of sulfuric acid and selenic acid. N- and P-concentrations in the digest were determined by colorimetry; K-, Ca- and Mg-concentrations by AAS. . Nutrient concentrations are expressed as weight percentages.

3.2.2. Data analysis

A. Critical nutrient values / sufficiency ranges (CNV/SR)

In this study, the 221 plant foliar observations from Rwanda and South-West Uganda, were compared to the critical nutrient values published (1) Lahav and Turner (1983, *cited in* Martin-Prével 1984), (2) Angeles et al. (1993) and (3) Wortmann et al. (1994a):

- Lahav and Turner (1983, *cited in* Martin-Prével, 1984): 2.60%N, 0.20%P, 3.00%K, 0.50%Ca, 0.30%Mg;

- Angeles et al. (1993): 3.03%N, 0.22%P, 3.40%K, 0.85%Ca, 0.33%Mg;

- Wortmann et al. (1994a): 3.10%N, 1.13%Ca, 0.48%Mg. No critical nutrient values were published for P and K. The mean P- and K-foliar contents of the banana plants constituting their high yield population were considered as approximates (0.25%P and 3.04%K).

For the cation ratios K/(K+Ca+Mg), Ca/(K+Ca+Mg), Mg/(K+Ca+Mg) ($cmol_c.kg^{-1}$ / $cmol_c.kg^{-1}$), the data in this database were compared to the sufficiency ranges published in the review by Martin-Prevel (1984) (K/(K+Ca+Mg)=0.50-0.70; Ca/(K+Ca+Mg)= 0.28-0.34; Mg/(K+Ca+Mg)=0.14-0.19) and in the study of Wortmann et al. (1994a) (K/(K+Ca+Mg)=0.54-0.67; Ca/(K+Ca+Mg)= 0.22-0.32; Mg/(K+Ca+Mg)=0.09-0.15).

B. Selection of a high bunch weight population

The discrimination of high and low bunch weight populations was performed using the procedure detailed in Khiari et al. (2001a) and adopted by various authors for diverse crops (Blanco-Macias et al., 2006 (Nopal Cactus); Garcia-Hernandez et al., 2009 (Pecan); Wairegi, 2010 (Banana)).

The observations of foliar data and bunch weights for all studied banana-plants, were ranked in a decreasing bunch weight order. For each plant, the filling value (Rd), geometric mean (G) and row-centered logratios ($V_{N,}$ $V_{P,}$ $V_{K,}$ $V_{Ca,}$ $V_{Mg,}$ V_{Rd}) were calculated according to the equations [1] to [3].

$$\mathrm{Rd} = 100 - (\mathrm{N} + \mathrm{P} + \mathrm{K} + \mathrm{Mg} + \mathrm{Ca}) \qquad [\mathrm{eq.}\ 1]$$

$$\mathrm{G} = (\mathrm{N\ x\ P\ x\ K\ x\ Ca\ x\ Mg\ x\ Rd})^{\frac{1}{h+1}} \qquad [\mathrm{eq.}\ 2]$$

$$\mathrm{V_N} = \ln(\mathrm{N}/\mathrm{G})\ ;\ \mathrm{V_P} = \ln(\mathrm{P}/\mathrm{G})\ ;\ \mathrm{V_K} = \ln(\mathrm{K}/\mathrm{G})\ ;\ \mathrm{V_{Ca}} = \ln(\mathrm{Ca}/\mathrm{G})\ ;\ \mathrm{V_{Mg}} = \ln(\mathrm{Mg}/\mathrm{G}) \qquad [\mathrm{eq.}\ 3]$$

where N, P, K, Ca and Mg represented respectively the total %N, %P, %K, %Ca and %Mg determined in the foliar sample and (h+1) related to the total number of components in G (h nutrients increased by the one filling value; in this case: h+1=6).

The database was then parted in two groups, using the iterative Cate-Nelson procedure (Khiari et al., 2001a). In the first subdivision, the first group retained the first two observations, while the rest was ascribed to the second group. In the second partition, the first group was constituted by the first three observations and the remainder of the dataset went to second group. The partition was successively repeated until the first group contained all but the last two observations, which are attributed to the second group. The number of observations in the first group was n_1; n_2 represented the number of observations in the second group. The total number of observations was represented by n (= n_1 + n_2). For each partitioning step i of the iterative procedure, the variance ratio for the component X was computed ($f_i(V_X)$) (eq.[4]):

$$f_i(V_X) = \frac{\text{variance of the } n_1 \text{ row centered log ratios for component X}}{\text{variance of the } n_2 \text{ row centered log ratios for component X}} \qquad [\mathrm{eq.}\ 4]$$

For each component X, equation [5] allowed to calculate the value of the cumulative variance ratio function ($F_i^C(V_X)$) at each iterative step i:

$$F_i^C(V_X) = \frac{\sum_{i=1}^{n_1-1} f_i(V_x)}{\sum_{i=1}^{n-3} f_i(V_x)} \text{ x } 100 \qquad [\text{eq. } 5]$$

The cumulative variance ratio function determined for each component X, followed a cubic pattern. The inflection point of the curve, given by root of the second derivative of the third degree polynomial equation, was the cut-off value for the component X. The cut-off value finally retained to discriminate between a high and a low bunch weight population is the maximum value for the cut-off values calculated for all of the components (h nutrients and 1 filling value Rd).

C. Compositional Nutrient Diagnosis (CND)

For each studied plant, the filling value (Rd), the geometric mean (G) and the row-centered logratios ($V_{N,}$ $V_{P,}$ $V_{K,}$ $V_{Ca,}$ $V_{Mg,}$ V_{Rd}) were computed applying the equations [1] to [3]. The means (V_N^*, V_P^*, V_K^*, V_{Ca}^*, V_{Mg}^*, V_{Rd}^*) and the standard deviations (SD_N^*, SD_P^*, SD_K^*, SD_{Ca}^*, SD_{Mg}^*, SD_{Rd}^*) of the row-centered logratios for the high bunch weight population of this study, were the CND-norms of this study. The CND-indices (I_N, I_P, I_K, I_{Ca}, I_{Mg}, I_{Rd}) were calculated using the equations [6]:

$$I_N = \frac{(V_N - V_N^*)}{SD_N^*}, \dots, I_{Ca} = \frac{(V_{Ca} - V_{Ca}^*)}{SD_{Ca}^*}, \dots, I_{Rd} = \frac{(V_{Rd} - V_{Rd}^*)}{SD_{Rd}^*} \qquad [\text{eq. } 6]$$

A measurement of the global nutrient imbalance for one plant was given by r^2_{CND} (eq.[7]):

$$r^2_{CND} = I^2_N + I^2_P + I^2_K + I^2_{Ca} + I^2_{Mg} + I^2_{Rd} \qquad [eq. 7]$$

The calculation of the row-centered logratios implied a division of each nutrient by the geometric mean of all components (nutrients and filling value) (see eq.[3]). The CND-indices were thus multi-elemental ratios, recognizing higher-order interactions between nutrients (Parent and Dafir, 1992). Indices could be ranked in order of decreasing values, hence highlighting the order in which the nutrients were the most limiting to the production (Parent et al., 1994). In theory, positive values for I_N, I_P, I_K, I_{Ca} and I_{Mg} represented nutrient excesses, and negative values nutrient insufficiencies. CND-indices close to zero evidenced nutrient balances (Parent and Dafir, 1992). In practice, “in balance” ranges around zero are sometimes used (Khiari et al., 2001b; Quesnel et al., 2006). In this study, deficiencies were interpreted with respect to the “in balance” ranges determined by the boundary line approach described below.

In the equations [6], the CND-indices were computed using the norms deduced from the high bunch weight population of this dataset. The calculation could also be performed by using published norms. In this study, CND-indices and the global index r^2_{CND} were calculated twice, once by taking into account the norms established here (abbreviated CND(D)), and a second time by referring to the norms established by Wairegi (2010, Table 3.3) (abbreviated CND(W)) for East African Highland bananas. For each nutrient in CND(D) and CND(W), the number of deficient banana plants was counted and expressed against the total number of plants (%).

D. Diagnosis and Recommendation Integrated System (DRIS)

The approach, developed by Beaufils (1957, 1971, 1973 *cited in* Walworth and Sumner, 1987) was largely broadcasted by the work of Walworth and Sumner (1987). Here-under follows a general description of the method and the calculation of its indices (summarized from Walworth and Sumner, 1987). The presented equations were adapted to the case-study of Wairegi (2010), which was used as a reference in this study.

In the conventional DRIS-approach, all pairs of the h nutrients available through foliar analysis were considered. For each pair of nutrients A and B, the ratios A/B and B/A were calculated. The one expression retained for further computation, was that one which maximizes the ratio between the variance of the low bunch weight population and the variance of the high bunch weight population. The criterion of maximizing the variance ratio, insured better chances to discriminate high and low bunch weight populations (Walworth and Sumner, 1987; Needham et al., 1990). Wairegi (2010) performed a DRIS-diagnosis on AAA-EA banana in different agro-ecoregions of Uganda. According to her, the maximum variance ratio was obtained for the ratios P/N, N/K, Ca/N, Mg/N, P/K, Ca/P, P/Mg, Ca/K, Mg/K, Ca/Mg.

For each expression retained, the means and coefficients of variation for the high bunch weight population were computed; these means and coefficients of variation (CV) are the DRIS-norms. Instead of calculating one's own norms it is also possible to use published norms when computing the DRIS indices and DRIS global index (Soltanpour et al., 1995), according to the equations [8] to [11].

If, for the nutrient data for one plant, the value of the selected expression, for instance $^{N}/_{P}$, is superior or equal to the corresponding norm $^{n}/_{p}$, then the DRIS function was calculated according to equation [8]:

$$\text{if } ^{N}/_{P} \geq {}^{n}/_{p}\,, \qquad \text{then } f\left(^{N}/_{P}\right) = \left(\frac{^{N}/_{P}}{^{n}/_{p}} - 1\right) x \left(\frac{1000}{CV}\right) \qquad [\text{eq. } 8]$$

If, the value for $^{N}/_{P}$ is inferior to the norm $^{n}/_{p}$, the function changed to (eq.[9]):

$$\text{if } ^{N}/_{P} < {}^{n}/_{p}\,, \qquad \text{then } f\left(^{N}/_{P}\right) = \left(1 - \frac{^{n}/_{p}}{^{N}/_{P}}\right) x \left(\frac{1000}{CV}\right) \qquad [\text{eq. } 9]$$

The index for one nutrient was calculated from the individual functions. The index of nutrient A, was a ratio adding/subtracting the individual functions in its numerator, and dividing that sum by the number of functions. In the numerator the functions were added or subtracted from each other depending on the place of the nutrient A in the individual ratios. When the nutrient A appeared in the numerator of nutrient ratio (f.i.: $^{A}/_{B}$), the value of the function was added (f.i.: $+f(^{A}/_{B})$). When the nutrient A appeared in the denominator of the ratio, the corresponding function was subtracted. Considering the ratios retained by Wairegi (2010), the equations to calculate the conventional DRIS-indices ($I_{N,conv.}$, $I_{P,conv.}$, $I_{K,conv.}$, $I_{Ca,conv.}$, $I_{Mg,conv.}$), were the following (eq.[10]):

$$I_{N,conv.} = \frac{\left(-f\left({}^{P}/_{N}\right) + f\left({}^{N}/_{K}\right) - f\left({}^{Ca}/_{N}\right) - f\left({}^{Mg}/_{N}\right)\right)}{4}, \dots,$$

$$I_{Mg,conv.} = \frac{\left(f\left({}^{Mg}/_{N}\right) - f\left({}^{P}/_{Mg}\right) + f\left({}^{Mg}/_{K}\right) - f\left({}^{Ca}/_{Mg}\right)\right)}{4}$$

[eq. 10]

A global nutrient imbalance index $NI_{conv.}$ was represented by the sum of the absolute values of each nutrient index taken separately (eq.[11]):

$$NI_{conv.} = abs(I_{N,conv.}) + abs(I_{P,conv.}) + abs(I_{K,conv.}) + abs(I_{Ca,conv.}) + abs(I_{Mg,conv.}) \quad [eq. 11]$$

The more negative a DRIS-nutrient index is, the more the plant is deficient in that nutrient. Positive values for a DRIS-nutrient index indicated a relative excess of that nutrient (Walworth and Sumner, 1987). A DRIS-index close to zero indicated an equilibrium but did not insure optimum concentrations for that nutrient (Walworth and Sumner, 1987), nor high yields (Angeles et al., 1993). In practice, the distinction between deficient plants and plants having a relative excess for a nutrient was not as clear-cut as having a negative or a positive DRIS-index. An “in balance” range is usually adopted to avoid diagnosing deficiencies when the deviations from zero are actually due to random errors (Baldock and Schulte, 1996). The use of “in balance” ranges was advocated by Savoy and Robinson (1990) in order to maximize correct diagnosis of nutrient balances and minimize incorrectly diagnosed deficiencies. In this study, deficiencies were interpreted with respect to “in balance” ranges determined by the boundary line approach described below.

Khiari et al. (2001c) proposed a slightly modified version of the conventional DRIS described above. In this adapted method, referred to as DRIS-Rd, the filling value Rd was considered along with the nutrients in each step of the procedure. Wairegi (2010) adopted the DRIS-Rd approach and retains the ratios $^{Rd}/_{N}$, $^{P}/_{Rd}$, $^{Rd}/_{K}$, $^{Ca}/_{Rd}$, $^{Rd}/_{Mg}$. The values of the corresponding functions were calculated by equations [8] and [9]. These additional values were taken into account when calculating the different DRIS-Rd-nutrient indices ($I_{N,Rd}$, $I_{P,Rd}$, $I_{K,Rd}$, $I_{Ca,Rd}$, $I_{Mg,Rd}$), an Rd-index (I_{Rd}), and the global index (NI_{Rd}) according to the principles already explained. The interpretation of the values for DRIS-Rd was the same than for the conventional DRIS.

In this study, the conventional DRIS and DRIS-Rd calculations were done twice. A first time by referring to the norms established by Wairegi (2010, Table 3.5) for the East African Highland banana in Uganda (abbreviated: conv.DRIS(W) and DRIS-Rd(W)). A second time by taking into account the norms computed from the high bunch weight population of present database (abbreviated: conv.DRIS(D) and DRIS-Rd(D)). For each nutrient in conv.DRIS(W), conv.DRIS(D), DRIS-Rd(W) and DRIS-Rd(D), the number of deficient banana plants was counted and expressed against the total number of plants (%).

E. Establishing optimal ranges

The critical nutrient values and sufficiency ranges are determined in two ways.

First, the existing critical nutrient values were adapted in such a manner that the conclusions drawn in terms of nutrient deficiencies tally those emanating from the CND-approach. For each nutrient, the percentage of deficient plants according to their CND(W)- and CND(D)-indices, were computed. The published critical values were incremented or decremented (0.01 steps) to scan a wide range of values. The percentages of deficient plants according to these changing critical nutrient values were successively compared to the percentages of deficient plants according to CND. The critical nutrient values finally retained minimized the sum of the absolute values of the differences between the percentages of deficient plants according to CND (%def.CND(W) and %def.CND(D)) with the percentages deficient with respect to the proposed critical nutrient values (%def.CNV) (eq.[12]):

$$\min [\ \mathrm{abs}(\%\mathrm{def.CND(W)} - \%\mathrm{def.CNV}) + \mathrm{abs}(\%\mathrm{def.CND(D)} - \%\mathrm{def.CNV})\ ] \qquad [\mathrm{eq.}\ 12]$$

The sufficiency ranges were established by a boundary line approach. The principles of the boundary lines are described in Webb (1972), and are adapted a.o. in Walworth et al. (1986), Vizcayno-Soto and Côté (2004), Quesnel et al. (2006), Blanco-Macias et al. (2009, 2010) to determine sufficiency ranges for various crops. For each nutrient, the scatterplots relating bunch weights to nutrient concentrations were made. For one nutrient, the line describing the highest bunch weights over the entire nutrient range wass known as the boundary line since it delimits the cloud of points on its upper edge.

In this study, the boundary line was established using the BOLIDES-algorithm of Schnug et al. (1996). The BOLIDES-algorithm of Schnug et al. (1996) constructs a new data base S_2 from the database (S_1) representing the N_1 points which remained after the elimination of outliers from the original database S_0. The data of the original dataset S_0 are ranked by increasing nutrient content. i_{BWmax} is the rank in S_0 of the observation having the highest bunch weight. The points ($x_i^{(2)}, y_i^{(2)}$) of S_2 are deduced from the data ($x_i^{(1)}, y_i^{(1)}$), constituting S_1, by the equations [13] to [17]:

$$x_i^{(2)} = x_i^{(1)} \quad \text{for} \quad i = 1, \dots, N_1 \qquad \text{[eq.13]}$$

$$y_1^{(1)} = y_1^{(2)} \qquad \text{[eq.14]}$$

$$y_{i+1}^{(2)} = \begin{cases} y_i^{(2)} & \text{if } y_{i+1}^{(1)} < y_i^{(2)} \\ y_{i+1}^{(1)} & \text{if } y_{i+1}^{(1)} \geq y_i^{(2)} \end{cases} \qquad 1 \leq i \leq i_{BWmax} - 1 \qquad \text{[eq.15]}$$

$$y_{i-1}^{(2)} = \begin{cases} y_i^{(2)} & \text{if } y_{i-1}^{(1)} < y_i^{(2)} \\ y_{i-1}^{(1)} & \text{if } y_{i-1}^{(1)} \geq y_i^{(2)} \end{cases} \qquad i_{BWmax} + 2 \leq i \leq N_1 \qquad \text{[eq.16]}$$

$$y_{N_1}^{(2)} = y_{N_1}^{(1)} \qquad \text{[eq.17]}$$

The succession of points ($x_i^{(2)}, y_i^{(2)}$) of the constructed database S_2 was fitted by a quadratic polynomial equation. That bell-shaped curve was the boundary line for the considered nutrient (Vizcayno-Soto and Côté, 2004; Quesnel et al., 2006). The bunch weight (Y_{BLmax}) related to the maximum of the curve was determined. The intersections of the boundary line with the straight horizontal line through 0.95*Y_{BLmax} were calculated. The interval between the x-values of the two intersections was the nutrient sufficiency range (Blanco-Macias et al., 2009, 2010).

The same approach was performed on conventional DRIS, DRIS-Rd and CND-nutrient indices to determine the optimum conditions delimitating the "in balance" ranges. This procedure already proved useful to Quesnel et al. (2006) using the combination of CND and boundary line to determine the optimum nutrient levels for trees. Here, in accordance with what was done for CND and to insure reproducible not-randomly chosen "in balance" ranges, the boundary line procedure was performed on the conventional DRIS- and DRIS-Rd-indices.

F. Computer software

All calculations and statistics were carried out in *MATLAB 7.4.0 (R2007a)*. Two-sample *t*-tests and paired-sample *t*-test were performed, after verifying normality of distributions (LillieFors-test) and equivalency of variances (*F*-test). The *t*-test is executed even if the distribution is slightly skewed, since the hypothesis test is robust to a certain violation of the assumption of normality (Smith and Wells, 2006). Differences in slopes and intercepts were assessed through MATLAB's *aoctool*. Graphs were drawn either in *Microsoft Excel 2007* or in *MATLAB*. Triangular plots were established in MATLAB using an adapted version of the script by Middleton (2000).

3.3. Results

This study provides data for 221 banana plants (AAA-EA, varieties *Intuntu* and *Enyeru*) for four agro-ecoregions in Rwanda and South-West Uganda. Throughout this study, all data are considered together.

As shown in Table 3.1, bunch weights range between 1.5 and 35.0 kg and the total nutrient contents for N, P, K, Ca and Mg between 1.49-3.11%N, 0.06-0.47%P, 1.95-4.74%K, 0.27-1.41%Ca, 0.18-0.79%Mg. The filling value Rd varies between 90.73% and 95.43%. The cation ratios of K/(K+Ca+Mg), Ca/(K+Ca+Mg), Mg/(K+Ca+Mg) ($cmol_c.kg^{-1}$ / $cmol_c.kg^{-1}$) encompass values between, respectively, 0.36-0.70, 0.08-0.41 and 0.12-0.32. The relationships between bunch weights *vs.* the total nutrient concentrations or the cation ratios show triangular patterns (Figure 3.1). Statistical tests pinpoint the distributions of N, P, Mg and K/(K+Ca+Mg) as non-normal (at the 95% significance level).

Table 3.1. Means and ranges of observed bunch weights, foliar nutrient contents and filling value (Rd). The filling value Rd is the total tissue composition minus the contents in N, P, K, Ca and Mg.

Origin of data	All data (4 regions, 2 varieties)		All data (4 regions, 2 varieties)			
			High bunch weight population		Low bunch weight population	
Statistics / Variable	Mean (N=221)	Range (N=221)	Mean (N=113)	Range (N=113)	Mean (N=108)	Range (N=108)
Bunch weight (kg)	14.5	1.5 – 35.0	19.7 (a)	14.6 – 35.0	9.6 (b)	1.5 – 14.2
N (%)	2.56	1.49 – 3.11	2.59 (a)	2.09 – 3.03	2.53 (a)	1.49 – 3.11
P (%)	0.17	0.06 – 0.47	0.17 (a)	0.10 – 0.22	0.16 (a)	0.06 – 0.47
K (%)	3.30	1.95 – 4.74	3.44 (a)	2.08 – 4.74	3.16 (b)	1.95 – 4.49
Ca (%)	0.73	0.27 – 1.41	0.73 (a)	0.27 – 1.41	0.72 (a)	0.27 – 1.13
Mg (%)	0.34	0.18 – 0.79	0.36 (a)	0.21 – 0.79	0.33 (b)	0.18 – 0.61
Rd (%)	92.86	90.73 – 95.43	92.71 (a)	90.73 – 93.90	93.10 (a)	91.06 – 95.43
K+Ca+Mg ($cmol_c.kg^{-1}$)	149.0	89.3 – 224.9	154.3 (a)	121.3 – 224.9	143.9 (b)	89.3 – 199.9
K/(K+Ca+Mg)	0.57	0.36 – 0.70	0.57 (a)	0.36 – 0.69	0.56 (a)	0.37 – 0.70
Ca/(K+Ca+Mg)	0.24	0.08 – 0.41	0.24 (a)	0.08 – 0.34	0.25 (b)	0.11 – 0.41
Mg/(K+Ca+Mg)	0.19	0.12 – 0.32	0.19 (a)	0.12 – 0.32	0.19 (a)	0.12 – 0.32

(a), (b) : horizontal comparison between high and low bunch weight populations. Means followed by different letters are significantly different ($P < 0.05$). Division of cation nutrient content ($cmol_c.kg^{-1}$) by the sum of cations ($cmol_c.kg^{-1}$) yields dimensionless values.

The cumulative variance ratio functions linking the variance ratios to the bunch weights are represented by third order polynomial equations (Table 3.2). The bunch weights related to the inflection points of the curves represented by these equations, correspond to the cut-off values between high and low bunch weight populations. The cut-off value is lowest for V_{Mg} (6.2kg) and highest for V_{Rd} (14.5kg). The highest cut-off value found is finally retained to distinguish the high bunch weight population from the low bunch weight population. The high bunch weight population comprises 49% of all observations. The mean bunch weights of both the low and the high bunch weight population are significantly different (Table 3.1). The nutritional characteristics of both populations are compared in Table 3.1. With mean K- and Mg-foliar concentrations of 3.44%K and 0.36%Mg the plants of the high bunch weight population have significantly ($P \leq 0.05$) higher foliar contents than the plants constituting the low bunch weight population (3.16%K and 0.33%Mg). The mean contents for the other nutrients do not differ significantly ($P > 0.05$) between the two populations. The means of the sum of cations and the ratio Ca/(K+Ca+Mg) are significantly ($P \leq 0.05$) different, with the high bunch weight population having higher sum of cations (154.3 vs. 149.3 $cmol_c.kg^{-1}$) and lower proportions of Ca (0.24 vs 0.25) than the low bunch weight population.

Table 3.2. Estimates of coefficients (coeff.) of the third degree polynomials representing the cumulative variance ratio function $F_i^C(V_X)$ for row-centered log-ratios (V_X) *vs.* bunch weight. Quality of fit is expressed by the determination coefficient, R^2. The cut-off values are the bunch weights (kg) corresponding to the inflection points of the curve.

	Third order polynomial p(x): $p = Ax^3 + Bx^2 + Cx + D$ relating $F_i^C(V_X)$ to bunch weight				R^2	Cut-off value
coeff. / V_X	A	B	C	D		
V_N	0.0085	-0.35	-1.19	115.82	0.98	13.5
V_P	0.0040	-0.11	-3.82	102.77	0.99	9.0
V_K	0.0080	-0.32	-1.35	111.12	0.98	13.4
V_{Ca}	0.0068	-0.23	-3.32	120.83	0.99	11.3
V_{Mg}	0.0039	-0.07	-5.52	125.05	0.92	6.2
V_{Rd}	0.0083	-0.36	-0.30	109.74	0.99	14.5

The observations of this database are compared to published critical nutrient values for banana. The conclusions in terms of nutrient deficiencies are graphically represented by the upper three bars in the barplots of Figure 3.2. The varying lengths of the bars, for a same nutrient, indicate that the conclusions may vary, depending on the set of critical nutrient values adopted. The most striking example is for Ca. According the critical values of Lahav and Turner (1983 *cited in* Martin-Prével, 1984), Angeles et al. (1993) or Wortmann et al. (1994a), respectively 10%, 79% or even 99% of the banana plants are not adequately provided with Ca. Compared to the critical values (or associated approximates) of Wortmann et al. (1994a) relating to East African Highland bananas, N-, P-, Ca- and Mg-deficiencies prevail over all the areas of interest to this study.

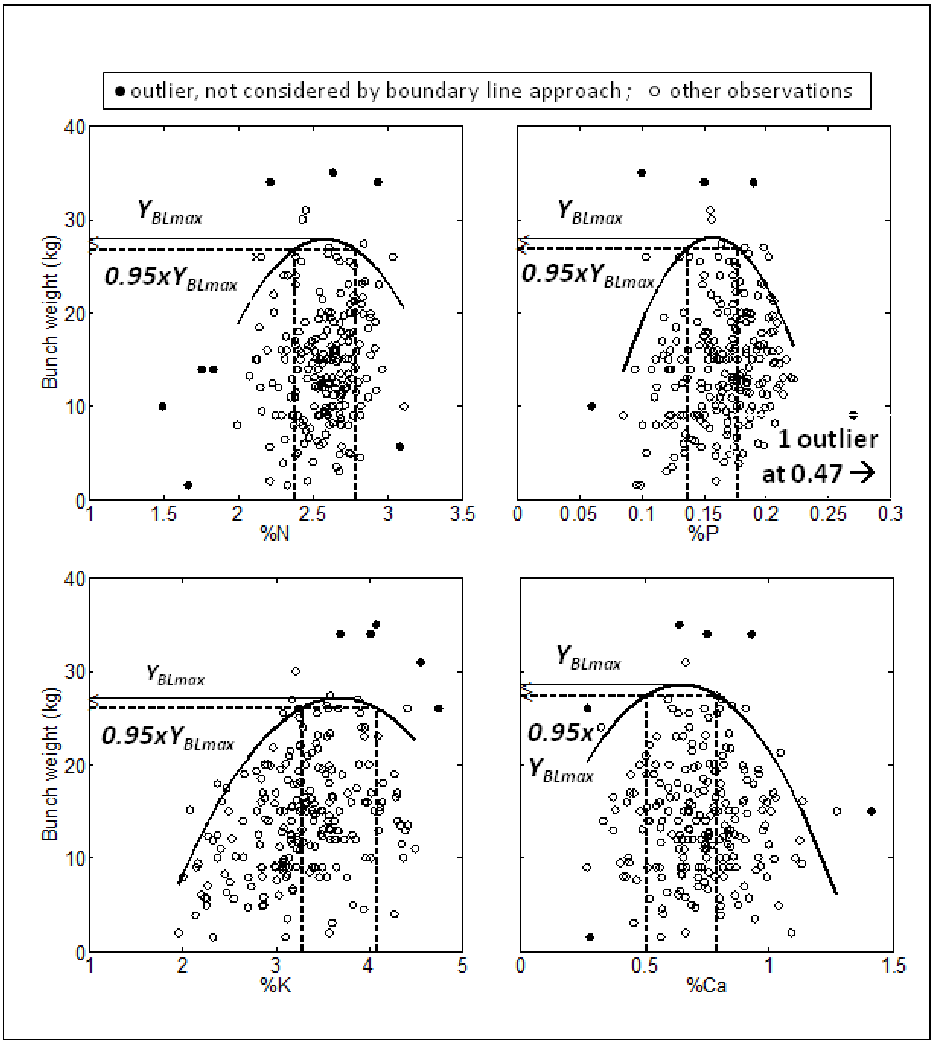

Figure 3.1 (continued on next page). Scatterplots for bunch weights against total N, P, K, Ca, Mg contents (%), K-, Ca- or Mg on sum of cations. Y_{BLmax} represents the bunch weight corresponding to the maximum of each boundary line. The intervals on the X-axis delimitated by the dotted lines are the sufficiency ranges.

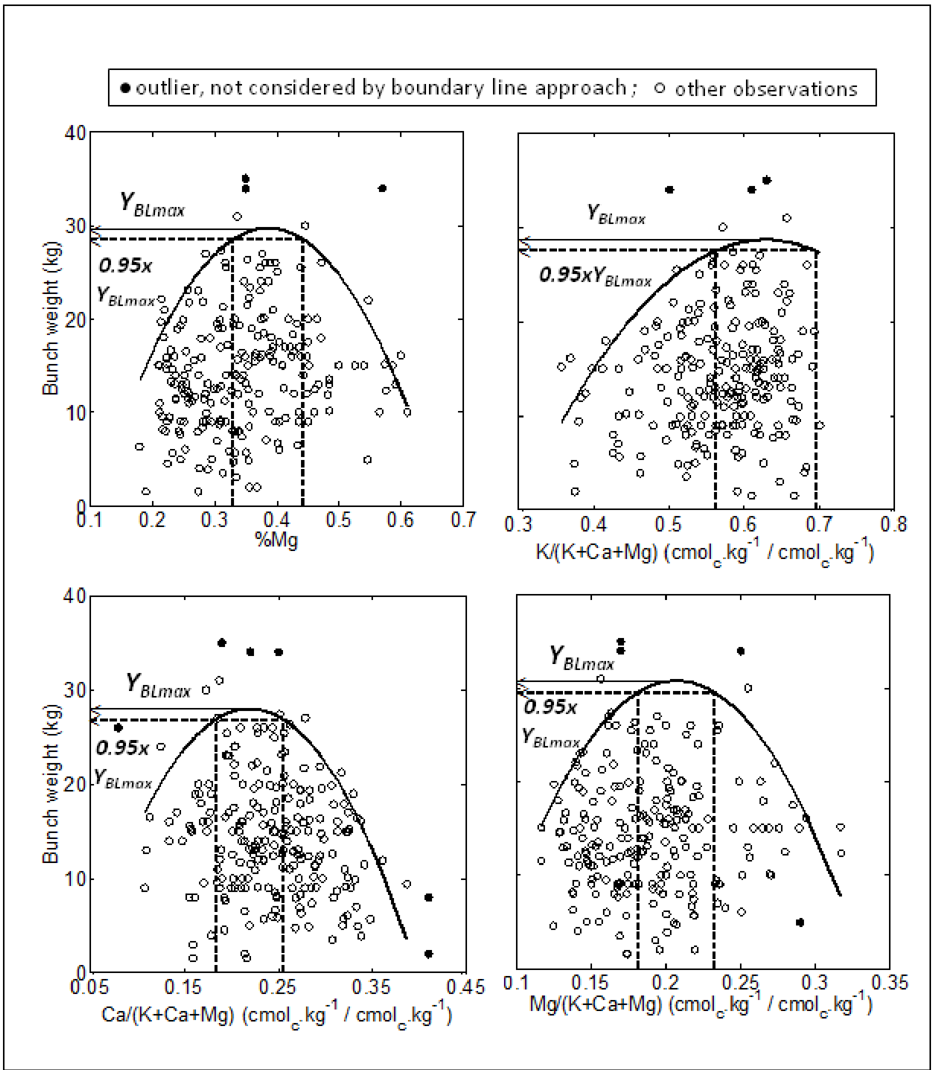

Figure 3.1 (continued). Scatterplots for bunch weights against total N, P, K, Ca, Mg contents (%), K-, Ca- or Mg on sum of cations. Y_{BLmax} represents the bunch weight corresponding to the maximum of each boundary lines. The intervals on the X-axis delimitated by the dotted lines are the sufficiency ranges.

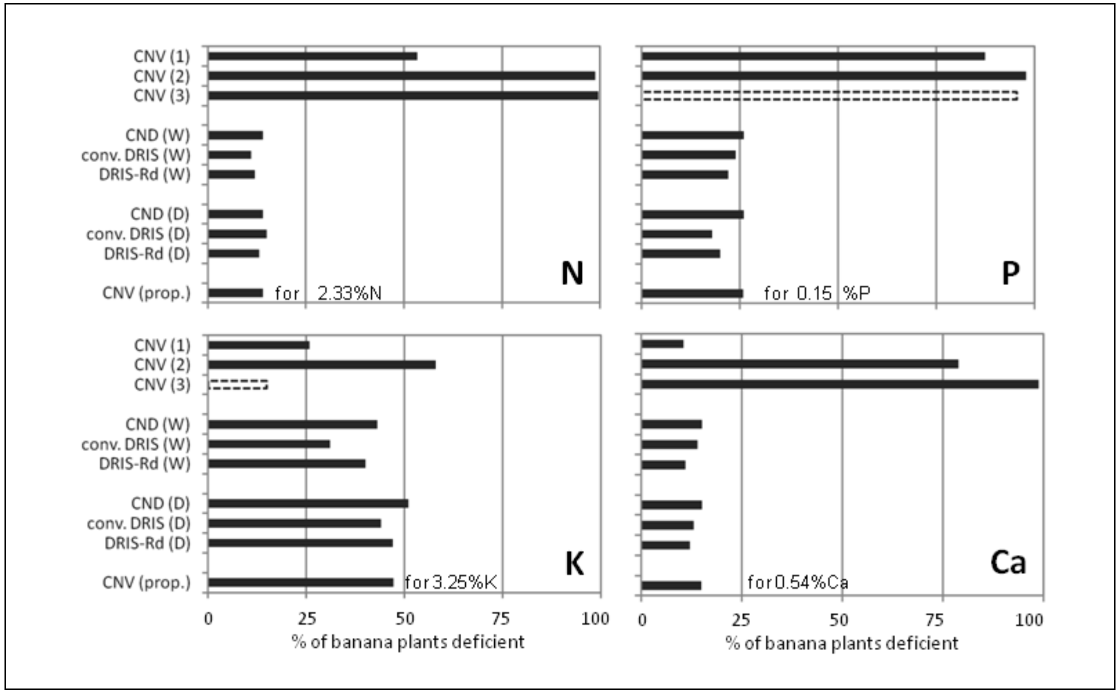

Figure 3.2 (continued on next page). Percentages of banana plants considered deficient in N, P, K, Ca or Mg according to (1, upper group of three bars) comparison to the critical nutrient values published by Lahav and Turner (1983, CNV (1)), Angeles et al. (1993, CNV (2)), Wortmann et al. (1994, CNV (3)), (2, second group of bars) the CND, conventional DRIS (conv.DRIS) and DRIS-Rd procedures, when using the norms established by Wairegi (2010) for the East African Highland banana, (3, third group of bars) the CND, conventional DRIS (conv.DRIS) and DRIS-Rd procedures, when using the norms calculated from the high bunch weight population of this study, (4, last bar) comparison to the critical nutrient values proposed in this study to tally the conclusions of CND.

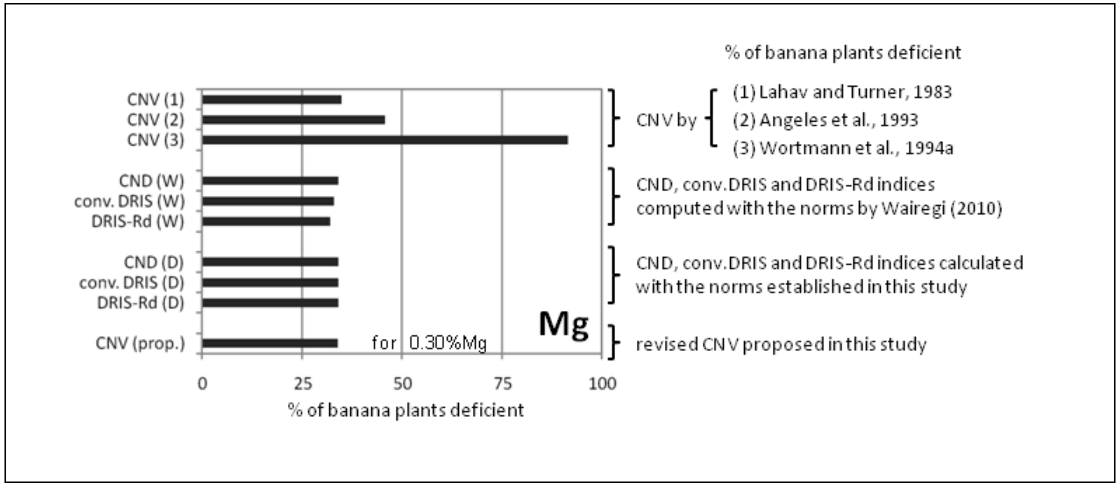

Figure 3.2 (continued). Percentages of banana plants considered deficient in N, P, K, Ca or Mg according to (1, upper group of three bars) comparison to the critical nutrient values published by Lahav and Turner (1983, CNV (1)), Angeles et al. (1993, CNV (2)), Wortmann et al. (1994, CNV (3)), (2, second group of bars) the CND, conventional DRIS (conv.DRIS) and DRIS-Rd procedures, when using the norms established by Wairegi (2010) for the East African Highland banana, (3, third group of bars) the CND, conventional DRIS (conv.DRIS) and DRIS-Rd procedures, when using the norms calculated from the high bunch weight population of this study, (4, last bar) comparison to the critical nutrient values proposed in this study to tally the conclusions of CND.

Table 3.3 lists the CND-norms established by Wairegi (2010), on one hand, and those calculated in this study, on the other hand. The norms are the means and standard deviations of $V_{N,}$ $V_{P,}$ $V_{K,}$ $V_{Ca,}$ $V_{Mg,}$ V_{Rd} for the respective high bunch weight populations in both studies. The two sets of norms are used to calculate the CND-indices for the studied banana plants; the indices are referred to by CND(W) (indices calculated with the Wairegi (2010)-norms) and CND(D) (using the norms of this database). The values of the CND(W)- and CND(D)-indices encompass positive and negative values, as can be seen in the plots of Figure 3.3 comparing CND(W) and CND(D). The distributions of values for CND(W) and CND(D) are quite similar. A majority of observations falls in the range between -1 and +1; the rest thins out symmetrically to both sides of this peak. Data for Mg, show a more evenly distribution over the entire range. The indices for P and Rd take occasionally extreme values (Figure 3.3). For all the nutrients and Rd, the values for the CND(W)- and CND(D)-indices for one plant, are significantly different ($P \leq 0.001$) when compared pairwise. The equations of the straight lines describing the relationships between the CND(W)- and CND(D)-indices for N, P, K, Ca, Mg and Rd are indicatedin the corresponding graphs of Figure 3.3. The intercepts are all different from 0. The slopes for N, P, K, Ca and Rd are lower than 1; the slope for Mg is higher than 1. Since the individual value of a CND(W)-index differs from the value of the corresponding CND(D)-index, the global indexes r^2_{CND} vary also (Y = 0.90X + 3.09 when CND(W) plots on the Y-axis and CND(D) on the X-axis; $R^2 = 0.75$; N = 221). The plants deficient in a nutrient, are those having a CND-index inferior to the “in balance” range for that nutrient. The “in balance” ranges are detailed in Table 3.4 and are represented as grey rectangles in Figure 3.3. The percentages of deficient plants are represented by bars in the barplots of Figure 3.2. The conclusions in terms of deficiencies are the same or similar for the two sets of norms considered in the computations. For both CND(W) and CND(D), 14% of the plants lacks N, 26% is deficient in P, about 48% is not adequately nourished in K, 15% of the plants lacks Ca and 34% is deficient in Mg.

Table 3.3. CND-norms calculated by Wairegi (2010) (left) or in this study (right) for East African Highland bananas (*Musa spp.* AAA-EA).

Source	Wairegi (2010)		This study	
Reference population	High bunch weight population		High bunch weight population	
CND-ratio	Mean	SD	Mean	SD
V_N^*	0.30	0.15	0.36	0.09
V_P^*	-2.31	0.18	-2.37	0.15
V_K^*	0.61	0.17	0.64	0.16
V_{Ca}^*	-0.86	0.29	-0.94	0.22
V_{Mg}^*	-1.55	0.20	-1.63	0.23
V_{Rd}^*	3.81	0.09	3.94	0.08

Table 3.4. "In balance" ranges around zero determined by the boundary line approach on the CND-, conv.DRIS- and DRIS-Rd-nutrient indices.

	N-index	P-index	K-index	Ca-index	Mg-index
Calculated with the Wairegi (2010)-norms					
CND(W)	-0.13	-0.96	0	-0.92	-1.07
	0.88	0.27	2.68	0.10	0.55
conv.DRIS(W)	0.00	-8.59	0.00	-13.64	-9.61
	10.37	4.38	19.27	0.00	7.95
DRIS-Rd(W)	-1.25	-12.63	0.00	-17.99	-12.50
	7.72	1.14	18.38	0.00	6.10
Calculated with the norms established in this study					
CND(D)	-0.85	-0.72	0	-0.84	-0.55
	0.82	0.73	2.57	0.48	0.83
conv.DRIS(D)	-4.62	-9.13	0.00	-11.82	-5.37
	5.31	5.08	27.36	3.24	10.27
DRIS-Rd(D)	-5.45	-9.58	0.00	-13.94	-5.66
	4.67	4.24	21.74	3.26	9.64

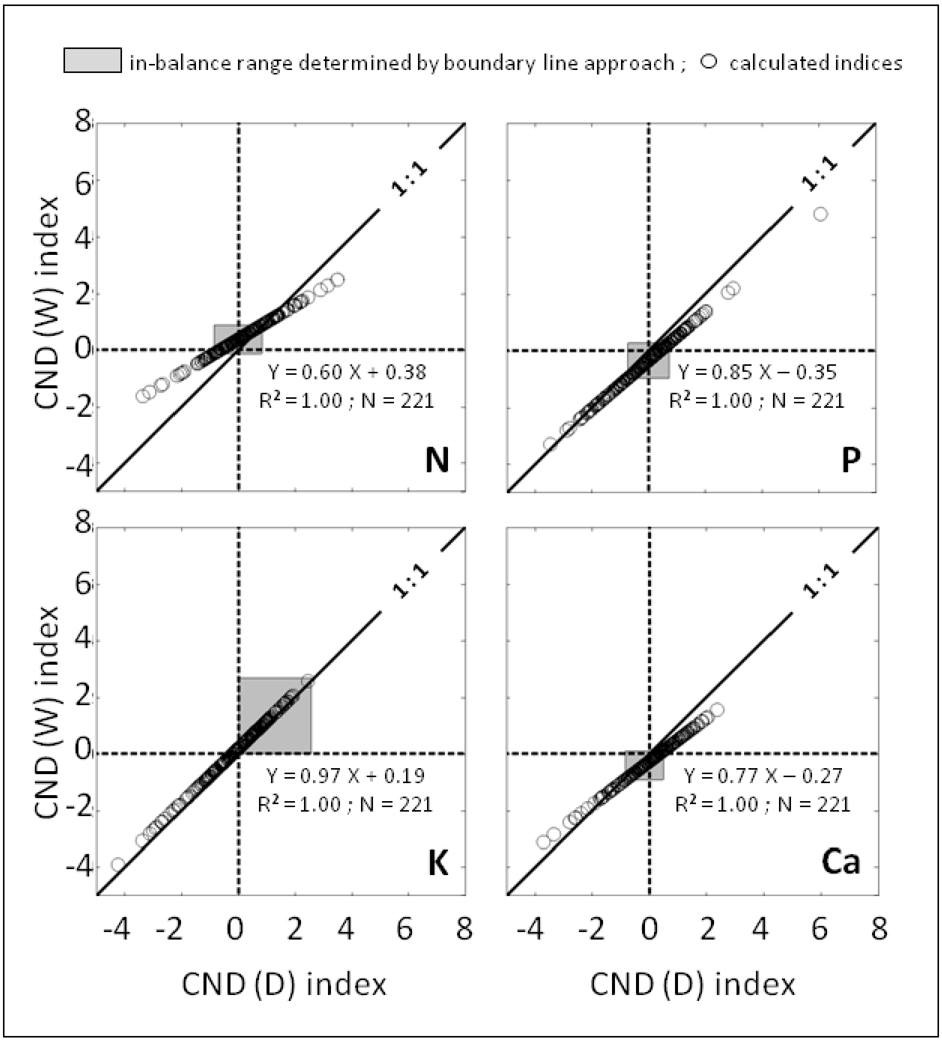

Figure 3.3 (continued on next page). Comparison of the CND-indexes for the bananas in this database, when calculated with the Wairegi (2010)-norms (Y-axis) or the norms established in this study (X-axis).

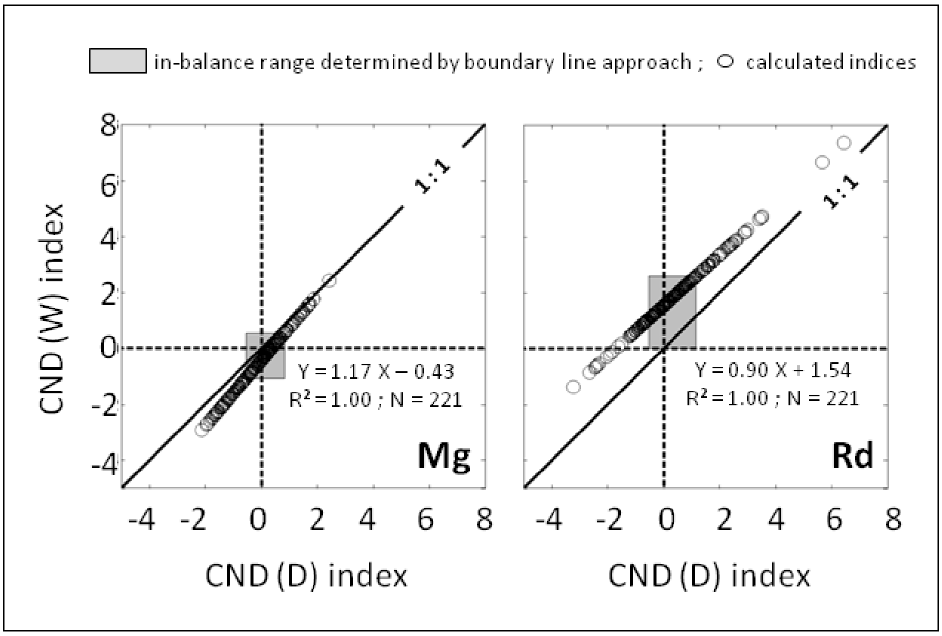

Figure 3.3 (continued). Comparison of the CND-indexes for the bananas in this database, when calculated with the Wairegi (2010)-norms (Y-axis) or the norms established in this study (X-axis).

The calculation of DRIS-indices, is performed once using the conventional DRIS (conv.DRIS), then again using the adapted DRIS-Rd approach. For each method, the use of the Wairegi (2010)-norms (conv.DRIS(W); DRIS-Rd(W)) is compared to the reliance on the norms established in this study (conv.DRIS(D); DRIS-Rd(D)). The norms of both studies are summarized in Table 3.5. The values for the nutrient- and Rd-indices by conv.DRIS(W), conv.DRIS(D), DRIS-Rd(W) and DRIS-Rd(D) all encompass positive and negative values (data not shown). The distributions of values resemble those observed for CND, with a majority of bananas having nutrient- or Rd-indices between -10 and +10 (data not shown). For all nutrient indices and the global index, the pairwise comparison between the values of conv.DRIS(W) and conv.DRIS(D) states significant differences ($P \leq 0.001$). The values are correlated, although slightly less well than in CND (R^2 = 0.94 -

1.00 for the nutrient indices; R^2 = 0.85 for the global index; N = 221). As in CND, the linear regressions relating the nutrient indices or global index by conv.DRIS(W) to conv.DRIS(D) have slopes and intercepts significantly ($P \leq 0.001$) different from, respectively, 1 and 0. As in CND, slopes are inferior to 1, except for Mg. When comparing the nutrient-, Rd-indices and global indices by DRIS-Rd(W) and DRIS-Rd(D), the same conclusions with respect to the differences in paired values, slopes and intercepts are drawn once again. The plants deficient in a nutrient, are those having a conv.DRIS- or DRIS-Rd-index inferior to the "in balance" range for that nutrient (Table 3.4). For each nutrient, the percentages of deficient plants according to conv.DRIS(W)-, conv.DRIS(D)-, DRIS-Rd(W)- or DRIS-Rd(D)-index are graphically represented in the barplots of Figure 3.2. For all nutrients but K, percentages determined by conv.DRIS and DRIS-Rd for both sets of norms, are close. 10-15% of the plants is not sufficiently nourished in N and/or Ca, about 20% lacks P and 30-35% is deficient in Mg. K-deficiency is the most widespread, extending to 30% of the plants according to conv.DRIS(W) and 40-45% with respect to the indices calculated for conv.DRIS(D), DRIS-Rd(W) and DRIS-Rd(D).

The linear regressions relating the nutrient indices of conv.DRIS or DRIS-Rd to CND, for both sets of norms, are all significant ($P \leq 0.05$) (data not shown). The coefficients of determination range from 0.90 to 0.98 for the relationship between conv.DRIS and CND, and vary between 0.92 and 0.99 for DRIS-Rd *vs.* CND. For all nutrients, the slopes for the regressions between conv.DRIS(W) and CND(W) are significantly ($P \leq 0.001$) different from those for DRIS-Rd(W) *vs.* CND(W). The intercepts are significantly different ($P \leq 0.001$) also, except for K ($P > 0.05$). Only the regressions between conv.DRIS(D) and CND(D) for the P- and Mg-indices have significantly ($P \leq 0.05$) different slopes than the corresponding relationships between DRIS-Rd(D) and CND(D). Only the regressions between conv.DRIS(D) and CND(D) for the N-, K- and Ca-indices have significantly ($P \leq 0.05$) different intercepts than the corresponding relationships between DRIS-Rd(D) and CND(D). The global indices for conv.DRIS ($\mathrm{NI}_{\mathrm{conv.}}$)

and DRIS-Rd ($\mathrm{NI_{Rd}}$) are related to the global CND-index ($\mathrm{r^2_{CND}}$) by a power relationship. The correlations between $\mathrm{r^2_{CND}}$ and $\mathrm{NI_{Rd}}$ are better (R^2 = 0.89, when using the Wairegi (2010)-norms, and 0.76 for the norms of this study) than those with $\mathrm{NI_{conv.}}$ (R^2 = 0.63 and 0.75, respectively) (data not shown).

Table 3.5. DRIS-norms established by Wairegi (2010) (left) or calculated in this study (right) for East African Highland bananas (*Musa spp.* AAA-EA).

Source	Wairegi (2010)		This study	
Reference population	High bunch weight population		High bunch weight population	
Elemental ratio	Mean	Coefficient of variation (%)	Mean	Coefficient of variation (%)
P/N	0.08	27.49	0.07	14.64
N/K	0.76	26.18	0.77	17.43
Ca/N	0.33	33.30	0.28	25.87
Mg/N	0.16	27.05	0.14	30.59
P/K	0.05	23.36	0.05	20.01
Ca/P	4.57	32.72	4.36	28.11
P/Mg	0.49	30.61	0.51	36.03
Ca/K	0.25	41.27	0.22	35.32
Mg/K	0.12	37.20	0.11	35.83
Ca/Mg	2.10	30.34	2.11	31.01
R_d/N	33.86	17.70	36.08	8.60
P/R_d	0.00	18.04	0.00	15.64
R_d/K	24.79	20.63	27.52	15.35
Ca/R_d	0.01	28.39	0.01	25.98
R_d/Mg	217.11	20.67	273.13	26.99

As explained in the method section, two approaches are called upon to determine the critical nutrient values or sufficiency ranges for the East African Highland bananas in this dataset. The critical nutrient values retained to insure concordance between the conclusions emanating from the CNV/SR-approach and from CND, are 2.33%N, 0.15%P, 3.25%K, 0.54%Ca and 0.30%Mg (see lower bar in the barplots of Fig.3.2). The sufficiency range determined by the boundary line procedure (Figure 3.1) on the scatterplots of bunch weight *vs.* nutrient contents, are 2.35-2.81%N, 0.13-0.18%P, 3.23-4.12%K, 0.49-0.80%Ca and 0.32-0.45%Mg. For the cation ratios, K/(K+Ca+Mg), Ca/(K+Ca+Mg) and Mg/(K+Ca+Mg) ($cmol_c.kg^{-1}$ / $cmol_c.kg^{-1}$), the boundary line procedure establishes sufficiency ranges between, respectively, 0.56-0.69, 0.18-0.26 and 0.18-0.24. The domain where the sufficiency ranges for the three cation ratios are simultaneously respected is represented in the triangular plots of Figure 3.4.A. The domain relating to the sufficiency ranges of this study (black patch in Fig.3.4.A) plots left to the domains delimited by the sufficiency ranges of Wortmann et al. (1994a, dark grey patch) or Martin-Prével (1984, light grey patch). This is true not only for the restricted domain mentioned above, but more generally for all the observations of this dataset, both for the high and the low bunch weight populations (Table 3.1., data not plotted). When constructing the triangular plot for the sufficiency ranges established in this study or those by Martin-Prével (1984), it appeared that the highest values of the ranges for K/(K+Ca+Mg) are not reconcilable simultaneously with the sufficiency ranges established for Ca/(K+Ca+Mg) and Mg/(K+Ca+Mg). For both studies, the straight lines through the respective upper values for K/(K+Ca+Mg) fall outside the domains respecting the sufficiency ranges for the three cation ratios simultaneously (Figure 3.4.B for data in this study). A similar situation exists, to a lesser extent, for the upper ranges of Ca/(K+Ca+Mg) established in this study (Figure 3.4.B).

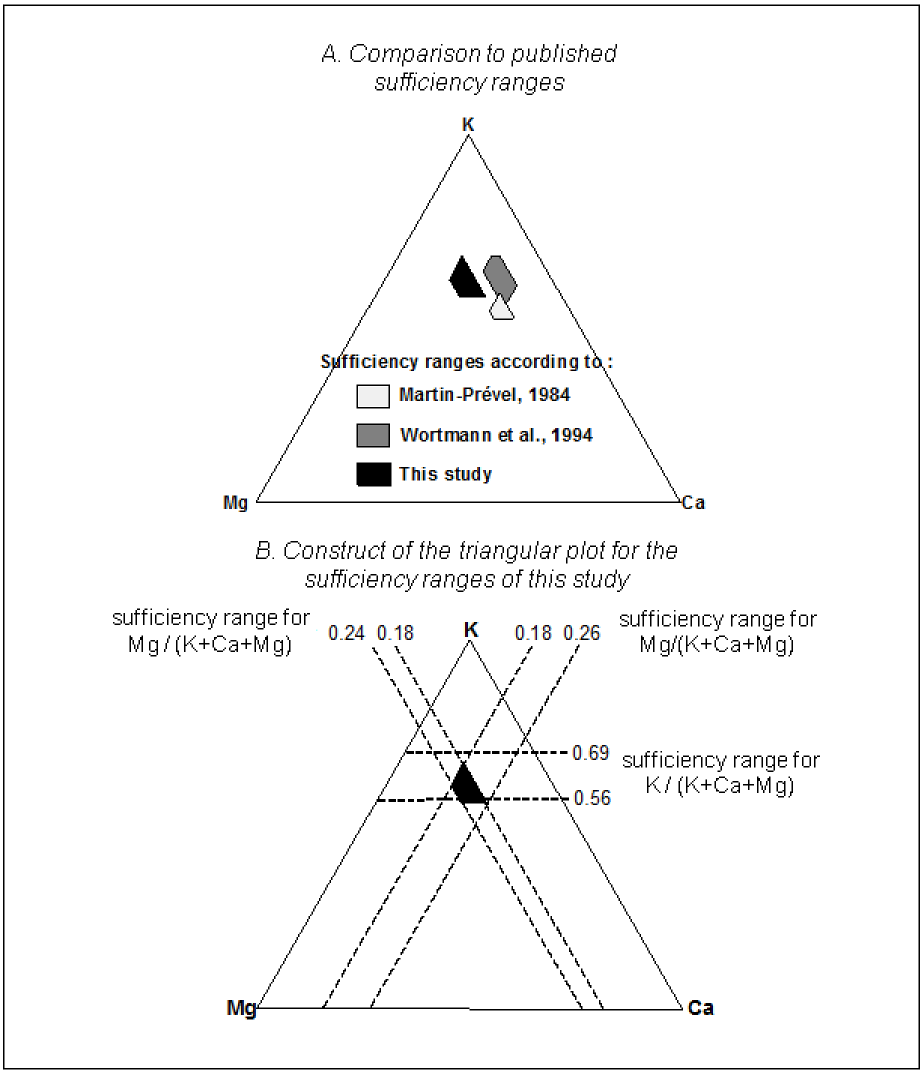

Figure 3.4. (A) Triangular plot representing the ratios between the cations K, Mg and Ca ($cmol_c.kg^{-1}/cmol_c.kg^{-1}$)measured in the inner lamina of third leaves of banana. By the colored patches are visualized the sufficiency ranges established by Martin-Prével (1984, light grey patch), Wortmann et al. (1994, dark grey patch) or this study (black patch). (B) In the right plot, is represented the construct for the domain (black patch) respecting simultaneously the sufficiency ranges for the three cation ratios as determined in this study. The highest values for K/(K+Ca+Mg) and Ca/(K+Ca+Mg) fall outside this domain.

3.4. Discussion

3.4.1. Foliar nutrient concentrations and their relationships to bunch weights

For all nutrients, the minimum and maximum values reported here and the observed ranges (Table 3.1) concord with the findings of other researchers working on the East African Highland banana in Tanzania, Rwanda or Uganda (Lassoudière, 1989; Wortmann et al., 1994a; Okech et al., 2000, 2004; Smithson et al., 2001, 2004; Nyombi et al., 2010; Wairegi, 2010; van Asten and Gaidashova, unpublished). The values for the cation ratios found for this database lie within the wide ranges observed by Lacoeuilhe and Martin-Prével (1971a) on bananas (var. Poyo) showing nutrient deficiency symptoms. The range of values for the sum of cations or proportion of Ca in this sum is larger in this study, than in the dataset of Lassoudière (1989) on AAA-banana in Kibungo (East Rwanda). The proportions of K and Mg in the sum of cations are, on the contrary, more restricted in present study. K, Ca and Mg can substitute for one another for what positive charges are considered and are the only major cations in banana (Martin-Prével and Montagut, 1966).

Variations in nutrient contents are attributed to different factors. Some of them do not apply to this study, others do. First, nutrient needs and foliar nutrient concentrations vary between banana genome groups (Turner and Barkus, 1981; Raghupathi et al., 2002; Borges et al., 2006; Hoffmann et al., 2010; van Asten and Gaidashova, unpublished data for *Intuntu* (AAA) and *Kibanya* (ABB) grown in 4 banana producing regions in Rwanda) and between morphological extremes in subgroups (for instance extreme dwarfing *vs. "Giant" Cavendish*, Turner and Barkus, 1981). Genetic studies show that, despite morphological differences, East African Highland bananas AAA-EA share a narrow genetic base (Pillay et al., 2001; Tugume et al., 2002). This genetic similarity explains why varietal differences are not suspected to influence the global conclusions of this study and why both AAA-EA varieties (*Enyeru* and *Intuntu*) are considered together throughout the analysis. Second, the influence of tissue sampled or phenological stage on nutrient contents (Martin-Prével and Montagut, 1966; Lacoeuilhe and Martin-Prével, 1971a) can be excluded in this study. Indeed, in agreement with the international reference method for sampling (*Méthode d'Echantillonnage Internationale de Référence,* Martin-Prével, 1980) the same tissues of plants of the same stage were sampled. Third, Borges et al. (2006) and Nyombi et al. (2010) report significant differences in foliar nutrient concentrations between plants in different growth cycles. Our data for Ntungamo (SW Uganda) only relate to first ratoons, but for the Rwandan sites growth cycle could explain part of the variation in foliar nutrient concentrations. Fourth, nutritional differences are also attributed to the diverse biophysical conditions prevailing at the various sites of interest: influence of seasons and rainfall (Martin-Prével, 1984; Smithson et al., 2004), temperature (Lahav, 1995), differences in soil type (Bidner-Barhava and Ravikovitch, 1958; van Asten and Gaidashova, unpublished) and nutrient supply. Intra-regional and intra-farm differences in nutrient contents could occur because of the heterogeneity of soil fertility due to, for instance, topographic position (Okech et al., 2004; Gaidashova et al., 2010) or differential management (Wortmann et al., 1993 *cited in* Bekunda et al., 2003; McIntyre et al., 2000). The question of cation ratios is less frequently addressed in literature. Lacoeuilhe and Martin-Prével (1971a) state that bananas could survive in a wide range of nutritional conditions for K, Ca and Mg. Variation in the values of the cation ratios is ascribed to environmental conditions (climate, soil, fertilizer, fertilizer amendment) (Lacoeuilhe and Martin-Prével, 1971a; McIntyre et al., 2000) or plant age (Lacoeuilhe and Martin-Prével, 1971a).

When bunch weights are plotted against nutrient contents or cation ratios, the scatterplots show triangular patterns (Figure 3.1). The boundary lines border the data on their upper edge (Figure 3.1). These are in line with the long-known "C"-shaped curves mentioned in the introduction. At lowest nutrient contents, low production is explained by nutrient deficiencies. At high nutrient contents, low production is attributed to nutrient excesses or nutrient interactions (Dow and Roberts, 1982; Havlin et al., 2004; Memon et al., 2005). Values below the boundary line result from the influence of other factors on crop production (Webb, 1972; Walworth and Sumner, 1987).

In this study, foliar data are considered as health indicators of individual plants. An attempt is thus made to distinguish high and low producing banana plants. Bunch weights, instead of the more usual units of yield ($t.ha^{-1}$, $t.ha^{-1}.year^{-1}$, $t.ha^{-1}.cycle^{-1}$) are retained when partitioning the data, in order to keep trace of the production of the individual plants. The dataset is partitioned by applying the Cate-Nelson procedure described in Khiari et al. (2001a). All the data are considered together to obtain a continuous curve for the cumulative variance ratio function and a realistic cut-off value (14.5kg) (Table 3.2).

In terms of nutritional characteristics of their foliar samples, the high and the low bunch weight populations differed in K- and Mg-concentrations, sum of major cations, and Ca on the sum of cations (Table 3.1). These observations suggest that cation imbalances contribute to the differences in bunch weights between the two populations. In Table 3.6, the means of the nutrient contents of the high bunch weight population are compared to the average nutrient contents in the high production populations of other studies concerning banana. The averages calculated for the N-, P-, Ca- and Mg-contents are lower than the values found in literature; K-concentration is mid-range (Angeles et al., 1993; Wortmann et al., 1994a; Raghupathi et al., 2002; Teixeira et al., 2007; Wairegi, 2010). Considering the wide ranges of the published values, the average nutrient concentrations of the high bunch weight population of this study are reasonably close to those found by Raghupathi et al. (2002) for *Robusta* and *Ney Poovan* or those of Wairegi (2010) for East African Highland bananas in Uganda.

Table 3.6. Mean nutrient contents ("norms") calculated by various authors for the high yield or high bunch weight populations of their respective studies on banana.

Reference	Angeles et al. (1993)	Raghupathi et al. (2002)	Teixeira et al (2007)	Wortmann et al. (1994)	Wairegi (2010)	This study
Banana variety	(Review) mainly *Cavendish*	*Robusta + Ney Poovan*	*Grande Naine,* Giant *Cavendish*	East African Highland Banana	East African Highland Banana	East African Highland Banana
Geographical location	(Review) world	Bangolare, India	2 areas in Sao Paulo State, Brazil	Kagera region, North-West Tanzania	Central, East, South, South-West Uganda	North-West, East, South Rwanda ; South-West Uganda
Criterion	Means for high yield population	Means for high yield population	Means for high yield population	Means for high yield population	Means for high bunch weight population	Means for high bunch weight population
N (%)	3.04	2.64	2.93	3.15	2.79	2.59
P (%)	0.23	0.17	0.17	0.25	0.21	0.17
K (%)	4.49	3.42	2.84	3.04	3.79	3.44
Ca (%)	0.80	0.87	1.12	1.13	0.91	0.73
Mg (%)	0.41	0.39	0.37	0.48	0.44	0.36

3.4.2. Critical nutrient values / sufficiency ranges (CNV/SR)-approach

The data of this study are compared to the critical nutrient values by Lahav and Turner (1983 *cited in* Martin-Prével, 1984), Angeles et al. (1993) and Wortmann et al. (1994a). Lahav and Turner (1983 *cited in* Martin-Prével, 1984) express themselves reservations against the values they tentatively assemble for fully grown ratoons of *Giant* and *Dwarf Cavendish* grown in diverse agro-ecoregions of Australia. The tissue samples comprise inner and outer limbs of leaves, and are analyzed by laboratories lacking interlaboratory calibration. The critical nutrient values in the review of Angeles et al. (1993) are the average values for the wide ranges of critical nutrient values established by 26 studies around the world. Angeles et al. (1993) consider the various ways to determine critical values, a limiting factor to the use of this approach. To our knowledge, Wortmann et al. (1994a) are the only ones having published critical nutrient values for AAA-EA. The use of these values could be restricted because of the limited geographical area considered in their study (Wairegi, 2010). For the cation ratios K/(K+Ca+Mg), Ca/(K+Ca+Mg) and Mg/(K+Ca+Mg) the observations are compared to the sufficiency ranges elaborated by Martin-Prével (1984) and, more interestingly, by Wortmann et al. (1994a) for East African Highland bananas. Compared to the sufficiency ranges of the latter, this study reports similar proportions of K relative to the sum of cations, but higher proportions for Mg and lower proportions for Ca.

The discrepancies between the conclusions drawn in terms of nutrient deficiencies (Figure 3.2) or optimum conditions (Figure 3.4.A) when different sets of critical nutrient values or sufficiency ranges are used hence exemplify the criticism thrown at the CNV/SR-approach (Table 3.7). The approach is appreciated because of the ease to compute the data and the facility to interpret them (a.o. Martin-Prével et al., 1984; Baldock and Schulte, 1996). The drawbacks of the approach are its dependency on all the before-mentioned factors influencing the nutrient contents in the tissue samples: plant chosen and tissue analyzed, sampling method, environmental conditions (Table 3.7) (a.o. Martin-Prével, 1980; Martin-Prével et al., 1984; Baldock and Schulte, 1996; Memon et al., 2001). The use of critical values / sufficiency ranges should thus be restricted to the plants and conditions for which they were determined (a.o. Turner et al., 1989; Memon et al., 2001, 2005). The differences between the sufficiency ranges for the cation ratios as established in Wortmann et al. (1994a) or in this study, for two geographically close areas, both for AAA-EA bananas, illustrate that critical nutrient values and sufficiency ranges are not easily exportable.

Other criticisms against the CNV/SR-approach is their categorical nature and the facts that they do not allow to rank deficient nutrients or do not provide a global index to measure the combined effect of nutrient levels on production (Table 3.7) (Baldock and Schulte, 1993). More important, the CNV/SR-approach considers the nutrients independently from one another. Yet, Dumas and Martin-Prével (1958), Angeles et al. (1993) or Baldock and Schulte (1996) state that nutrient concentrations higher than the critical nutrient values when taken individually, do not insure high production. The triangular plot of Figure 3.4.B proves graphically that the sufficiency ranges determined individually for K/(K+Ca+Mg), Ca/(K+Ca+Mg) and Mg/(K+Ca+Mg) are not necessarily respected simultaneously. The triangular plot is a first solution to consider the ratios between K, Ca and Mg simultaneously (Martin-Prével, 1962; Lacoeuilhe and Martin-Prével, 1971a). The DRIS- and CND-approaches are further alternatives, considering respectively dual and multi-elemental ratios. Both approaches address the drawbacks inherent to the critical nutrient values / sufficiency ranges (CNV/SR)-approach (Table 3.7).

Table 3.7. Review of the advantages and inconveniences commonly cited in literature for the critical nutrient values / sufficiency ranges (CNV/SR)-, DRIS- and CND-approaches.

Method / Criterion	CNV / SR	DRIS	CND
Independence of nutrient indices	yes (o)	no (h,k,r)	no (j,l)
Ease to compute indices	yes (o)	no (o)	fair (p)
Ease to interpret	yes (f)	yes (m,o)	yes (j,l)
Continuous range of indices	no	yes (m)	yes (j,l)
Ranking of deficiencies	no (o)	yes (g)	yes (j,l)
Global index summarizing	no (o)	yes (h)	yes (l)
Applicability of values / ranges / norms	local (h,i,k,q)	wider (k)	wider
* Dependence on sampling	yes (a,b,c,e,f,h,o,q)	yes (d,g,k,o)	
* Dependence on environmental conditions	yes (a,b,c,e,f,g,h,n)	yes (m,o)	

References : (a) Bates, 1971; (b) Martin-Prével, 1980a; (c) Escano et al., 1981b; (d) Beverly et al., 1984; (e) Martin-Prével, 1984; (f) Martin-Prével et al., 1984; (g) Walworth et al., 1986; (h) Walworth and Sumner, 1987; (i) Turner et al., 1989; (j) Parent and Dafir, 1992; (k) Angeles et al., 1993; (l) Parent et al., 1994; (m) Wortmann et al., 1994a; (n) Lahav, 1995; (o) Baldock and Schulte, 1996; (p) Khiari et al., 2001b+c; (q) Memon et al., 2001.

3.4.3. Conventional DRIS-, DRIS-Rd- and CND-approaches

According to statistical tests, foliar N-, P- and Mg-concentrations have skewed distributions. Walworth and Sumner (1987) warn that the use of skewed distributions could represent problems when establishing reference norms. To overcome the difficulty they advocate the use of normally distributed high producing subpopulations to calculate norms. As in Angeles et al. (1993), Wortmann et al. (1994a), Teixeira et al. (2007) or Wairegi (2010), the choice is made of determining DRIS-norms on the high bunch weight population only, instead of using all the observations. Analogously, the sole high producing population is used when establishing the CND-norms. The same decision is made by Parent et al. (1994), Khiari et al. (2001c), Raghupathi et al. (2002), Garcia-Hernandez et al. (2004, 2005, 2009), Blanco-Macias et al. (2006, 2009) and Wairegi (2010) when establishing CND-norms for various crops. The DRIS- and CND-norms calculated from this dataset are reported against the data of Wairegi (2010) in Tables 3.3 and 3.5. The two sets of norms relating to AAA-EA in the African Great Lakes Region are close, both for the mean values as for their estimates of variability.

In order to verify the choice of a set of norms on the final conclusions by DRIS or CND, the computations for the conventional DRIS, adapted DRIS-Rd and CND-approaches are performed once with the norms of Wairegi (2010), then again with the norms established here. For the need of this comparison, the conventional DRIS and DRIS-Rd calculations are performed in exactly the same way as in Wairegi (2010).

For the conventional DRIS, DRIS-Rd and CND, the values for the indices calculated with both sets of norms are significantly different. In CND, the differences between indices are explained solely by the different values of both sets of norms. For DRIS, an additional factor has to be considered. The computation of the DRIS-indices, demands, for each nutrient ratio, to chose between two functions (eq.[8] and [9]) depending on the values of the nutrient ratio relatively to the corresponding norm. When the norms change, the choice between the two functions may thus vary. For the conventional DRIS, DRIS-Rd and CND, the slopes of the linear regressions of the N-, P-, K- and Ca-indices calculated with the Wairegi (2010)-norms (Y-axis) against those calculated with the norms established here (X-axis), are inferior to one. The relatively larger changes on the X-axis compared to those on the Y-axis, indicate a higher sensitivity of the norms of this study when analyzing this dataset. The indices calculated by conventional DRIS, DRIS-Rd or CND are interpreted in terms of nutritional disorders suffered by the plants. Plants with $\mathrm{I_N}$, $\mathrm{I_P}$, $\mathrm{I_K}$, $\mathrm{I_{Ca}}$ and/or $\mathrm{I_{Mg}}$ indices lower than the calculated "in balance" ranges are interpreted as deficient with the considered nutrient. The "in balance" ranges for the three approaches, with both sets of norms, are summarized in Table 3.4. The "in balance" ranges are asymmetrical around zero, as is also proposed by Kelling et al. (2000) for DRIS, or observed by Quesnel et al. (2006) for CND. For all the nutrients, conventional DRIS gives, for both sets of norms, similar conclusions in terms of percentage of deficient plants. The same is true for the conclusion for DRIS-Rd and CND. The conclusions drawn from a set of norms established here for different agro-ecoregions in Rwanda and South-West Uganda corroborate those drawn from a set of norms established for different agro-ecoregions across Uganda. The use of both sets for an ever larger geographical region than that for which they are developed, seems thus plausible.

Both conventional DRIS and DRIS-Rd are closely correlated to CND, for their nutrient-, Rd- and global indices. The same relationships are reported by Parent et al. (1994) for potato, Khiari et al. (2001c) for sweet corn and Wairegi (2010) for banana. The linear relationships between the nutrient indices for conv.DRIS *vs.* CND, on one hand, and DRIS-Rd *vs.* CND, on the other hand, may be significantly different with respect to their intercepts and/or their slope. These differences explain that, for one banana plant, the order of nutrients – sorted with increasing values for their respective indices – can change between conv.DRIS and DRIS-Rd. The differences in order can even induce sign inversions of one nutrient: negative values in conv.DRIS and positive values in DRIS-Rd, or vice versa. For what the similarity for order of nutrients is considered, DRIS-Rd and CND accord slightly better than conv.DRIS and CND. The global index of DRIS-Rd ($\mathrm{NI}_{\mathrm{Rd}}$) is slightly better correlated to the global index for CND (r_{CND}^2) than is $\mathrm{NI}_{\mathrm{conv.}}$. The slightly better correlation between DRIS-Rd and CND is also reported by Khiari et al. (2001c) and Wairegi (2010).

The conclusions drawn from conventional DRIS and DRIS-Rd with respect to nutrient deficiencies are close for all the nutrients, with some larger differences for K (Figure 3.2). These conclusions are similar to those by CND for all nutrients (Figure 3.2).

From the data available here, it cannot be established whether conv.DRIS, DRIS-Rd or CND is the best diagnostic tool for nutritional disorders. Since various studies report interactions between more than two nutrients (Martin-Prével and Montagut, 1966; Lacoeuilhe and Martin-Prével, 1971a; Raghupathi et al., 2002; Garcia-Hernandez et al., 2005; Wairegi, 2010), CND, which considers higher-order interactions, should be expected superior to DRIS, which relies on pairs of nutrients. A hint in that direction is given by the fertilizer experiment of Khiari et al. (2001b), where CND proved superior to DRIS in diagnosing P-deficiencies on potato. As already suggested by Wairegi (2010), DRIS-Rd may be superior to conventional DRIS since it is closer to CND. DRIS is validated as a diagnostic tool in the studies of Sumner (1981), Walworth and Sumner (1987) and Smithson et al. (2004). Both CND and DRIS (conventional DRIS or DRIS-Rd) are usually considered superior to the CNV/SR-approach as diagnostic tools (Table 3.7). Indeed, Parent et al. (1994), working on potato, observed more correct diagnoses with CND than with critical nutrient values. In terms of deficiency diagnosis and subsequent guide for correction by fertilizers, DRIS provided more often correct diagnoses than critical nutrient values in experiments with sugarcane (Beaufils and Sumner, 1977), corn, soybeans, sugarcane and potatoes (Sumner, 1979), corn (Escano et al., 1981b) and banana (Randhawa et al., 1973 *cited in* Angeles et al., 1993).

3.4.4. Proposition of new critical nutrient values and sufficiency ranges for the East African Highland banana

The ease to interpret critical nutrient values and sufficiency ranges, far more accessible than the elaborated DRIS or CND, explains why the CNV/SR-approach has been used for over 60 years (*references in* Leece, 1976) to diagnose nutritional disorders and make fertilization recommendations. For the East African Highland banana, only Wortmann et al. (1994a) published critical nutrient values for N, Ca and Mg and sufficiency ranges for K/(K+Ca+Mg), Ca/(K+Ca+Mg) and Mg/(K+Ca+Mg). These critical nutrient values and sufficiency ranges are based on observations coming from one eco-region in North-West Tanzania and may not be applicable outside this area. In this study, a set of critical nutrient values and sufficiency ranges are proposed to complete the information useful to interpret foliar data for Musa AAA-EA.

The critical nutrient values are elaborated by attempting to tally the conclusions of the CND-approach. The CND-approach is used as reference, since published studies recognize CND as being a diagnostic tool superior to CNV/SR-approach and possibly DRIS. The critical nutrient values proposed here are: 2.33%N, 0.15%P, 3.25%K, 0.54%Ca and 0.30%Mg. These values are for N and P and Mg are lower than the critical nutrient values published by Lahav and Turner (1983), Angeles et al., (1993) and Wortmann et al. (1994a). The proposed critical nutrient values for these two nutrients are nevertheless superior to the nutrient concentrations provided by Lacoeuilhe and Martin-Prével (1971b) for nutrient deficient banana (var. Poyo) grown in hydroponic solutions. Lacoeuilhe and Martin-Prével (1971) observe deficiency symptoms at 2.0%N, 2.4%K, 0.7%Ca and 0.22%Mg. The same authors report one case of a P-deficient plant grown in a field in Guadeloupe and having P-concentrations as low as 0.08%P. The critical nutrient value proposed here for K (3.25%K), is slightly higher than the values proposed by Lahav and Turner (1983) (3.00%K) and Wortmann et al. (1994a) (3.04%K). A critical nutrient value for K, between 3.01% and 4.49% is also proposed by Smithson et al. (2001) for AAA-EA in Uganda. The critical nutrient value proposed here for Ca (0.54%Ca) is close to the values by Lahav and Turner (1983) (0.5%Ca) but inferior to those of Angeles et al. (1993) (0.85%Ca) and Wortmann et al. (1994a) (1.13%Ca). It is also in line with the values considered as "low" (0.50%Ca) or "good" (0.60-1.00%Ca) by Messing (1974) when interpreting his data on banana grown on St Lucia in the Windward Islands. The proposed critical nutrient value of 0.30%Mg is similar to the critical values published by Lahav and Turner (1983) and Angeles et al. (1993), but lower than the value established by Wortmann et al. (1994a) (0.48%Mg).

The sufficiency ranges for N, P, K, Ca and Mg are established using a boundary line approach. The sufficiency ranges are respectively: 2.35-2.81%N, 0.13-0.18%P, 3.23-4.12%K, 0.49-0.80%Ca, 0.32-0.45%Mg. The critical nutrient values mentioned above, are below or at the lower part of the sufficiency ranges, in agreement with the definitions of "critical values" and "sufficiency ranges". The sufficiency ranges for K/(K+Ca+Mg), Ca/(K+Ca+Mg) and Mg/(K+Ca+Mg) are determined in the same way and are, respectively, 0.56-0.69 ($cmol_c.kg^{-1}$ / $cmol_c.kg^{-1}$), 0.18-0.26 ($cmol_c.kg^{-1}$ / $cmol_c.kg^{-1}$) and 0.18-0.24 ($cmol_c.kg^{-1}$ / $cmol_c.kg^{-1}$).

3.5. Conclusions

Plant tissue analysis is considered to be a practical method for evaluating nutritional disorders and formulating fertilizer recommendations. Various methods exist to interpret plant tissue analyses, all have advantages and drawbacks. Here, CNV/SR, conventional DRIS, DRIS-Rd and CND are evaluated when studying foliar data and plant performance of 221 highland banana-plants (Musa spp. AAA-EA, varieties *Intuntu* and *Enyeru*) grown in three agro-ecoregions in Rwanda and one in South-West Uganda. The data confirm the difficulty to export critical nutrient values and sufficiency ranges established under certain environmental conditions, to other regions. The critical nutrient values and sufficiency ranges (CNV/SR) approach remains however interesting because of the ease of analyzing the data and the accessibility of the method. New critical values and sufficiency ranges are proposed to interpret foliar data for Musa AAA-EA. Since the values and ranges are established for a wide range of agro-ecoregions, they could be used for other areas in the East African Highlands. The same is true for the DRIS- and CND-norms calculated in this study. Compared to a set of norms exterior to this database, the norms established in this study have a greater sensitivity when analyzing the dataset from which they are developed. As diagnostic tools, a literature survey indicates that the multi-nutrient procedures as conventional DRIS, DRIS-Rd and CND are superior to the CNV/SR-approach. From the data available here, it cannot be established whether conventional DRIS, DRIS-Rd or CND is the best diagnostic tool for nutritional disorders. DRIS-Rd conforms slightly better to CND than conventional DRIS. CND has the advantage on DRIS to rely on an easier calculation method.

4. Diagnosis of nutrient imbalances in East African Highland banana (Musa spp. AAA-EA) by CND and PCA approaches

Abstract

Banana is a major food and cash crop in the African Great Lakes region. Low and declining banana yields are attributed to various biotic and abiotic constraints, among which poor soil fertility. Blanket fertilizer recommendations exist to counter the problem, but fertilizer use by smallholder farmers remains low because of high costs. Site-specific recommendations taking into account the large regional variability in nutrient deficiencies could make fertilizers an economically viable solution. Through Compositional Nutrient Diagnosis (CND), Principal Component Analysis (PCA) and comparisons at various geographic scales, this study contributes to the recognition and understanding of regional differences. Bunch weights and foliar data (N, P, K, Ca and Mg) are collected for 221 points distributed over 4 agro-ecoregions on contrasting soils, in Rwanda (Butare, Kibungo, Ruhengeri) and South-West Uganda (Ntungamo). The calculation of CND-indices relies on the norms established for the high bunch weight population (>14.5 kg.bunch^{-1}) of this dataset. CND highlights an overall K-deficiency in Rwanda, with additional deficiencies in Mg in Ruhengeri and in Mg and Ca in Butare. Phosphorus seems the most constraining problem in Ntungamo; with co-deficiencies of K or Ca in some plots. PCAs on the CND-indices reveal interactions between nutrients or between nutrients and Rd, the filling value of the CND analysis. The positive interactions between N-Rd, P-K, the negative interactions between P-Rd, P-Ca, P-Mg, K-Mg, K-Ca and the variable sign interaction between Ca-Mg appear recurrently throughout this study. P-K and Ca-Mg discriminate best ($P<0.05$) the high and low bunch weight population of this study, hence emphasizing the influence of cationic disequilibria on banana production. Comparing the CND-indices between regions, within regions and within farms, illustrates that the large variability in nutrient deficiencies are not only caused by differences in geology but also by gradients in soil management.

Keywords
East African Highland banana; CND; nutrient deficiencies; nutrient interactions; Rwanda; Uganda

4.1. Introduction

The East African Highland banana (*Musa spp.* AAA-EA) is one of the major crops for the population in the African Great Lakes Region, because of the food and cash it provides to about 85% of the people (FAOstat, estimates for 2010). Despite the efforts of smallholder farmers, on-farm banana yields are low (5-30 $t.ha^{-1}.year^{-1}$) and well below the potential yields obtained in research stations or plantations (40-70 $t.ha^{-1}.year^{-1}$) (Bekunda et al., 2004; van Asten et al., 2004). Poor soil fertility is recognized, by scientists and farmers, as a major constraint on agricultural production (Sanchez et al., 1997; Nandwa and Bekunda, 1998; Ssali, 2001; Bouwmeester et al., 2009; Mugwe et al., 2009).

Amongst the different methods allowing the assessment of the soil nutrient status, plant tissue analysis combines the advantages of long-time use, convenience and actual verification that available nutrients are effectively taken up (Lahav, 1995; Kelling et al., 2000; Memon et al., 2001). Okech et al. (2000) consider that plant tissue analysis reflects the relation between soil nutrients and the nutritional status of the plant better than do soil analyses. As such, plant tissue analyses are commonly used (1) to identify nutrients that limit production and growth by deficiencies or excesses, or

(2) to evaluate fertilizer recommendations (Lahav, 1995; Kelling et al., 2000; Memon et al., 2001).

Over the past 20 years, researchers developed the Compositional Nutrient Diagnosis (CND) norms to interpret plant tissue analyses. CND evaluates the adequacy of each nutrient in relation to the other nutrients included in the diagnosis, by using multi-nutrient ratios (Parent and Dafir, 1992; Parent et al., 1994). The possibility to study higher order nutrient interactions, the ease of calculation of ratios and CND-indices, and the possible integration of the indices in Principal Component Analysis, are the major assets of CND (Parent and Dafir, 1992; Parent et al., 1994). Compared to other classical interpretation methods of plant chemical data, CND is less restrictive in use than the evaluation against Critical Nutrient Levels (CNL) or Sufficiency Ranges (SR) (Parent and Dafir, 1992; Parent et al., 1994), and CND is considered a globally superior diagnostic tool to CNL or SR and, maybe, the Diagnosis and Recommendation Integrated System (DRIS) (Parent et al., 1994; Khiari et al., 2001a).

CND is used on various crops to establish nutrient deficiencies. Complementarily, a Principal Component Analysis is regularly performed on the CND-indices to identify nutrient interactions and unravel the nutritional differences between high and low yielding populations of a same crop (Parent et al., 1994 (potato); Raghupathi et al., 2002 (banana); Garcia-Hernandez et al., 2004 (yellow pepper), 2005 (cowpea), 2006 (aloe vera) 2009 (pecan nut); Magallanes-Quintanar et al., 2006 (maize); Wairegi, 2010 (banana)).

In this study, CND is used to diagnose nutrient disorders in the East African Highland Banana (*Musa AAA-EA*) grown in four different agro-ecological regions in Rwanda and South-West Uganda. Nutrient interactions are studied by (1) identifying recurrent combinations of deficiencies and/or excesses within a same region, by (2) comparing the calculated CND indices for high producing bananas to those relating to low producing populations and (3) by performing PCA's on the CND-indices. Comparisons are made at regional, intra-regional and intra-farm scales in order to verify homogeneity or differences in production and nutritional status.

4.2. Material and methods

4.2.1. Study area

In this study, the areas of interest are situated between the latitudes S 00°46' – S 2°17' and the longitudes E 29°38 – E 30°37'. More specifically, they are located near the towns of Butare, Kibungo and Ruhengeri in Rwanda, and Ntungamo in the south-western part of Uganda. The study areas represent different agro-ecoregions, varying in altitude, climate and/or soil type (Table 4.1). Altitude was about 1500 m*asl* in Kibungo and rises to about 1700 m*asl* in Ruhengeri and 1800 m*asl* in Butare. Mean annual temperatures are about 19-20°C. The mean annual rainfall ranges from 820 to 1350 $mm.year^{-1}$; the rainfall has a bimodal distribution with rainy seasons occurring between March to May and September to December. The soils in the area around Ruhengeri are Andosols developed on Cenozoic volcanic ashes, while soils in the other regions are old and highly weathered, developed on various parent materials (Table 4.1). Land is fragmented between the numerous smallholder farmers who grow their crops in intensively exploited banana-based systems. Farmers rely almost exclusively on traditional techniques (rudimentary tools, no machinery, no animal draft power, no or rare inorganic fertilizer) to manage their fields (Oduol and Aluma, 1990 ; Roose and Ndayizigiye, 1994 ; Wortmann and Kaizzi, 1998 ; Aniku et al., 2001 ; Clay et al., 2001 ; National Institute of Statistics of Rwanda, 2010). All crop-production is rain-fed.

Table 4.1. Characteristics of the studied agro-ecoregions.

Area	**Altitude (m*asl*)**	**Mean annual rainfall (mm.year^{-1})**	**Mean annual temperature (°C)**	**Soil type (IUSS, 2006)**
Rwanda				
Butare (S 2°17-27'/ E 29°45-47')	1675-1763	1150-1260 (*)	19.2 (**,°)	Acrisol, on granite
Kibungo (S 2°12-17'/ E 30°35-37')	1498-1623	900-980 (*)	19-20.6 (**,°)	Nitisol, on pelitic rocks
Ruhengeri (S 1°32'/ E 29°38')	1659-1692	1300-1350 (*)	19.6 (**,°)	Andosol, on mafic volcanic ash
Uganda				
Ntungamo (S 00°46-47'/ E 30°13-14')	1535-1611	1100-1200 (*) wide variability between years : 820-1300	19 (**)	Acrisol, on quartzite or micaschist
References: Location coordinates and altitudes were measured in the field (GPS). Soil type was ascribed in accordance with the FAO World Reference Base. Other data were found in literature: (*) Roark and Dickson, (1986, *cited in* Byers, 1990), Delepierre (1974, *cited in* Ndindahizi and Gwabije, 1991), Verdoodt and Van Ranst (2003), Smithson et al. (2004), FAO (2005b), Bouwmeester et al. (2009), Nyombi et al. (2009), Gaidashova et al. (2009), van Asten et al. (2011), ISAR online (http://www.isar.rw, accessed on October 12th 2010). (**) FAO (2005b), (°) Gaidashova et al. (2009). "m*asl*": meters above sea-level.				

4.2.2. Data collection

A. Diagnostic survey in Butare, Kibungo and Ruhengeri (Rwanda)

Selection of farms, plots and plants

The description here-under is based on the detailed report of Gaidashova et al. (2009). The field survey in the eco-regions of Butare, Kibungo and Ruhengeri was conducted in March and April 2006 and considered only the common East Africa Highland cultivar *Intuntu* (AAA-EA). The restriction to only one cultivar minimized the effect of the genotype on the collected data. In the three eco-regions, respectively 20, 20 and 22 farms were visited. For each area, farms were selected for the survey if they responded simultaneously to two criteria. The selected farms needed to (1) have plots with variable plant vigor, and (2) have, in one plot, at least five flowering *Intuntu*-plants at the stage of fully opened hands. Plant vigor was evaluated by (1) visual appraisal, and (2) measurement of growth- and yield-related components (height, girth at 1 m, number of functional leaves, number of fingers per bunch). Two plots showing extremes in plant vigor were chosen per farm, one with high-potential vigorous plants (plots A), one where the plants looked poor (plots B). The farms in the region of Butare were small and the contrasting plots (A and B) could belong to neighboring farmers. Described plots and selected plants were GPS-positioned.

Plant data

The distance between banana-plants was evaluated by measuring and averaging the distances between the selected mat and the four mats surrounding it. This allowed the calculation of the mean plant population density (plants.ha^{-1}). Bunch weights of the chosen plants were estimated by the allometric relationship established by Gaidashova et al. (2007). Per plot, a composite foliar sample was constituted by putting together the inner laminas of third leaves of the five selected flowering plants. Foliar samples were in agreement with the international reference method for banana (Martin-Prével, 1980, 1984). Foliar samples were oven-dried at 60°C for two days and then finely ground. Analysis was performed in the laboratory of UCL-Michamps, Michamps (Belgium). Total N contents in the foliar samples were determined by the Kjeldahl titration. To assess their total P-, K-, Ca- and Mg-contents, the foliar samples were dry ashed at 450°C for at least 12 hours. The ashes were then digested in hot concentrated nitric acid (Novozamsky et al., 1986). K-, Ca- and Mg-concentrations in the digest were determined using an atomic absorption spectrophotometer (AAS); P-concentrations were determined by colorimetry. Nutrient concentrations were expressed as elemental weight percentages.

Soil sampling and chemical analyses

At the base of each studied plant a composite soil sample was taken by thoroughly mixing the soil withdrawn between 0 and 25 cm depth from three places at horizontal distances of 50-70 cm from the plant. The soil samples were air-dried, softly ground and sieved to pass a 2 mm mesh. Soil chemical analysis was done in the UCL-laboratories at Michamps or Louvain-la-Neuve (Belgium). Soil pH was measured in a 1 : 5 soil : water-suspension after 3 to 4 hours of contact. Total carbon contents were determined by dry combustion. Exchangeable K, Ca and Mg were extracted using a 1M ammonium acetate solution at pH7. The cation contents in the extract were determined by AAS. The amount of ammonium retained by the soil, after washing it free of the excess of ammonium acetate by denatured ethanol, was considered an estimate of the cation exchange capacity of the soil. The retained ammonium was released by leaching the soil with a 1M potassium chloride solution at pH3. Ammonium contents in the leachate were determined by distillation. All data are expressed against dry soil weight (105°C). Total chemical analysis was performed by digesting finely ground powder (mineralized at 950°C for 72 h) in a mixture of lithium tetra- and metaborate (Chao and Sanzolone, 1992) at 950°C. The cooled digestion beads were dissolved in hot (100°C) 2M nitric acid. Elemental (Al, Fe, Si, Ti, Ca, K, Mg, Mn and P) contents in 100 ml 2M HNO_3 were determined by inductively coupled plasma – atomic emission spectrometry (ICP-AES). Elemental contents were expressed as percentages of oxides. Total reserve in bases (TRB) was calculated as the sum of total contents of alkaline-earth and alkaline cations (K_{tot}+Na_{tot}+(2xCa_{tot})+(2xMg_{tot}) (all expressed in $cmol_c.kg^{-1}$)) (Herbillon, 1986).

B. Monitoring in Ntungamo (Uganda)

Selection of farms and plants

Ten farms (farms 1 to 10) located in a same valley near Ntungamo were selected on basis of relative wealth status of the household and slope position of the farm. To represent an intra-farm range of plant performance and management, 15 banana-mats were selected along the topographic slope, at varying distances from the homestead. The distances between the kitchen's door and the selected banana-mats were measured. Five mats were located at relative distances "close" to the homestead, 5 at "intermediate" and 5 at "remote" relative distances (< 100 m) from the kitchen. All the selected banana-mats were of the dominant variety *Enyeru* (AAA-EA), to avoid influence of genotype in the collected data. Described plots and selected plants were GPS-positioned.

Plant data

The distance between banana-plants was evaluated by measuring and averaging the distances between the selected mat and the four mats surrounding it. The average surface between mats allowed the calculation of the mean plant population density (plants.ha^{-1}). For each selected mat, the plant growth for one follower ratoon was monitored monthly, between March 2005 and April 2007, from sucker emergence to harvest. Plants were harvested when farmers considered bunches mature. Harvested bunches were weighted using a balance (±0.5 kg). In accordance with the international reference for sampling banana tissue (Martin-Prével, 1980, 1984), the inner laminas of the third leaves of the selected plants were sampled in the 14 days following flowering. Foliar samples were oven-dried at 60°C for 2 to 4 days, and then ground to pass a 2mm-mesh sieve. Chemical analysis of the samples was done at the laboratory in Kawanda, Uganda, by standard methods (Okalebo et al., 2002). The dried samples were digested by a mixture of sulfuric acid and selenic acid. N- and P-concentrations in the digest were determined by colorimetry; K-, Ca- and Mg-concentrations by AAS. Nutrient concentrations were expressed as elemental weight percentages.

Soil chemical analyses

By mixing three to five cores of soil taken around the banana-plant and covering the 0-30 cm depth, a composite sample was obtained as representative of the soil at the base of each selected plant. The soil samples were air-dried, softly ground and sieved to pass a 2 mm mesh. Soil chemical analysis was done in the soil science laboratories at Kawanda (Uganda) or Louvain-la-Neuve (Belgium). Soil pH was measured in a 10g : 20ml soil : water-suspension according to Okalebo et al. (2002). Exchangeable K, Ca and Mg were evaluated by the Mehlich 3-procedure detailed in Okalebo et al. (2002). Total carbon contents were determined by dry combustion. Total analysis was performed as for the samples from Rwanda.

When revisiting the site in September 2009, 3 mats previously selected in farms 7, 9 and 10, and 1 mat in farms 2 and 3 were re-localized. A volume of 1.5*1.5*1.5 m^3 of soil was excavated. The soil profile at the foot of the banana-plant was described according to the FAO guidelines (2006) and bulk soil samples collected for each horizon of each profile. The soil samples were air-dried, softly ground and sieved to pass a 2 mm mesh. Soil particle distribution was determined at the UCL-laboratory in Louvain-la-Neuve (Belgium). Sand, silt and clay fractions were obtained through ultrasonic dispersion, sieving and prolonged dispersion with Na^+-resins, without preliminary destruction of organic matter (Rouiller et al., 1972). Distribution was expressed as percentages.

4.2.3. Data analysis

A. CND and associated "in balance" ranges

For each selected plant, the filling value (Rd), geometric mean (G) and row-centered logratios ($V_{N,}\ V_{P,}\ V_{K,}\ V_{Ca,}\ V_{Mg,}\ V_{Rd}$) are calculated according to the equations [1] to [3].

$$\mathrm{Rd} = 100 - (\mathrm{N} + \mathrm{P} + \mathrm{K} + \mathrm{Mg} + \mathrm{Ca}) \qquad [\mathrm{eq.}\,1]$$

$$\mathrm{G} = (\mathrm{N \ x\ P\ x\ K\ x\ Ca\ x\ Mg\ x\ Rd})^{\frac{1}{\mathrm{h}+1}} \qquad [\mathrm{eq.}\,2]$$

$$\mathrm{V_N} = \ln\left(\mathrm{N}/_{\mathrm{G}}\right)\ ;\ \mathrm{V_P} = \ln\left(\mathrm{P}/_{\mathrm{G}}\right)\ ;\ \mathrm{V_K} = \ln\left(\mathrm{K}/_{\mathrm{G}}\right)\ ;$$
$$\mathrm{V_{Ca}} = \ln\left(\mathrm{Ca}/_{\mathrm{G}}\right);\ \mathrm{V_{Mg}} = \ln\left(\mathrm{Mg}/_{\mathrm{G}}\right);\ \mathrm{V_{Rd}} = \ln\left(\mathrm{Rd}/_{\mathrm{G}}\right) \qquad [\mathrm{eq.}\,3]$$

where N, P, K, Ca and Mg represent respectively the total %N, %P, %K, %Ca and %Mg determined in the foliar sample and (h+1) relates to the total number of components in G (h nutrients increased by the one filling value; in this case: h+1 = 6).

The CND-indices ($I_N, I_P, I_K, I_{Ca}, I_{Mg}, I_{Rd}$) are calculated using the equation [4]:

$$I_N = \frac{(V_N - V_N^*)}{SD_N^*}, \ldots, I_{Ca} = \frac{(V_{Ca} - V_{Ca}^*)}{SD_{Ca}^*}, \ldots, I_{Rd} = \frac{(V_{Rd} - V_{Rd}^*)}{SD_{Rd}^*} \quad \text{[eq. 4]}$$

where $V_N^*, V_P^*, V_K^*, V_{Ca}^*, V_{Mg}^*, V_{Rd}^*$ and $SD_N^*, SD_P^*, SD_K^*, SD_{Ca}^*, SD_{Mg}^*, SD_{Rd}^*$ are the CND-norms, respectively, means and standard deviations of the row-centered logratios for the high bunch weight population of this study. The high bunch weight population is determined by the Cate-Nelson iterative procedure detailed by Khiari et al. (2001a).

A measurement of the global nutrient imbalance for one plant is given by r_{CND}^2 (eq. [5]) :

$$r_{CND}^2 = I_N^2 + I_P^2 + I_K^2 + I_{Ca}^2 + I_{Mg}^2 + I_{Rd}^2 \quad \text{[eq. 5]}$$

The calculation of the row-centered logratios implies a division of each nutrient or Rd by the geometric mean of all components (nutrients and filling value Rd) (see eq. [3]). The CND-indices are thus multi-elemental ratios, recognizing higher-order interactions between nutrients (Parent and Dafir, 1992). Indices can be ranked in order of decreasing values, hence highlighting the order in which the nutrients are most limiting the production (Parent et al., 1994). In theory, positive values for $\mathrm{I_N}$, $\mathrm{I_P}$, $\mathrm{I_K}$, $\mathrm{I_{Ca}}$ and $\mathrm{I_{Mg}}$ represent relative nutrient excesses, and negative values nutrient insufficiencies. CND-indices close to zero evidence nutrient balances (Parent and Dafir, 1992). In practice, “in balance” ranges around zero are sometimes used (Khiari et al., 2001c; Quesnel et al., 2006). In this study, nutrient deficiencies or excesses are interpreted with respect to the “in balance” ranges determined by the boundary line approach described below. Plants having a CND-index for one nutrient inferior to the lower end of the “in balance” range are considered deficient in that nutrient. Plants with a CND-index for one nutrient superior to the highest value of the “in balance” range have a relative excess of that nutrient. For each nutrient, the number of deficient banana plants and the number of plants having a relative excess is counted and expressed against the total number of plants (%).

The “in balance” ranges are established by the Boundary Line procedure. The principles of the boundary lines are described in Webb (1972), and are adapted a.o. in Walworth et al. (1986), Vizcayno-Soto and Côté (2004), Quesnel et al. (2006) and Blanco-Macias et al. (2009, 2010) to determine sufficiency ranges for various crops. For each chemical element X, the scatterplots relating bunch weights to CND-index (V_X) are plotted. For one nutrient, the line describing the highest bunch weights over the entire index range is known as the boundary line since it delimits the cloud of points on its upper edge. In this study, the boundary line is established using the BOLIDES-algorithm of Schnug et al. (1996). The boundary lines are fitted through the boundary points generated by BOLIDES, using a second degree polynomial. The bunch weight (Y_{BLmax}) related to the maximum of the curve is determined. The intersections of the boundary line with the straight horizontal line through $0.95 * Y_{BLmax}$ are calculated. The interval between the x-values of the two intersections is considered the “in balance” range for the CND-indices of the element X.

B. Principal Component Analysis (PCA)

Because of the log-transformation (eq. [3]) of the compositional data it is dealing with, CND is entirely compatible with Principal Component Analysis (PCA) (Aitchison, 1983; Parent et al., 1994). As in Garcia-Hernandez (2004, 2005, 2006, 2009) and Magallanes-Quinatar et al. (2006), the PCA is performed on CND-indices, without standardization. The j out of (h+1) original principal components showing eigenvalues superior to 0.7 (Parent et al., 1994), are varimax rotated in order to maximize the loadings of each variable on only one principal component and hence simplify the global structure (Sharma, 1996). When interpreting the Principal Components in the rotated structure, only the variables having loadings superior to the selection criterion of Ovalles and Collins (1988, eq. [6]) are considered influential in the formation of the Principal Components:

$$\text{selection criterion } = \frac{0.5}{\sqrt{\text{eigenvalue of the PC}}} \qquad [\text{eq. } 6]$$

The Principal Component Analysis is performed on the CND-indices calculated (1) for all of the plants studied with no distinction made between regions, (2) for the same plants but with data for each region taken separately, (3) for the high and (4) the low producing plants of each region. This procedure is applied by Parent et al. (1994), Raghupathi et al. (2002), Garcia-Hernandez et al. (2004, 2005, 2006, 2009), Magallanes-Quintanar et al. (2006) and Wairegi (2010) to study nutrient interactions in various crops.

For the interacting pairs of nutrients deduced from the Principal Component Analyses, the ratios between the implicated nutrients are computed. The expression of the nutrient ratio retained (A/B or B/A) is the one that maximizes the ratio between the variance of the low bunch weight population and the variance of the high bunch weight population (Walworth and Sumner, 1987).

C. Computer software

All calculations and statistics are carried out in *MATLAB 7.4.0 (R2007a)*. Two-sample *t*-tests are performed, after verification of the normality of distributions (LillieFors-test). The *t*-test is executed even if the distribution is slightly skewed, since hypothesis testing is robust to a certain violation of the assumption of normality (Smith and Wells, 2006). Graphs are drawn in *MATLAB*.

4.3. Results

4.3.1. Soil data

Table 4.2 summarizes some chemical characteristics for the soils encountered in the four regions of interest. Data from Butare, Kibungo or Ruhengeri are grouped as representatives of their respective region; for the data from Ntungamo, a further intra-regional distinction is made: farms 1+3, farms 2+4+5+7+8 and farms 6+9+10. Variations in texture and significant ($P<0.05$) differences in total chemical analysis justify this subdivision (Figure 4.1, Table 4.2, Appendix 2[1]).

Farms 1+3 are installed on steep slopes. Contrary to the soils in the other farms studied in the Ntungamo area soils are shallow, the parent micaschists appearing at about 1 m depth. The soils of farm 3 (no data for farm 1) are very gravelly, since more than 50% of the soil does not pass a 2 mm mesh grid. With a significantly ($P<0.05$) higher proportion of silt and a significantly ($P<0.05$) lower proportion of sand, the soils of farms 2+7 (no

[1] Soil chemical analyses for soils of all regions and subregions are analyzed by Principal Component Analysis in Appendix 2.

data for farms 4, 5, 8) differ from the soils of the other two groups for what the texture of their fine earth (<2 mm) is considered (Figure 4.1). Relatively to the soils in neighboring farms, the soils of farms 1+3 are characterized by significantly ($P<0.05$) lower silicon contents but significantly ($P<0.05$) higher total aluminum contents (Figure 4.1). The soils of farms 6+9+10 have significantly ($P<0.05$) higher silicon contents and significantly ($P<0.05$) lower aluminum contents than soils in farms 1+3 or 2+4+5+7+8. The comparison of the classical indicators of soil fertility points to slightly richer soils in farms 1+3. All chemical properties vary in wide ranges, but mean total carbon content (4.39 $\%C_{tot}$), sum of exchangeable K, Ca and Mg (13.07 $cmol_c.kg^{-1}$) and total reserve in bases (TRB, 98.86 $cmol_c.kg^{-1}$) are significantly ($P<0.05$) higher than in the other farms studied in the valley (Table 4.2; Figure 4.1). Mean total phosphorous (0.42 $\%P_2O_{5,tot}$) contents are higher too. Soils of all farms are acid (pH4.7-4.9) to neutral or slightly basic (pH7.0-7.7) (Table 4.2).

Soils in Ruhengeri are Andosols developed on Quaternary mafic volcanic parent material. The chemical characteristics of these soils vary in a wide range. Overall, they possess sufficient reserves in nutrients as attested by a mean TRB (382.45 $cmol_c.kg^{-1}$, N=40) significantly ($P<0.05$) higher than in all the other regions of this study. The sum of exchangeable K, Ca and Mg explains, in average, a mere 6.4% of TRB. The total phosphorus contents (mean 0.82 $\%P_2O_5$) are amongst the highest observed.

Despite being old and weathered, soils in Kibungo are relatively more fertile than their counterparts in Ntungamo 2+4+5+7+8 or Ntungamo 6+9+10. pH varies between 6.4 and 8.2. The total carbon contents (4.63 $\%C_{tot}$ on average) are amongst the highest observed in the all the regions of interest. Cation exchange capacity (mean 31.00 $cmol_c.kg^{-1}$) and sum of exchangeable K, Ca and Mg (mean 29.29 $cmol_c.kg^{-1}$) are significantly higher than in the other Rwandan sites; comparison with Ntungamo is not possible because of a lack of data or dissimilarities in the laboratory techniques applied. On average 46.3% of the total reserve in bases is explained by exchangeable cations. Total iron content is significantly ($P<0.05$) higher in the Kibungo soils (11.61-15.77%Fe_2O_3, mean 12.95%Fe_2O_3) than in all the other regions of interest to this study.

The soils in Butare are deep, highly weathered and poor. They are acid to neutral (pH 5.2-7.4), with total carbon (mean 1.80 %C_{tot}) and phosphorus (mean 0.15 %P_2O_5) contents as low as in Ntungamo farms 2+4+5+7+8 or 6+9+10. TRB (40.78 $cmol_c.kg^{-1}$) is amongst the lowest observed. Cation exchange capacity (12.05 $cmol_c.kg^{-1}$ on average) and sum of exchangeable K, Ca and Mg (mean 9.70 $cmol_c.kg^{-1}$) are significantly ($P<0.05$) lower than in Kibungo or Ruhengeri (no comparison with Ntungamo, Table 4.2).

Table 4.2 (continued on next page). Soil chemical properties for the four regions of interest. Heterogeneity of chemical data for soils in Ntungamo, led to distinction of three groups of farms having similar soils (farms f.1+3, f.2+4+5+7+8 and f.6+9+10).

Region	Variable / Statistics	pH_{H2O}	C_{tot} (%)	CEC ($cmol_c.kg^{-1}$)	$(K+Ca+Mg)_{exch}$ ($cmol_c.kg^{-1}$)	TRB ($cmol_c.kg^{-1}$)	$(K+Ca+Mg)_{exch}$ / TRB (%)	Total P_2O_5 (%)
Butare	**range**	5.2-7.4	0.80-3.14	6.20-18.30	3.67-20.83	23.67-104.12	9.0-46.3	0.07-0.33
(N=30)	**mean(±SD)**	6.1(±0.5)	1.80(±0.58)	12.05(±2.87)	9.70(±4.36)	40.78(±17.65)	25.2(±10.3)	0.15(±0.06)
	stat.comp.	(a)	(a)	(a)	(a)	(a,b)	(b)	(ln-transf: a)
Kibungo	**range**	6.4-8.2	3.69-5.63	24.20-38.10	16.69-43.45	38.17-91.86	33.9-59.2	0.12-0.49
(N=38)	**mean(±SD)**	7.2(±0.5)	4.63(±0.44)	31.00(±3.21)	29.29(±5.44)	63.83(±12.34)	46.3(±6.1)	0.26(±0.08)
	stat.comp.	(b)	(b)	(c)	(c)	(b)	(c)	(ln-transf: b)
Ruhengeri	**range**	6.1-7.9	1.54-7.33	9.10-40.90	8.94-37.00	146.26-610.02	1.6-13.5	0.26-1.28
(N=40)	**mean(±SD)**	7.0(±0.4)	4.06(±1.67)	23.75(±10.11)	21.44(±8.57)	382.45(±93.63)	6.4(±3.6)	0.82(±0.24)
	stat.comp.	(b)	(b)	(b)	(b)	(d)	(a)	(ln-transf: d)
Ntungamo	**range**	4.9-7.0	1.18-6.70		3.15-20.27	26.68-128.36	4.2-48.4	0.13-0.92
f.1,3	**mean(±SD)**	6.4(±0.6)	4.39(±1.93)	ND	13.07(±5.06)	98.86(±39.03)	13.9(±8.3)	0.42(±0.27)
(N=30)	**stat.comp.**	(a)	(b)		(*B*)	(c)	(*C*)	(ln-transf: c)
Ntungamo	**range**	4.7-7.7	1.23-2.94		0.76-12.30	45.96-82.25	1.5-14.2	0.09-0.27
f.2,4,5,7,8	**mean(±SD)**	6.2(±0.9)	1.91(±0.46)	ND	4.71(±2.69)	61.91(±13.73)	7.1(±3.4)	0.15(±0.05)
(N=75)	**stat.comp.**	(a)	(a)		(*A*)	(b)	(*A*)	(ln-transf: a)
Ntungamo	**range**	4.8-7.3	0.99-4.30		0.72-8.19	23.18-94.32	2.0-20. 9	0.10-0.34
f.6,9,10	**mean(±SD)**	6.2(±0.7)	1.62(±0.49)	ND	3.53(±1.90)	37.35(±15.67)	10.0 (±5.1)	0.14(±0.04)
(N=45)	**stat.comp.**	(a)	(a)		(*A*)	(a)	(*B*)	(ln-transf: a)

Legend : analyses performed on the fine earth fraction (<2mm): CEC = cation exchange capacity ; $(K+Ca+Mg)_{exch}$= sum of exchangeable K, Ca and Mg ($cmol_c.kg^{-1}$) ; TRB = total reserve in bases; SD = standard deviation ; ND = no data ; N = number of samples ; stat.comp.: multiple comparison test, (a) (b) (c) (d) and (*A*) (*B*) (*C*) : vertical comparison between the Butare, Kibungo, Ruhengeri and Ntungamo regions. The farms of the Ntungamo area are subdivided in three groups for this comparison. Mean values followed by different letters are significantly ($P<0.05$) different; test performed on log-trans-formed data for total phosphorous content. For $(K+Ca+Mg)_{exch}$ ($cmol_c.kg^{-1}$) and $(K+Ca+Mg)_{exch}$/TRB ($cmol_c.kg^{-1}/cmol_c.kg^{-1}$), data from Butare, Kibungo and Ruhengeri are not directly comparable to those from Ntungamo because of differences in methods used when acquiring the data, hence the difference in letter case (respectively, (a) (b) (c) (d)) and (*A*) (*B*) (*C*)).

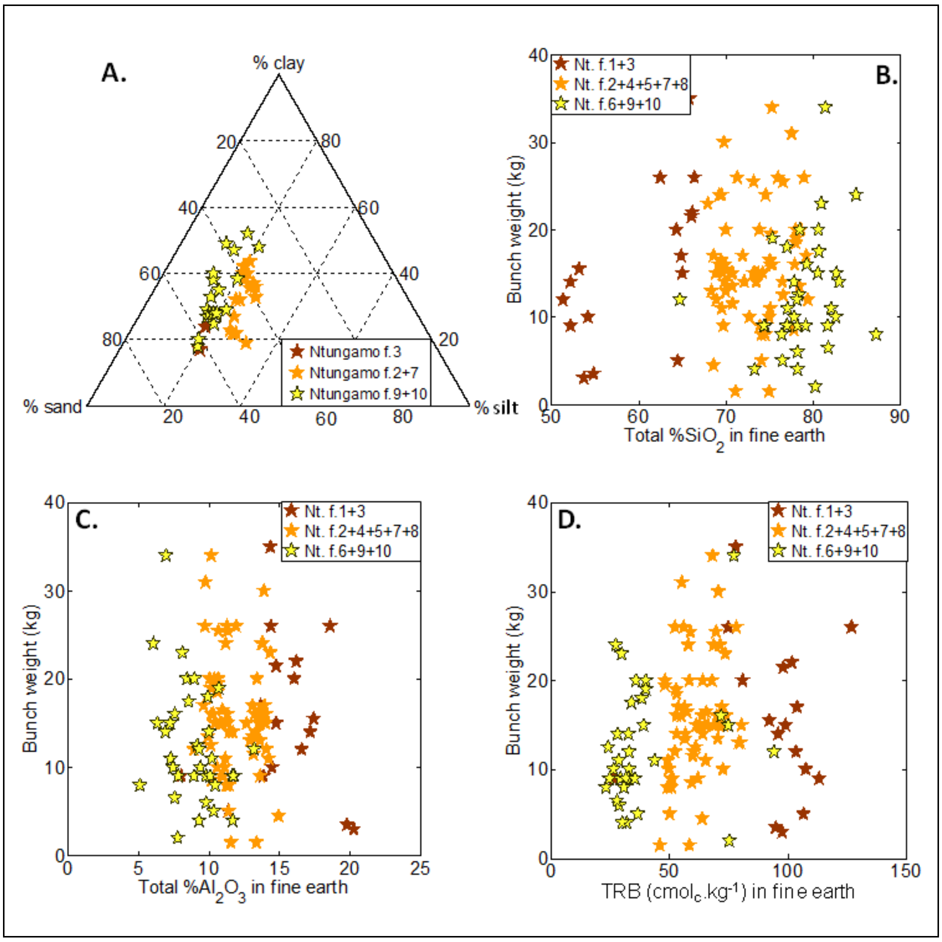

Figure 4.1. Differences in (A) texture and (B, C, D) chemical composition of fine earth (<2 mm) sampled in 10 farms in the Ntungamo-area. Farms are subdivided in three groups presenting similar soils for what their texture and chemical composition is considered: farms f.1+3, farms f.2+4+5+7+8 and farms f.6+9+10. Total reserve in bases (TRB) was calculated as the sum of total contents of alkaline-earth and alkaline cations (Herbillon, 1986).

4.3.2. Plant data

Measured or estimated bunch weights range between 1.5 and 35.0 kg (Table 4.3). Bunch weights vary widely within a same region and, in addition, differences between regions appear. The highest mean bunch weights are, in decreasing order, 15.9±6.1 kg in Kibungo, 15.8±7.6 kg in Ntungamo farms 2+4+5+7+8 and 15.3±4.4 kg in Ruhengeri. Ntungamo farms 1+3 (15.4±9.9 kg) and Ntungamo 6+9+10 (12.8±8.1 kg) have intermediate mean bunch weights. Mean bunch weights for Butare (10.4±5.2 kg) are significantly ($P<0.05$) lower than in all the other regions of this study. Average banana-plant population densities are 3058 (Butare), 1711 (Kibungo), 3746 (Ruhengeri), 2329 (Ntungamo farms 1+3), 3132 (Ntungamo farms 2+4+5+7+8) and 2661 plants.ha^{-1} (Ntungamo farms 6+9+10) for the different regions. The mean yields of 54.7 t.ha^{-1} in Ruhengeri and 46.9 t.ha^{-1} in Ntungamo 2+4+5+7+8 are significantly ($P<0.05$) higher than the yields in the other regions or subregions. The lowest mean yield is computed for the Kibungo region (25.2 t.ha^{-1}) (Table 4.3).

Table 4.3 (continued on following pages). Mean values for plant production, population density and nutrient contents of inner lamina of third leaves of banana-plants grown in four agro-ecoregions. Heterogeneity of chemical data for soils in Ntungamo, led to distinction of three groups of farms having similar soils (farms 1+3, f.2+4+5+7+8 and f.6+9+10).

Region	Variable / Statistics	Bunch weight (kg)	Yield ($t.ha^{-1}$)	Population density ($pl.ha^{-1}$)
Butare (N=30)	**range**	2.0-23.1	3.4-107.6	1171-5646
	mean(±SD)	10.4(±5.2)	34.5(±26.2)	3058(±1306)
	stat.comp.	(a)	(a)	(b)
Kibungo (N=38)	**range**	4.7-27.4	9.8-47.6	873-3073
	mean(±SD)	15.9(±6.1)	25.2(±8.3)	1711(±508)
	stat.comp.	(b)	(a)	(a)
Ruhengeri (N=40)	**range**	8.1-27.0	25.6-90.4	1822-7182
	mean(±SD)	15.3(±4.4)	54.7(±16.1)	3746(±1158)
	stat.comp.	(b)	(b)	(c)
Ntungamo f.1+3 (N=20)	**range**	3.0-35.0	6.9-56.6	773-5000
	mean(±SD)	15.4(±9.9)	29.9(±18.1)	2329(±1091)
	stat.comp.	(a,b)	(a)	(a,b)
Ntungamo f.2+4+5+7+8 (N=66)	**range**	1.5-34.0	3.6-126.4	1171-6897
	mean(±SD)	15.8(±7.6)	46.9(±25.4)	3132(±1247)
	stat.comp.	(b)	(b)	(b)
Ntungamo f.6+9+10 (N=36)	**range**	2.0-34.0	6.1-79.9	1300-6173
	mean(±SD)	12.8(±8.1)	32.4(±22.2)	2661(±942)
	stat.comp.	(a,b)	(a)	(b)

Legend: $t.ha^{-1}$ = tons per hectare ; $pl.ha^{-1}$ = plants per hectare ; SD = standard deviation ; stat.comp.: multiple comparison test, (a) (b) (c): vertical comparison between the Butare, Kibungo, Ruhengeri and Ntungamo regions. The farms of the Ntungamo area are subdivided in three groups for this comparison. Mean values followed by different letters are significantly ($P < 0.05$) different.

Table 4.3 (continued). Mean values for plant production, population density and nutrient contents of inner lamina of third leaves of banana-plants grown in four agro-ecoregions. Heterogeneity of chemical data for soils in Ntungamo, led to distinction of three groups of farms having similar soils (farms 1+3, f.2+4+5+7+8 and f.6+9+10).

Region	Variable / Statistics	Foliar N (%)	Foliar P (%)	Foliar K (%)
Butare (N=30)	**range**	2.07-3.08	0.14-0.47	1.95-3.76
	mean(±SD)	2.55(±0.23)	0.19(±0.06)	2.86(±0.49)
	stat.comp.	(a,b)	(ln-trans : b,c)	(a)
Kibungo (N=38)	**range**	2.38-2.91	0.14-0.21	2.08-3.59
	mean(±SD)	2.65(±0.12)	0.17(±0.01)	3.06(±0.45)
	stat.comp.	(b)	(ln-trans : b)	(a,b)
Ruhengeri (N=40)	**range**	2.36-2.91	0.18-0.27	2.66-3.67
	mean(±SD)	2.67(±0.13)	0.20(±0.01)	3.25(±0.25)
	stat.comp.	(b)	(ln-trans : c)	(b)
Ntungamo f.1+3 (N=20)	**range**	2.09-3.12	0.10-0.21	2.85-4.40
	mean(±SD)	2.58(±1.30)	0.13(±0.07)	3.66(±1.87)
	stat.comp.	(a,b)	(ln-trans : a)	(c)
Ntungamo f.2+4+5+7+8 (N=66)	**range**	1.49-3.03	0.06-0.21	2.01-4.74
	mean(±SD)	2.50(±0.86)	0.15(±0.06)	3.41(±1.25)
	stat.comp.	(a)	(ln-trans : a)	(b,c)
Ntungamo f.6+9+10 (N=36)	**range**	1.83-3.11	0.12-0.22	2.37-4.49
	mean(±SD)	2.45(±1.01)	0.16(±0.07)	3.63(±1.53)
	stat.comp.	(a)	(ln-trans : a,b)	(c)

Legend: $t.ha^{-1}$ = tons per hectare ; $pl.ha^{-1}$ = plants per hectare ; SD = standard deviation ; stat.comp.: multiple comparison test, (a) (b) (c): vertical comparison between the Butare, Kibungo, Ruhengeri and Ntungamo regions. The farms of the Ntungamo area are subdivided in three groups for this comparison. Mean values followed by different letters are significantly ($P < 0.05$) different.

Table 4.3 (continued). Mean values for plant production, population density and nutrient contents of inner lamina of third leaves of banana-plants grown in four agro-ecoregions. Heterogeneity of chemical data for soils in Ntungamo, led to distinction of three groups of farms having similar soils (farms 1+3, f.2+4+5+7+8 and f.6+9+10).

Region	Variable / Statistics	Foliar Ca (%)	Foliar Mg (%)	Filling value Rd (%)
Butare (N=30)	**range**	0.38-1.13	0.18-0.41	92.53-94.34
	mean(±SD)	0.65(±0.18)	0.29(±0.06)	93.47(±0.51)
	stat.comp.	(a)	(a)	(b)
Kibungo (N=38)	**range**	0.52-1.14	0.22-0.60	92.21-93.74
	mean(±SD)	0.83(±0.13)	0.39(±0.08)	92.90(±0.38)
	stat.comp.	(b)	(b,c)	(a)
Ruhengeri (N=40)	**range**	0.63-1.04	0.21-0.36	92.28-93.24
	mean(±SD)	0.83(±0.11)	0.27(±0.04)	92.78(±0.21)
	stat.comp.	(b)	(a)	(a)
Ntungamo f.1+3 (N=20)	**range**	0.27-1.10	0.31-0.57	91.60-93.59
	mean(±SD)	0.65(±0.37)	0.43(±0.22)	92.56(±0.54)
	stat.comp.	(a)	(c)	(a)
Ntungamo f.2+4+5+7+8 (N=66)	**range**	0.27-1.41	0.19-0.79	90.73-95.43
	mean(±SD)	0.69(±0.31)	0.37(±0.17)	92.88(±0.87)
	stat.comp.	(a)	(b,c)	(a)
Ntungamo f.6+9+10 (N=36)	**range**	0.33-0.87	0.22-0.46	91.06-93.76
	mean(±SD)	0.66(±0.28)	0.35(±0.15)	92.75(±0.58)
	stat.comp.	(a)	(b)	(a)

Legend: $t.ha^{-1}$ = tons per hectare ; $pl.ha^{-1}$ = plants per hectare ; SD = standard deviation ; stat.comp.: multiple comparison test, (a) (b) (c): vertical comparison between the Butare, Kibungo, Ruhengeri and Ntungamo regions. The farms of the Ntungamo area are subdivided in three groups for this comparison. Mean values followed by different letters are significantly ($P < 0.05$) different.

Foliar nutrient contents for N, P, K, Ca and Mg vary between 1.49-3.12 %N, 0.06-0.47 %P, 1.95-4.74 %K, 0.27-1.41 %Ca, 0.18-0.79 %Mg. The mean nutrient contents vary between regions, with some differences being significant (P<0.05). Banana leaves from Butare show the lowest contents in all nutrients, except P. Filling values Rd are significantly (P<0.05) higher in Butare than in the other regions. N, P and Ca contents are highest in the plants from Kibungo and Ruhengeri. Foliar K is low in Kibungo; foliar Mg in Ruhengeri. Foliar data from the three groups of farms in Ntungamo are characterized by high K and Mg contents, but low Ca and P contents. Low foliar P contents are determined for plants growing in farms 1+3, on soils showing nonetheless significantly (P<0.05) higher total and available phosphorus contents. Foliar data for Ntungamo vary widely, even within a same subgroup (Table 4.3).

The CND-norms used to calculate the CND-indices for all the plants of each region, are those deduced from the high bunch weight population of this study. The high bunch weight population comprises all the plants with bunch weights superior to 14.5 kg, it is to say 49% of all the observations. The CND-norms are summarized in Table 4.4. The "in balance" ranges computed to interpret the calculated CND-indices are the following: [-0.85, 0.82] for N, [-0.72, 0.73] for P, [0.00, 2.57] for K, [-0.84, 0.48] for Ca, [-0.55, 0.83] for Mg and [-0.53, 1.16] for the filling value Rd.

Table 4.4. CND-norms calculated from the high bunch weight population (>14.5 kg.bunch^{-1}) of this dataset related to the East African Highland bananas (*Musa spp.* AAA-EA) grown in four agro-ecoregions in Rwanda and South-West Uganda.

CND-norms		
Expression	**Mean**	**SD**
V_N^*	0.36	0.09
V_P^*	-2.37	0.15
V_K^*	0.64	0.16
V_{Ca}^*	-0.94	0.22
V_{Mg}^*	-1.63	0.23
V_{Rd}^*	3.94	0.08

4.3.3. CND-indices, deficiencies and excesses

For each region or subregion, the deficiencies or relative excesses regarding to the “in balance” ranges are represented in Table 4.5 and Figure 4.2.

According to the interpretation of the CND-indices relative to the “in balance” ranges, 60% of all the plants studied in Butare (N=30) are deficient in K and 57% in Mg. The Rd-indices are superior to their “in balance” ranges in 43% of the cases. N and P are in relative excess in respectively 50 and 53% of the plants. The results around the Ca-index are mitigated since 27% of the plants are deficient in Ca and another 23% have a relative excess in calcium. Sorting the values for the different nutrient indices from highest to lowest, allows a ranking of the nutritional problems.

For Butare the following order appears: N > Ca,P > 0 > K > Mg,Ca where positive values represent relative excesses and negative values deficiencies. The consideration of the relative excesses *vs.* the deficiencies for each plant individually, highlights certain tendencies, possible witnesses of nutrient interactions. Half of the plants are deficient in Ca and/or Mg but have relative excesses in N and/or P. The 7 plants having a relative excess in Ca, are deficient in K. In Kibungo (N=38), 87% of the plants are deficient in K and 45% have CND-values for Rd inferior to the “in balance” range. Calcium is in relative excess in 50% of the plants. The order of nutritional problems is Ca > 0 > K in Kibungo. 19 of the 33 plants suffering a K-deficiency have a relative excess of Ca or Ca and Mg. 14 of the 19 plants having Ca-excesses, have values of their Rd-indices inferior to the “in balance” ranges. On the Andosols of Ruhengeri (N=40), the sequence of nutritional problems is easily summarized by P > Ca > 0 > K > Mg. 90% of the plants are deficient in Mg, 68% in K. P and Ca are in relative excess in respectively 80 and 68% of the cases. Apart that P is the most deficient element and that contrasting situations exist about Ca, conclusions relating to deficiencies or excesses are not as clear-cut in Ntungamo. 94, 45 and 30% of the plants in farms 1+3 (N=16), 2+4+5+7+8 (N=64) and 6+9+10 (N=33) suffer P-deficiencies. In farms 1+3, 44% of the plants lack Ca. Mg and N are in relative excess in respectively 69 and 38% of the plants of that group of farms. 11 plants out of the 15 lacking P, have a relative excess in Mg. 36% of the plants in farms 2+4+5+7+8 lack K. 23 plants suffer K-deficiencies and have relative excesses in Ca, Mg or both.

Table 4.5 (continued on next page). Percentage of plants interpreted as deficient (<IBR, values of CND-index inferior to lower limit of the established "in balance" ranges) or having a relative excess (>IBR) in N, P, K, Ca, Mg or other nutrients (all gathered in Rd) for the different areas of interest.

CND indices compared to the IBR / region & plant population		I_N		I_P		I_K	
		< IBR (%)	> IBR (%)	< IBR (%)	> IBR (%)	< IBR (%)	> IBR (%)
Butare	all (N=30)	3	50	0	53	60	0
	HBWt (N=6)	0	17	0	10	3	0
	LBWt (N=24)	4	42	0	43	57	0
Kibungo	all (N=38)	5	5	11	8	87	0
	HBWt (N=24)	5	5	5	5	53	0
	LBWt (N=14)	0	0	5	3	34	0
Ruhengeri	all (N=40)	5	23	0	80	68	0
	HBWt (N=22)	0	18	0	48	33	0
	LBWt (N=18)	5	5	0	33	35	0
Ntungamo f.1+3	all (N=16)	25	38	94	0	25	0
	HBWt (N=8)	13	25	50	0	13	0
	LBWt (N=8)	13	13	44	0	13	0
Ntungamo f.2+4+5+7+8	all (N=64)	23	25	45	3	36	0
	HBWt (N=36)	14	5	20	3	27	0
	LBWt (N=28)	9	20	25	0	9	0
Ntungamo f.6+9+10	all (N=33)	21	12	30	3	21	0
	HBWt (N=12)	12	3	6	3	0	0
	LBWt (N=21)	9	9	24	0	21	0

Legend: < IBR (%) / > IBR (%): respectively, percentage of plants having values lower/higher than the lower/upper limit of the established "in balance" range; HBWt and LBWt represent respectively the high and low bunch weight banana populations. N = number of observations.

Table 4.5 (continued). Percentage of plants interpreted as deficient (<IBR, values of CND-index inferior to lower limit of the established "in balance" ranges) or having a relative excess (>IBR) in N, P, K, Ca, Mg or other nutrients (all gathered in Rd) for the different areas of interest.

region & plant population \ CND indices compared to the IBR		I_{Ca}		I_{Mg}		I_{Rd}	
		< IBR (%)	> IBR (%)	< IBR (%)	> IBR (%)	< IBR (%)	> IBR (%)
Butare	all (N=30)	27	23	57	0	7	43
	HBWt (N=6)	13	3	17	0	0	10
	LBWt (N=24)	13	20	40	0	7	33
Kibungo	all (N=38)	0	50	8	18	45	3
	HBWt (N=24)	0	32	8	8	32	3
	LBWt (N=14)	0	18	0	11	13	0
Ruhengeri	all (N=40)	0	68	90	0	13	0
	HBWt (N=22)	0	33	50	0	8	0
	LBWt (N=18)	0	35	40	0	5	0
Ntungamo f.1+3	all (N=16)	44	19	0	69	6	25
	HBWt (N=8)	25	6	0	31	0	13
	LBWt (N=8)	19	13	0	38	6	13
Ntungamo f.2+4+5+7+8	all (N=64)	22	28	23	22	34	34
	HBWt (N=36)	14	13	3	19	25	8
	LBWt (N=28)	8	16	20	3	9	27
Ntungamo f.6+9+10	all (N=33)	15	18	15	12	15	15
	HBWt (N=12)	15	0	3	3	9	0
	LBWt (N=21)	0	18	12	9	6	15

Legend: < IBR (%) / > IBR (%): respectively, percentage of plants having values lower/higher than the lower/upper limit of the established "in balance" range; HBWt and LBWt represent respectively the high and low bunch weight banana populations. N = number of observations.

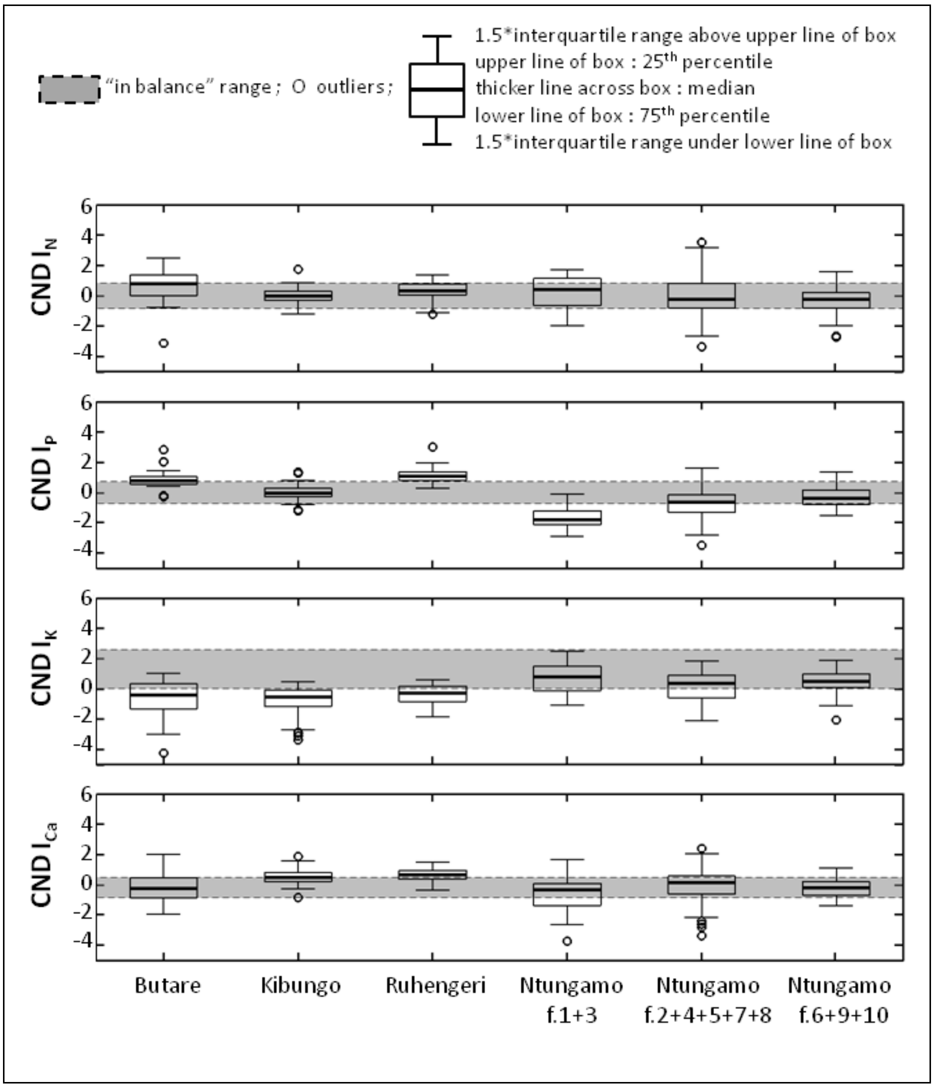

Figure 4.2 (continued on next page). Boxplots representing the range of values of the CND-indices for N, P, K, Ca, Mg and Rd for the regions of Butare, Kibungo, Ruhengeri and the subregions Ntungamo farms 1+3, farms 2+4+5+7+8 and farms 6+9+10. The grey strips across the plots represent the "in balance" ranges calculated using a boundary line approach.

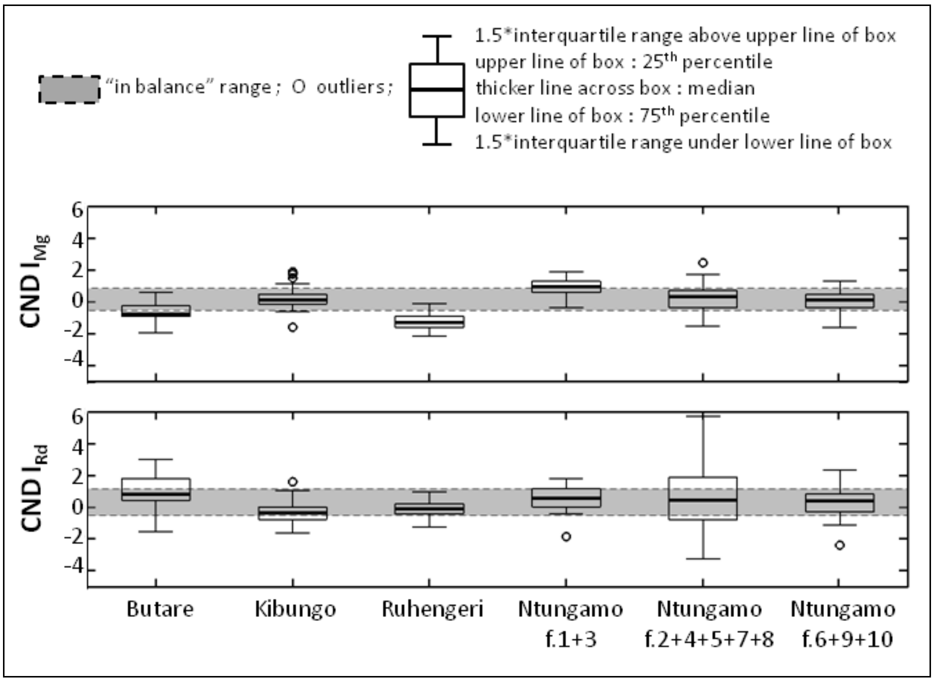

Figure 4.2 (continued). Boxplots representing the range of values of the CND-indices for N, P, K, Ca, Mg and Rd for the regions of Butare, Kibungo, Ruhengeri and the subregions Ntungamo farms 1+3, farms 2+4+5+7+8 and farms 6+9+10. The grey strips across the plots represent the "in balance" ranges calculated using a boundary line approach.

4.3.4. PCA-analysis and nutrient interactions

In the original Principal Component Analysis (PCA) performed on 6 variables (CND-indices for N, P, K, Ca, Mg and Rd: I_N, I_P, I_K, I_{Ca}, I_{Mg}, I_{Rd}) for 221 plant studied in the 4 regions of interest, the three first Principal Components have eigenvalues superior to 0.7. They explain respectively 40, 24 and 19% of the total variance. The PCA-structure after varimax rotation of the three first principal components, is detailed in Table 4.6. The selection criterion of Ovalles and Collins (1988, eq. [6], Table 4.6) is used to determine which variables are influential in the formation of the Principal Components (PC). I_N and I_{Rd} have high negative loadings on PC1. I_P and I_{Mg} contribute, respectively, positively and negatively to the second PC. I_K has a high positive loading on PC3 while I_{Ca} contributes negatively to this same Component. The biplots of Figure 4.3 represent simultaneously the loadings of the three first PCs and the related Principal Component scores. Visual examination of the plots highlights that data for a same region or subregion cluster together. Plants in Butare have low to intermediate positive values for I_N, I_P, I_{Rd} and negative values for I_{Mg}. Values for I_K and I_{Ca} vary widely, some are positive, others negative. The bananas studied in Kibungo have low to high positive values for I_{Ca}, and negative values for I_K. Plants in Ruhengeri are characterized by low to medium positive values for I_P, negative values for I_{Mg}, mostly positive values for I_{Ca} but mainly negative values for I_K. General tendencies for the plants in Ntungamo are the negative values for I_P and the low to high positive values for I_{Mg}. There is a certain segregation of groups of farms along the second and third PC. Farms 1+3 have more negative values for I_P than F6+9+10. Most of the bananas in farms 1+3 and 6+9+10 have negative values for I_{Ca} and positive values for I_K. In farms 2+4+5+7+8 the values for I_{Ca} and I_K cover the entire range between positive and negative values.

When performing Principal Component Analyses on (1) data for each region separately, on (2) data for the high or (3) low bunch weight populations of each region, a few more relationships recurrently appear. On the total of 21 PCA's performed the following 8 relationships appear at least 5 times: the positive relationships between N and Rd, P and K and the negative relationships between the couples P and Ca, P and Mg, P and Rd, K and Mg, K and Ca. The relationship between Ca and Mg seems more variable, being sometimes positive, sometimes negative. For the interacting pairs of nutrients deduced from the Principal Component Analyses, the ratios between the two nutrients are computed (P/K, Ca/P, Mg/P, K/Mg, Ca/K, Ca/Mg). The same is done for Rd/N and P/Rd implying the filling value Rd. In the comparison of the means of these ratios for the high and the low bunch weight population, it appears that the ratios Ca/Mg and P/K discriminate more often the high and low bunch weight populations than do the other ratios.

Table 4.6 Eigenvectors and eigenvalues describing the three first Principal Components (PC) after orthogonal axis rotation (varimax rotation).

	PC1	PC2	PC3
I_N	**-0.58**	0.16	-0.07
I_P	0.18	**0.83**	0.04
I_K	0.05	-0.02	**0.77**
I_{Ca}	0.04	-0.02	**-0.62**
I_{Mg}	0.29	**-0.52**	0.03
I_{Rd}	**-0.74**	-0.13	0.10
Eigenvalues	2.42	1.76	1.87
Selection criterion [eq. 6]	0.32	0.38	0.37
Percentage of variance explained	40%	29%	31%

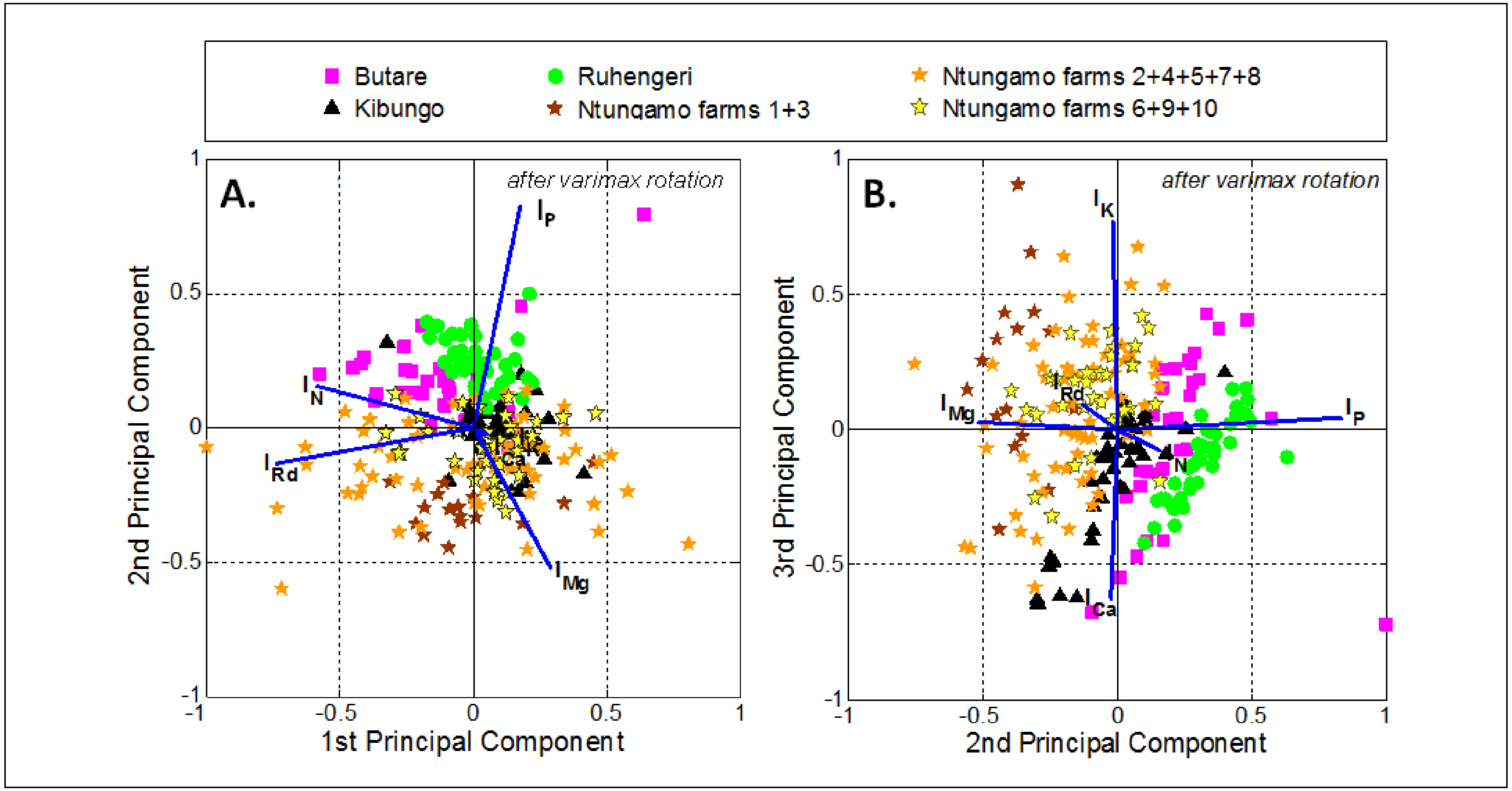

Figure 4.3. **Biplots representing the principal component scores (individual squares, triangles, circles and pentagrams) and the considered variables (I_N, I_P, I_K, I_{Ca}, I_{Mg}, I_{Rd}- vectors) in the planes described by (A) the 1st and 2nd or (B) the 2nd and 3rd Principal Components.**

4.3.5. Intra-farm variability

The arbitrary choice of "high producing plots usually close to the homestead (plots A)" and "plots with low potential further away (plots B)" during the Rwandan campaign, induces a certain bias in the description of potential intra-farm gradients in production or plant nutrition. The consideration of a higher number of plants per farm and the actual measurement of distances between the selected plants and the homestead, make the Ntungamo-dataset a more appropriate basis for these kind of comparison. Production and nutrition vary within a same farm; certain tendencies emerge despite the absence of significant differences. Three farms (farms 7, 8 and 9) are selected as representatives of the various situations encountered in the field. The related data are graphically represented in Figure 4.4. Figure 4.4.A (farm 7) shows the homogeneity of production and plant nutrition on the entire farm. The data from farm 9 (Figure 4.4.C) exemplify the existence of "normal gradients" where the plants close to the homestead have CND-indices (for nutrients and Rd) closer to zero and produce heavier bunches than plants further away. Figure 4.4.B (farm 8) illustrates the opposite case where production increases and absolute values of CND-indices decrease with distance from homestead ("inverse gradient").

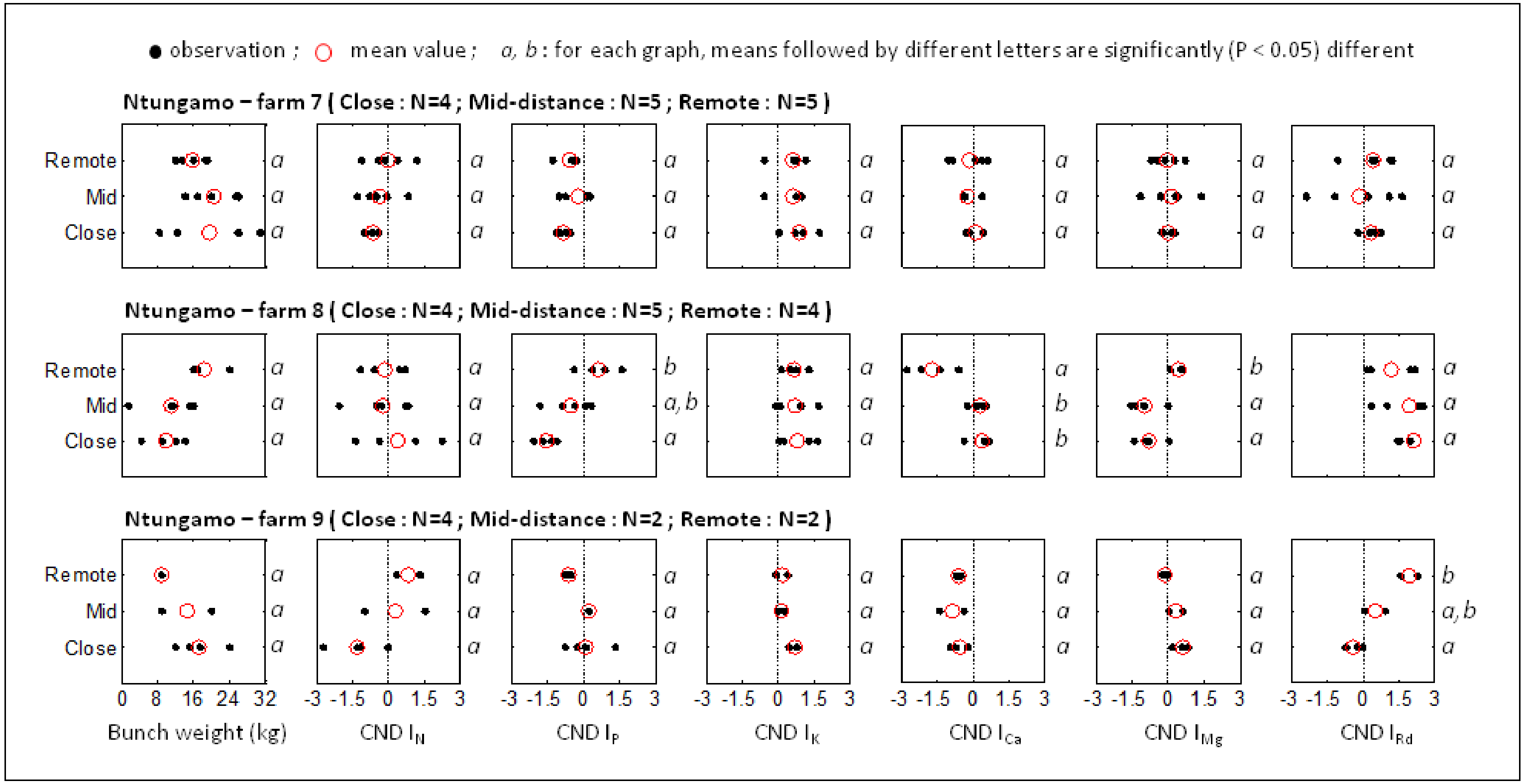

Figure 4.4. Intra-farm variability of bunch weight (kg) and CND indices (I_N, I_P, I_K, I_{Ca}, I_{Mg}, I_{Rd}) in function of distance to homestead (Close, Mid-distance and Remote). The farms 7, 8 and 9 studied in the Ntungamo-region are represented as examples for the different situations encountered in the field.

4.4. Discussion

4.4.1. Four agro-ecoregions with contrasting soils

The data reported here confirm the general perception that the banana-system in Butare consists of relatively poor banana groves (Table 4.3) installed on poor soils (Table 4.2). The soils are highly weathered (Lassoudière, 1989; Ndindabahizi and Gwabije, 1991), developed on Precambrian muscovite-bearing granites (Table 4.1, Tahon et al., 1991).

Kibungo is the main banana producing region in Rwanda. The region insures the supply of the urban market of Kigali (Okech et al., 2005). Farmers are reputed for the good management given to their fields. Bananas are cultivated on deep, finely textured, well structured and well drained (Lassoudière, 1989) soils developed from pelitic rocks (Gérards et al., 1967). The relatively low total reserve in bases (63.83 $cmol_c.kg^{-1}$ on average; Herbillon, 1986) and total P content (mean 0.26 $\%P_2O_5$) compared to the young Andosols of Ruhengeri (resp. 382.5 $cmol_c.kg^{-1}$ and 0.82 $\%P_2O_5$) and the high contribution of exchangeable cations to the total reserve in bases (46.3% on average), recall the highly weathered nature of the soils in Kibungo. Despite their advanced weathering, soils are inherently more fertile than in Butare. This good fertility can be related to the judicious recycling of organic matter (Lassoudière, 1989) which is reflected in the high total carbon (Table 4.2) and nitrogen (not shown) contents of these soils. Another factor explaining the high carbon contents is the soil's mineralogy and the possible stabilization of organic matter on iron oxides (*review in* Zech et al 1997; Kaiser and Guggenberger, 2000, 2003, 2007) or its protection inside organo-clay aggregates (Mayer and Xing, 2001; Mayer et al., 2004). This high organic matter content contributes positively to the cation exchange capacity ($CEC=(5.88*\%C_{tot})+1.67$, $R^2=0.88$) and sum of exchangeable K, Ca and Mg ($(K+Ca+Mg)_{exch}=(5.46*\%C_{tot})+1.10$, $R^2=0.74$).

High carbon contents also positively impacts soil pH and reduces Al toxicity (*review in* Haynes and Mokolobate, 2001).

Field observation confirm the soil heterogeneity in Ntungamo: soils on quartzites (farms 6+9+10) or micaschists (farms 2+4+5+7+8, farms 1+3), possible mixing of rock-residues, deep soils (farms 2+4+5+7+8) or, on the contrary, soils on steep slopes (farms 1+3) where the parent material appears at less than 1 m depth. This heterogeneity is reflected in the wide ranges of chemical characteristics of the soils analyzed in Ntungamo (Table 4.2). Relatively low total carbon contents, low exchangeable bases, possible acid pH, indicate globally poor soils in farms 2+4+5+7+8 and 6+9+10. Poor soils are also reported by Okech et al. (2000). In farms 1+3, the parent material is close to the surface; soils have significantly ($P < 0.05$) higher nutrient reserves than in farms 2+4+5+7+8 and 6+9+10 and seem globally more fertile from a chemical point of view.

As opposed to the highly weathered soils in Butare, Kibungo, Ntungamo2+4+5+7+8 or 6+9+10, soils in Ruhengeri are young soils with good nutrient reserves (Table 4.2). Total reserve in bases, cation exchange capacity, total phosphorous content, and ratio between the sum of exchangeable K, Ca, Mg and total reserve in bases all vary in wide ranges (Table 4.3). Since altitude, rainfall and temperature regimes (Nizeyimana, 1997) are homogeneous in the restricted area of this study, chemical differences in parent volcanics (Antun et al., 1971) and/or differences in their ages (Vander Zaag and Fox, 1983; Mizota and Chapelle, 1988) must be called upon to explain the variations in TRB.

4.4.2. Plant production and nutrient deficiencies

Bunch weights are the production units effectively measured and they witness the production potential of individual plants. As such, they are used throughout the rest of this study. Whatsoever, in order to allow comparison of production between regions, yields ($t.ha^{-1}$) are approximated here by multiplying bunch weights and banana-plant densities (Table 4.3). The average yields calculated are, in decreasing order 54.7, 46.9, 34.5, 32.4, 29.9 and 25.5 $t.ha^{-1}$ for Ruhengeri, Ntungamo farms 2+4+5+7+8, Butare, Ntungamo 6+9+10, Ntungamo 1+3 and Kibungo, respectively.

For all nutrients, the minimum and maximum values reported here and the observed ranges (Table 4.3) concord with the findings of other researchers working on the East African Highland banana in Tanzania, Rwanda or Uganda (Lassoudière, 1989; Wortmann et al., 1994a; Okech et al., 2000, 2004; Smithson et al., 2001, 2004; Nyombi et al., 2010; Wairegi, 2010; van Asten and Gaidashova, unpublished). The Compositional Nutrient Diagnosis (CND) norms calculated from the high bunch weight population of this dataset (Table 4.4) are close to the norms established by Wairegi (2010) for the highland banana in Uganda, both for the mean values as for their estimates of variability. The "in balance" ranges computed using the boundary line approach of Quesnel et al. (2006) to interpret the nutrient indices of individual plants, are asymmetrical around zero. Asymmetric intervals are also observed by Quesnel et al. (2006) for CND on spruce, or proposed by Kelling et al. (2000) for interpretation of "Diagnosis and Recommendation Nutrient Integrated System (DRIS)"-indices on banana.

Variations in nutrient contents and values of CND-indices are attributed to different factors. Some of them do not apply to this study, others do. Differences due to genetic dissimilarities or sampling procedures are not considered important since East African Highland bananas AAA-EA share a narrow genetic base (Pillay et al., 2001; Tugume et al., 2002) and sampling was done according to the international reference procedure (Martin-Prével, 1980). Variations in growth cycles could influence the foliar nutrient concentrations measured in the Rwandan sites, not in Ntungamo where only first ratoons were considered. Nutritional differences are also attributed to the diverse biophysical conditions prevailing at the various sites of interest: influence of seasons and rainfall (Martin-Prével, 1984; Smithson et al., 2004), temperature (Lahav, 1995), differences in soil type (Bidner-Barhava and Ravikovitch, 1958; van Asten and Gaidashova, unpublished) and nutrient supply.

According to the results of this study, K-deficiencies are an overall problem in Rwanda. Next to potassium, bananas in Ruhengeri also lack Mg and those in Butare Mg and Ca. The fact that, in Butare, Rd-indices are often superior to their "in balance" ranges, stress that the contents in one or more of the analyzed nutrients (N, P, K, Ca, Mg) are inferior to the average contents of the high bunch weight population. This is the case for K, Ca and Mg in a large majority of the studied plants. Rd-values inferior to the "in balance" ranges in Kibungo, recall the relative excess in Ca. Our results in terms of deficiencies in cations in Rwanda, correspond to the observations by other scientists using other diagnostic methods. Comparing their soil observations to sufficiency levels, Vander Zaag et al. (1984) and Yamoah et al. (1990) report that N, P, K deficiencies are widespread in Rwanda. According to Yamoah et al. (1990), soil Ca and Mg contents are "borderline" and the nutrients are expected to lack after a few years of cultivation. Vander Zaag et al. (1984) indicate Mg-deficiencies in Rwanda but do not situate them geographically. Schlichting (1983) predicts nutritional problems for Butare in the order K > Mg > Ca. Comparing their soil chemical data to sufficiency levels, Godefroy et al. (1991) report K, followed by P, as the most limiting nutrients in Kibungo. K-deficiencies in banana are reported by Lassoudière (1989) for that area. Vander Zaag and Fox (1983) consider soil P, K and Mg contents, respectively, as "adequate", "marginal" and "low" in the Andosols around Ruhengeri.

Phosphorous appears to be the most limiting nutrient in Ntungamo, followed by K in some plots, and by Ca in others. The low foliar phosphorous contents of the plants in farms 2+4+5+7+8 or 6+9+10 (Table 4.3) are attributed to the low phosphorous contents in the soils of those farms. The plants of farms 1 and 3 have equally low foliar P (Table 4.3), and this despite the high total phosphorus contents (Table 4.2) and significantly ($P<0.05$) higher Mehlich 3-P (data not shown) of their soils compared to those of the other farms studied in Ntungamo. Low foliar phosphorus is possibly due to a negative interaction with Mg (Table 4.3) as explained in the following section. According to Nyombi et al. (2010) nutrients limit banana production in the order K > P > N on a field at Ntungamo recently planted with banana after 10 years of fallow. Based on the "Diagnosis and Recommendation Integrated System (DRIS)", Smithson et al. (2001, 2004) conclude that K and Mg are the most limiting nutrients in South-West Uganda. In their trials, bananas respond positively to N, N+K (Smithson et al., 2001) and K fertilization (Smithson et al., 2004). In both studies, P was systematically applied (25 $kg.ha^{-1}$) all treatments. When Okech et al. (2000, 2004) compare their foliar data to the critical nutrient levels established by Wortmann et al. (1994a) for the highland banana in Tanzania, they repeatedly identify K as a major constraint to banana production in Southwestern Uganda. Smithson et al. (2001) draw the attention to the fact that the critical nutrient levels from other regions may not be suitable for Uganda. They consider the critical nutrient level for K as particularly low; K-deficiencies deduced from the use of this value may thus be exaggerated.

Present study is limited to the nutrients N, P, K, Ca and Mg, while micronutrients may be a problem too. Deficiencies in Zn are reported for banana in North-West Tanzania (Bekunda et al., 2003). A rapid screening of micronutrient nutritional status in banana, beans and sweet potato in the Kivu-provinces of the Democratic Republic of Congo, in Rwanda, Burundi and Uganda indicates possible deficiencies in Co and Mo (*comm. by* R. Graham, G. Lyons, University of Adelaide - School of Agriculture, food and wine). Se levels are low in the Great Lakes Region and its availability varies over short distances (*comm. by* R. Graham, G. Lyons, University of Adelaide - School of Agriculture, food and wine). Mn toxicities could be a problem on the acid soils.

4.4.3. Nutrient interactions

The present study highlights various nutrient interactions in the East African Highland banana, by (1) the opposition of deficiencies and excesses in the different areas of study and (2) Principal Component Analyses on CND-indices (a) for all the regions together, (b) for the regions separately or (c) for the high and (d) low producing plants in each area. The positive interactions between N and Rd, P and K, the negative interactions between P and Rd, P and Ca, P and Mg, K and Mg, K and Ca and the interaction between Ca and Mg are considered further. For some of the highlighted interactions, the physiological reasons are not understood or information concerning them is still scarce.

The filling value Rd includes all the nutrients not chemically analyzed; it is calculated as 100 minus the sum of nutrients actually measured. Our results suggest that Rd interacts positively with N and negatively with P. The positive relation between Rd and N is also observed by Garcia-Hernandez et al. (2005, 2009) on cowpea and pecan nut. According to Garcia-Hernandez et al. (2006) Rd and P are negatively associated in aloe vera. Relationships with Rd are interpreted as a signal of the importance of the equilibrium between the major elements and the minor ones, regrouped in Rd (Garcia-Hernandez et al., 2009). The best bets of elements with which N and P interact are S or possibly Mn, since they are the only elements present in sufficiently large amounts to contribute significantly to the value of Rd in bananas grown on soils with low Na and supposedly low Cl contents (Marchal and Mallessard, 1979; Turner and Barkus, 1983; Martin-Prével, 1984; Lahav, 1995; Borges et al., 2006). The synergism between N and S and the antagonism between P and S in bananas are mentioned but not explained in, respectively, Lahav (1995) and Lacoeuilhe et al. (1971b). A negative relationship between P and Mn is observed by Raghupathi et al. (2002) on banana. Next to the interactions between N or P and the nutrients comprised in Rd (S or Mn), the relationships with Rd could also be interpreted as the antagonistic interaction of N and the synergistic relation of P with one or more of the other foliar constituents actually analyzed (P, K, Ca, Mg). High values of Rd implicate, indeed, low values of one or more of them. The synergism of P and K found here, are also reported by Garcia-Hernandez et al. (2006, aloe vera), Magallanes-Quinatar et al. (2006, maize) and Wairegi (2010, East African Highland banana).

The negative relationships between P and Ca and P and Mg concord, on one hand, with the observations in studies on bananas (Lahav, 1995; Raghupathi et al., 2002; Wairegi, 2010) or other crops (Parent et al., 1994; Raghupathi et al., 2004; Garcia-Harnandez et al., 2004, 2005, 2006; Magallanes-Quintanar et al., 2006). Martin-Prével and Montagut (1966, banana) and Fageria (2001, annual crops), on the other hand, expect positive interactions between P and Mg since Mg is a necessary co-factor in most reactions involving phosphate transfer. Authors finding a negative relationship between P and Ca, P and Mg (Parent et al., 1994; Raghupathi et al., 2002; Garcia-Hernandez et al., 2004, 2005, 2006) explain these interactions by the fact that the concentrations of Ca and Mg vary in the opposite direction to P when the plants mature (Walworth and Sumner, 1987). The precipitation of insoluble Ca-phosphates reduces phosphorus availability to plants on calcareous soils (Tunesi et al., 1999; Garcia-Hernandez et al., 2004, 2005, 2006) or, more generally, when pH is superior to 7.2 (Foth, 1990). The negative relationship between K and Ca is repeatedly observed for banana (Martin-Prével and Montagut, 1966; Raghupathi et al., 2002; Wairegi, 2010), and for other crops (Robson and Pitman, 1983; Walworth and Sumner, 1987; Garcia-Hernandez et al., 2005; Magallanes-Quintanar et al., 2006). Martin-Prével and Montagut (1966), Lacoeuilhe et al. (1971a), Martin-Prével (1980), Lahav (1995), Raghupathi et al. (2002), Wairegi (2010), Lassoudière (2007) all report negative relationships between K and Mg for banana. Robson and Pitman (1983) explain the negative interactions of K and Ca, K and Mg by a competition at absorption. Walworth and Sumner (1987) and Raghupathi et al. (2002) rely on the difference in mobility of K and Ca in banana to explain the interaction. Others interpret their observations in terms of antagonisms between K and Ca (Martin-Prével and Montagut, 1966; Magallanes-Quintanar et al., 2006) or K and Mg (Martin-Prével and Montagut, 1966; Lacoeuilhe et al., 1971a; Martin-Prével, 1980; Lahav, 1995; Lassoudière, 2007).

The interaction between Ca and Mg, as deduced from the Principal Component Analysis, is sometimes positive, sometimes negative. Contradictory observations are also published. Garcia-Hernandez et al. (2004, 2005, 2006) report positive relationships between Ca and Mg but relate this to the calcareous nature of the soil they are working on. Positive interactions are also found by Raghupathi et al. (2002) and Wairegi (2010) for banana. Martin-Prével and Montagut (1966), Lacoeuilhe and Martin-Prével (1971a+b) and Lassoudière (2007) report negative relationships between Ca and Mg for banana. Parent et al. (1994) and Fageria (2001) make the same observations on potato or annual crops. In their experiences with *Spiradela polyrhiza*, Appenroth et al. (1999) and Appenroth and Gabrys (2003) actually evidence a competitive antagonism between Ca and Mg. It seems that antagonisms between Ca, K and Mg express themselves more or less in function of calcium (Fageria, 2001; Lassoudière, 2007) or magnesium (Martin-Prével and Montagut, 1966) concentrations and related deficiencies.

The P/K and Ca/Mg relationships discriminate best the high and the low bunch weight populations, indicating that cation imbalances may be the most important nutritional problem encountered by the East African Highland banana in Rwanda and South-West Uganda.

4.4.4. Variability of production potential and nutrition issues on three different scales

The differences between regions in nutritional problems considered as most important, recall the influence of the agro-ecological conditions on plant nutrition (Figures 4.2 and 4.3). The wide ranges of values for the CND-indices (Figures 4.2 and 4.3) and the variable combinations of deficiencies and excesses within a same region, evidence the heterogeneity of the nutritional status of plants on an even smaller scale. The consideration of the CND-indices and plant performance indicators against distance to homestead (Figure 4.4), illustrates that nutritional differences also occur within a same exploitation. In the Ntungamo region, three situations appear. All three of them are exemplified in Figure 4.4. In some farms there is a normal (Figure 4.4.C) or an inverse (Figure 4.4.B) gradient of production and nutrition quality; in others things seem more homogeneous (Figure 4.4.A). Intra-farm differences in crop production have been related to variations in husbandry or soil fertility within the farm (Bekunda and Woomer, 1996; Wortmann and Kaizzi, 1998; Briggs and Twomlow, 2002; *references in* Esilaba et al., 2005; Vanlauwe et al., 2006; Wopereis et al., 2006; Tittonnell et al., 2005b, 2007; Okumu et al., 2011). In order to provide the most adequate solution to target production issues, a more detailed study of soil fertility at different scales and its relation with plant nutrition is thus definitely needed.

4.5. Conclusions

CND analyses and PCAs on the entire dataset, on subsets per region, or high and low bunch weight subpopulations, demonstrate the large variability in nutritional status of bananas that exist at inter-regional, intra-regional and even intra-farm scale. Bananas require large amounts of K, making it the most deficient nutrient in the region, followed by Mg and P. Recommendations should take into account the geographic spread of these deficiencies, as related to the underlying geology. Fertilizer use efficiency may also be influenced by nutrient interactions. Various nutrient interactions within the plant appeared recurrently throughout the study: N-Rd, P-K, P-Rd, P-Ca, P-Mg, K-Mg, K-Ca, Ca-Mg. The recognition of variability of production and nutritional issues, should be relied upon when compiling fertilizer recommendations. Recommendations targeting actual problems and avoiding the unnecessary, would indeed be a more sustainable and economically viable response offered to small-holder farmers than the current blanket recommendations.

PART 2

Soil Analysis

Chapter 5. Using phosphorus as a tracer of management practices in contrasting soils of the East African Highlands

Abstract

Phosphorus (P) is a rather immobile element in soils because of its easy fixation by geochemical processes. Because of its immobile nature and of its close relation to human activities, archaeologists have been using P for years when studying century-old settlements. They recognize the sites of food preparation, organic refuse areas, kitchen gardens and amended cropland by their P contents. In the present study, phosphorus is used as a tracer of cultural practices in banana-based traditional farms in Rwanda (Butare, Kibungo, Ruhengeri) and South-Western Uganda (Ntungamo). The aim is to confirm the differential management so often invoked to explain fertility gradients in smallholder farms of the East African Highlands and hence confirm farmers in their role of fertility manipulators. To do so, phosphorus is subdivided in fractions of differing availabilities (labile, moderately labile and non-labile P) by a sequential chemical fractionation procedure. Comparison between total P contents and P fractions between surface and deep soil samples, indicate that amendments in organic matter increase significantly ($P<0.05$) total phosphorus contents and induce shifts in P fractions towards the more labile forms. In the regions of Butare and Ntungamo, significant ($P<0.05$) within-farm differences in total P contents and contributions of labile P to total phosphorus are observed. Since soil, climate and nature of the amended organic matter are the same within one farm, differences in P contents and fractions are due to differences in the quantities of organic matter distributed on the various parts of the farm over time. Variations in P are closely related to variations of other indicators of soil fertility (pH_{H2O}, total carbon content, total reserve in bases, exchangeable base cations, cation exchange capacity). The fertility gradient thus parallels the management gradient and differential management by farmers can be confirmed as the cause of the fertility gradient. The absence of differences in total phosphorus contents and P fractions in Kibungo and Ruhengeri, suggest uniform organic matter distribution by farmers of those areas. In Ruhengeri, uniformity of present and/or past organic matter distribution is confirmed by the absence of within-farm significant ($P<0.05$) differences in values for total carbon contents, total reserve in bases, exchangeable base cations and cation exchange capacity. Smallholder farmers thus manipulate the fertility of their soils through the recycling of organic matter, hence creating soil fertility gradients or, on the contrary, insuring constant soil fertility over their farms. This study thus confirms P as a useful tool to capture the human imprint on soil fertility by past or present activities in systems where quantitative data on organic matter distribution are scarce.

Keywords
Phosphorus; tracer; fractionation; soil fertility; differential management; Rwanda; Uganda

5.1. Introduction

Smallholders in the East African Highlands often depend on banana production around their homestead for their food and income. Actual yields are low, which is largely attributed to medium to poor soil fertility and the little use of fertilizer inputs. In fact, farmers try to maintain the productivity of their system by managing locally available organic nutrient sources. African farmers are reputed manipulators of soil fertility, creating rich patches of land at the expense of others (Smaling et al., 2002). In

Western Africa, variable cropping patterns and differential allocation of labor and time, generate what is known as the ring management system (Prudencio, 1993). In East Africa, high population densities and land fragmentation explain the disappearance of this neat ring pattern for a patchwork of pieces of land with diverse fertility status (Defoer et al., 2000, *cited in* Wopereis et al., 2006). Small farm sizes limit variations of fertility because of biophysical factors such as topography, soil type, soil degradation or physical discontinuities (Tittonell et al., 2005a). As a consequence, observed soil fertility gradients within small farms (< 1 ha) are repeatedly attributed to differential management and allocation of resources by farmers (*e.g.* Bekunda and Woomer, 1996; Baijukya and De Steenhuysen Piters, 1998; Wortmann and Kaizzi, 1998; Briggs and Twomlow, 2002; Mtambanengwe and Mapfumo, 2005; Haileslassie et al., 2007; Tittonell et al., 2007; Zingore et al., 2007; Okumu et al., 2011).

Archeologists rely on phosphorus (P) to trace human activities, such as organic refuse disposal, food preparation, field amendments or burials (*e.g.* Eidt, 1973, 1977; Cavanagh et al., 1988; Lippi, 1988; Lillios, 1992; Parnell et al., 2002; Lehmann et al., 2004; Holliday and Gartner, 2007; Hutson et al., 2009). Indeed, phosphorus is a rather immobile element in soils because of easy fixation by geochemical processes (Smeck, 1973; Walker and Syers, 1976; Parfitt, 1978, 1989; Hedley et al., 1982; Tiessen et al., 1983, 1984; Cross and Schlesinger, 1995, 2001). Total phosphorus contents (Cavanagh et al., 1988; German, 2004; Holliday and Gartner, 2007) or fractions of phosphorus with varying availabilities (Eidt, 1977; Lillios 1992; Lehmann et al., 2004; Holliday and Gartner, 2007; Hutson et al., 2009) are considered when tracing human activities. The fractionation procedures commonly used are those of Syers et al. (1972), Hedley et al. (1982) or Tiessen and Moir (1993). They aim to extract easily soluble P, Fe- and Al- bound P, Ca-bound P, occluded or residual P fractions with reagents of increasing strengths. The same procedures are also called upon in agricultural research when evaluating phosphorus availability to plants or assessing the influence of land-use and management on phosphorous quantities and forms (Sharpley and Smith, 1985; Paniagua et al., 1995; Iyamuremye et al., 1996; Selles et al., 1997; Guo et al., 2000; Solomon and Lehmann, 2000; Negassa and Leinweber, 2009).

The present study aims to evaluate the human imprint on soil fertility in smallholder banana-based farms of Rwanda and south-Western Uganda. Possible within-farm soil fertility gradients are highlighted by the comparisons of classical indicators of soil fertility (pH, total carbon and phosphorus contents, total reserve in bases, exchangeable cations, cation exchange capacity). Using phosphorus and its fractions as tracers of human activities, soil fertility gradients are considered along with intra-farm management differences.

5.2. Material and Methods

5.2.1. Study sites

The areas of interest to the present study are situated between the latitudes S 00°46’ – S 2°17’ and the longitudes E 29°38 – E 30°37’. More specifically, they are located near the towns of Butare, Kibungo and Ruhengeri in Rwanda, and Ntungamo in the south-western part of Uganda (Figure 5.1). The study areas represent different agro-ecoregions, varying in altitude, climate and/or soil type (Table 5.1).

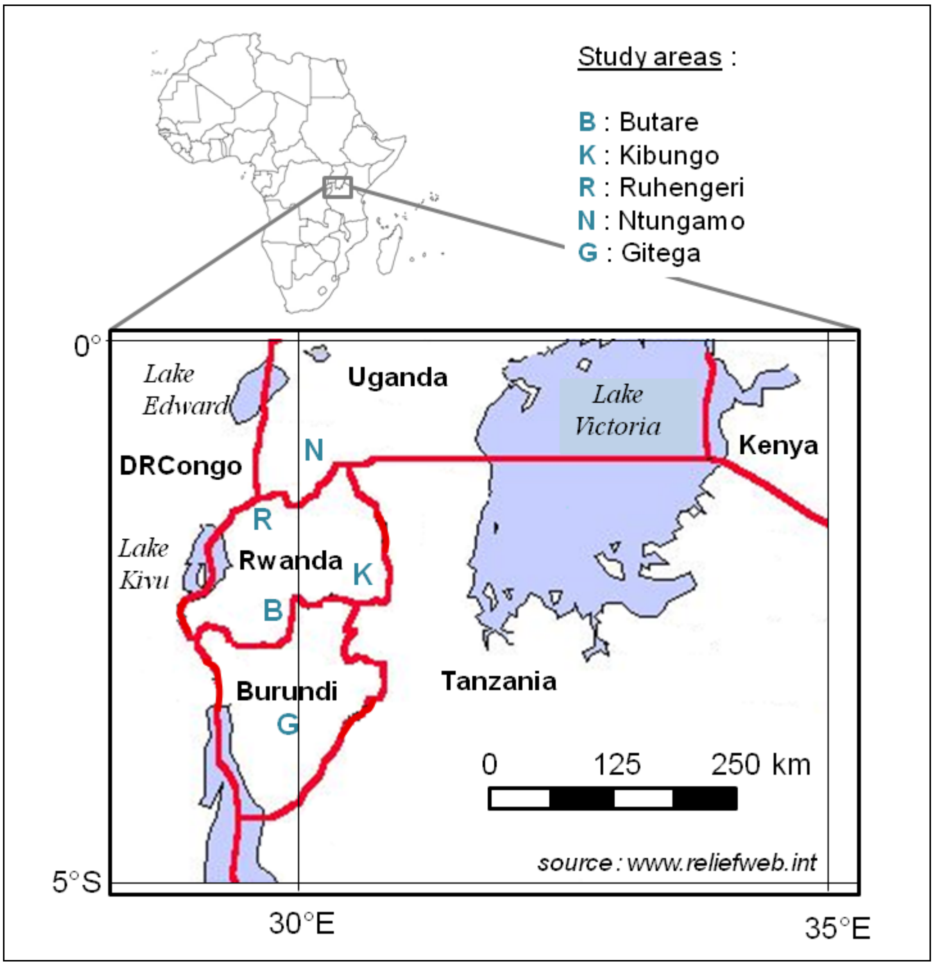

Figure 5.1. Map of the African Great Lakes Region, situating the four study areas.

Near Butare (South Rwanda, 1675-1763 meters abose sea-level (m*asl*)), mean annual temperatures and mean annual rainfall are 18-21°C and 1150-1260 mm.year^{-1}. The soils are Acrisols developed on granite. Kibungo is located in the eastern part of Rwanda. It is the lowest area (1498-1623 m*asl*), with the highest temperatures (19-24°C) and the lowest annual rainfalll (900-980 mm.year^{-1}). Nitisols develop on precambrian pelitic rocks. Sites near Ntungamo (SW Uganda, 1535-1611 m*asl*) have Acrisols on micaschist or quartzite. Mean annual temperatures are 16-20°C; annual rainfall varies widely (820-1300 mm.year^{-1}) but is usually about 1100 mm.year^{-1}. While soils in Butare, Kibungo or Ntungamo are old, Andosols in Ruhengeri form on cenozoic mafic volcanic ashes. Ruhengeri is located in the volcanic mountain range in western Rwanda; the studied sites are at 1659-1692 m*asl*. Mean annual temperatures are about 19-20°C; mean annual rainfall is 1300-1350 mm.year^{-1}. In the four areas, rainfall has a bimodal distribution with rainy seasons occurring between March to May and August/September to November/December. The foregoing descriptions are summarized in Table 5.1.

In all the regions, land is fragmented between the numerous smallholder farmers who grow their crops in intensively exploited banana-based systems. Farmers rely almost exclusively on traditional techniques (rudimentary tools, no machinery, no animal draft power, no or rare inorganic fertilizer) to manage their fields (Oduol and Aluma, 1990 ; Roose and Ndayizigiye, 1994 ; Wortmann and Kaizzi, 1998 ; Aniku et al., 2001 ; Clay et al., 2001 ; National Institute of Statistics of Rwanda, 2010).

Table 5.1 (continued on next page). Overview of the 4 field campaigns over the 4 regions of interest to this study.

<table>
<tr><td></td><td>Lateral distribution of data</td><td>Vertical distribution of data</td></tr>
<tr><td>REGION
Description of physical environment (altitude, mean annual rainfall and temperature, soil type and parent material) (*)</td><td>CAMPAIGN 1</td><td>CAMPAIGN 2 revisit</td></tr>
<tr><td>BUTARE, South Rwanda
1675-1763 masl
1150-1260 mm.year^{-1}
18-21°C
Acrisol, on granite</td><td>March-April 2006
20 farms per region
2 plots per farm (A/B-potential)

<u>Data specific to this campaign:</u>
Mulch thickness</td><td>January 2007
2 farms in Butare; 3 in Kibungo
1-2 soil profiles per farm

<u>Data specific to this campaign:</u>
Fine earth particle size distribution
$Fe_{oxalate}$, Fe_{DCB}</td></tr>
<tr><td>KIBUNGO, East Rwanda
1498-1623 masl
900-980 mm.year^{-1}
19-24°C
Nitisol, on pelitic rocks</td><td colspan="2"><u>Data available for both campaigns:</u>
pH_{H2O}; C_{tot}; exchangeable Na, K, Ca, Mg; CEC (pH7); total chemical analysis; %kaolinite (normative calculation); P fractions</td></tr>
<tr><td>RUHENGERI, North-West Rwanda
1659-1692 masl
1300-1350 mm.year^{-1}
16-20°C
Andosol, on mafic volcanic rock</td><td></td><td>not revisited</td></tr>
</table>

Table 5.1 (continued). Overview of the 4 field campaigns over the 4 regions of interest to this study.

	Lateral distribution of data	Vertical distribution of data
REGION Description of physical environment (altitude, mean annual rainfall and temperature, soil type and parent material) (*)	**CAMPAIGN 3**	**CAMPAIGN 4 revisit**
NTUNGAMO, South-West Uganda 1535-1611 m*asl* 1100-1200 mm.year^{-1} 16-20°C Acrisol, on quartzite or micaschist	March 2005-April 2007 10 farms 15 plants/spots per farm <u>Data specific to this campaign:</u> Bunch weight Mulch thickness Exchangeable K,Ca,Mg (Mehlich3)	September 2009 5 farms 1-3 soil profiles per farm <u>Data specific to this campaign:</u> Fine earth particle size distribution $Fe_{oxalate}$, Fe_{DCB} Exchangeable Na,K,Ca,Mg ($acNH_4$) P fractions
	<u>Data available for both campaigns:</u> pH_{H2O}; C_{tot}; total chemical analysis; %kaolinite (normative calculation)	

(*) Description found in lietrature: Neel, 1983; Roark and Dickson, 1986 *cited in* Byers, 1990; Delepierre, 1974 *cited in* Ndindahizi and Gwabije, 1991; Verdoodt and Van Ranst, 2003; Smithson et al., 2004; FAO, 2005a; FAO, 2005b; Bouwmeester et al., 2009; Nyombi et al., 2009; Gaidashova et al., 2009; van Asten et al., 2011; ISAR official website (http://www.isar.rw, accessed on October 12th 2010).

5.2.2. Data collection

A. Soils from Butare, Kibungo and Ruhengeri (Rwanda): sampling and classical laboratory analyses

This study relied on data gathered during a diagnostic survey in Butare, Kibungo and Ruhengeri (campaign 1, Table 5.1). The survey was detailed in Gaidashova et al. (2009). Briefly, between March and April 2006, 20 smallholder farms were visited in each region. Two plots showing extremes in banana plant vigor were chosen per farm, one with high-potential vigorous plants (plots A), one where the plants looked stunted (plots B). Mulch thickness was measured at five random points around the selected plants and averaged. A soil sample was taken at the base of each selected plant. The composite soil sample was obtained by mixing thoroughly the soil withdrawn between 0 and 25 cm depth from three places at horizontal distances of 50-70 cm from the plant.

Subsequent to the first field campaign, 2 farms in Butare and 3 in Kibungo were revisited (January 2007, campaign 2, Table 5.1). The soils of the revisited farms were considered representative of the soils of their respective regions. In all the farms, 1 or 2 pits (± 1.5 x 1.5 x 1.5 m^3) were excavated in the banana grove. The soil profiles at the foot of the banana-plants were described according to the FAO (2006) guidelines. Bulk soil samples were collected for each horizon of each profile. Augering from the floor of the pits allowed sampling of even deeper soil parts (max depth 300 cm).

Bulk soil samples from both campaigns were air-dried, softly ground and sieved to pass a 2 mm mesh. Soil chemical analyses were performed at UCL (Michamps or Louvain-la-Neuve, Belgium) (1) on all the samples of the diagnostic survey and (2) on a selection of the samples collected during the second campaign. pH was measured in a 1 : 5 soil : water-suspension

(5g : 25 ml) after 1 hour of contact. Total carbon contents were determined by dry combustion on finely ground powder. Exchangeable Na, K, Ca, Mg were extracted using a 1M ammonium acetate solution at pH7. The cation contents in the extract were determined by atomic absorption spectrophotometry (AAS). The amount of ammonium retained by the soil, after washing it free of the excess of ammonium acetate by denatured ethanol, was considered an estimate of the cation exchange capacity of the soil. The retained ammonium was released by leaching the soil with a 1M potassium chloride solution at pH3. Ammonium contents in the leachate were determined by distillation. Iron oxide contents in the fine earth soil samples were evaluated by dark oxalate and Dithionite-Citrate-Bicarbonate (DCB) extractions according to, respectively, the Blakemore et al. (1981) and Mehra and Jackson (1960) procedures. Fe (Fe_o, Fe_{DCB}) and Al contents (Al_o, Al_{DCB}) in the extracts were determined by inductively coupled plasma – atomic emission spectrometry (ICP-AES). The P sorption capacity was estimated by $\alpha*(Fe_o+Al_o)$ (van der Zee et al., 1987; van der Zee and van Riemsdijk, 1988) with the frequently used α value of 0.5, adopted without experimental justification. Total chemical analyses were performed by digesting finely ground powder (mineralized at 950°C for 72 h) in a mixture of lithium tetra- and metaborate at 950°C (Chao and Sanzolone, 1992). The cooled digestion beads were dissolved in hot (100°C) 2M nitric acid. Elemental (Al, Fe, Si, Ti, Ca, K, Mg, Mn and P) contents in 100 ml 2M HNO_3 were determined by ICP-AES. Elemental contents were expressed as percentages of common oxides. Total reserve in bases (TRB) was calculated as the sum of total contents of alkaline-earth and alkaline cations (Herbillon, 1986). All chemical data were expressed against dry soil weights (105°C). Qualitative analysis of the mineralogical compositions of soil samples was performed by X-Ray Diffractometry. The weight percentage of kaolinite in the samples was estimated through a normative calculation of the CIPW (Cross et al., 1902) type. Considering the total chemical analysis of the samples and the qualitative knowledge of the minerals composing them, a formalized sequence of calculations allocated the major elemental oxides to, successively, anatase/rutile, vermiculite, albite, muscovite/sericite, microcline/orthoclase, hematite, kaolinite, gibbsite and quartz. Two keys of the calculations need to be highlighted. First, the calculation relied on the Mineralogical Index of Alteration of Voicu et al. (1997) to allocate potassium to muscovite/sericite and/or K-feldspars. Second, Al-oxides could not be quantified when both kaolinite/nacrite and gibbsite/bayerite were simultaneously present in the sample. In order not to overestimate the abundances of minerals containing Na, K, Ca and Mg, it was required to subtract exchangeable Na, K, Ca and Mg contents from, respectively, the total Na, K, Ca and Mg contents determined for fine earth samples (< 2 mm).

On the selected samples from the second campaign in Butare and Kibungo, particle size distribution was determined. Sand (63-2000 µm), silt (2-63 µm) and clay (0-2 µm) fractions were obtained through ultrasonic dispersion, sieving and prolonged dispersion with Na^{+}-resins (Rouiller et al., 1972), without preliminary destruction of organic matter. Particle size distribution was expressed as percentages (%, $g.100g^{-1}$).

B. Soils from Ntungamo: sampling and classical laboratory analyses

Newton (2009) detailed the monitoring campaign held in the Ntungamo area between March 2005 and April 2007 (campaign 3, Table 5.1). Briefly, ten smallholder farms in a same valley were selected on basis of (1) the relative wealth status of the household and (2) the position of the farm on the topographic slope. To represent an intra-farm range of plant performance and management, 15 banana-plants (Musa spp. AAA-EA, cv. *Enyeru*) were selected along the topographic slope, at varying distances from the homestead. For each selected mat, the plant growth for one follower ratoon was monitored monthly from sucker emergence to harvest. Plants were harvested when farmers considered bunches mature. Bunch weights were measured using a balance (±0.5 kg). The bunch weights were used in our study to evaluate if subplots were of high (plot A) or low (plot B) potential. Indeed, unlike the Rwandan campaign, the distinction was not made directly in the field by visual observation, but was based on comparison of the weights of the harvested bunches. Plants providing bunches which weights were superior to the median bunch weight of one farm, were considered high vigor plants (on "subplot A") for that farm. Other plants of the same farm were assumed to be low vigor plants (on "subplot B"). Mulch thickness was measured at five random points around the studied plant and averaged.

In Ntungamo, a composite soil sample was taken at the foot of each selected plant. Three to five cores taken around the banana-plant and covering the 0-30 cm depth were thoroughly mixed. The soil samples were air-dried, softly ground and sieved to pass a 2 mm mesh. Chemical analyses were performed at the Kawanda Research Station (Kawanda, Uganda). pH was measured in a 1 : 2 soil : water-suspension (Okalebo et al., 2002). Exchangeable K, Ca and Mg were evaluated by the Mehlich 3-procedure detailed in Okalebo et al. (2002). Additional chemical data were obtained at UCL (Louvain-la-Neuve, Belgium): total carbon contents, total elemental compositions were determined as for the Rwandan samples in section 5.2.2.A ("Soils from Butare, Kibungo and Ruhengeri (Rwanda): sampling and classical laboratory analyses"). Weight percentages of kaolinite in the Ntungamo samples were computed using the normative calculation already mentioned in section 5.2.2.A.

Subsequent to the monitoring campaign, 5 farms were revisited in September 2009 (campaign 4, Table 5.1). In all the farms, 1 to 3 pits (± 1.5 x 1.5 x 1.5 m^3) were excavated in the banana grove. The soil profiles at the foot of the banana-plants were described according to the FAO (2006) guidelines. Bulk soil samples were collected for each horizon of each profile. Augering from the floor of the pits allowed sampling of even deeper soil parts (max depth 265 cm). Bulk soil samples were air-dried, softly ground and sieved to pass a 2 mm mesh. Soil chemical analyses were performed at UCL (Louvain-la-Neuve, Belgium). pH in water, total carbon contents, exchangeable Na, K, Ca, Mg, cation exchange capacity, oxalate and DCB Fe and Al, total chemical analyses and particle size distributions were all determined as for the Rwandan samples in section 5.2.2.A.

C. Phosphorous sequential fractionation

A few samples from both field trips in Rwanda (campaigns 1 and 2, Table 5.1) and from the revisit of farms in Ntungamo (campaign 4, Table 5.1), were selected for the sequential fractionation of phosphorus.

Laboratory protocol (Figure 5.2, Appendix 1)

The procedure used to fractionate soil phosphorus was a modified version of the laboratory protocol by Tiessen and Moir (1993). The applied laboratory protocol is schematically represented in Figure 5.2 and detailed in Appendix 1. The procedure aimed to extract P fractions of varying availabilities by allowing contact (20 h) between a soil subsample (0.5 g unground fine earth (< 2 mm)) and reagents of increasing strengths (H_2O + strongly basic anion-exchange resin, $NaHCO_3$ 0.5M pH8.5, NaOH 0.1M, HCl 1M, concentrated hot HCl). In the final step of the procedure the sample residue was digested by a mix of three concentrated hot acids (HNO_3/HF/$HClO_4$). Digest was solubilized in a mix a concentrated hot HCl and HNO_3 (Voïnovitch, 1988; Sahwney and Stilwell, 1994). P contents were determined in all the extracts by ICP-AES. P contents in each extractant solution were corrected for the pollution induced by the preceding extractant. Indeed, when a fresh solution was added, a minor fraction of the previous reagent still remained in contact with the soil. The volume of the solution remaining in the tube was evaluated by weight. Knowing the volume of solution remaining and the P concentrations therein, correction for the P concentrations in the following solution was possible. The resin used in the first step was the BDH no.55164 resin-membrane (in HCO_{3-} form, 2 strips of 9 x 62 mm) recommended by Myers et al. (2005).

Organic P was determined indirectly in the $NaHCO_3$ 0.5M and NaOH 0.1M extracts. Organic P was precipitated by acidification (H_2SO_4 0.9M, pH1.5) of the extracts. Inorganic P was determined in the supernatant solution by ICP-AES. Organic P was determined as the subtraction of the inorganic P content from the total P content.

The non-subdivided fractions extracted by resin, $NaHCO_3$, NaOH, HCl 1M or concentrated hot HCl are here-after indicated by resin-P_i, $NaHCO_3$-P_{tot}, NaOH-P_{tot}, HCl1M-P and $HCl_{conc.}$-P. $NaHCO_3$-P_o, $NaHCO_3$-P_i, NaOH-P_o and NaOH-P_i represent the organic (P_o) or inorganic (P_i) fractions recognized in the $NaHCO_3$ or NaOH extracts. Phosphorus forms remaining in the residue after the extraction by afore-mentioned reagents are referred to by "residual-P".

Modifications of the original method, practical considerations

The procedure used in this study differed from the original protocol by Tiessen and Moir (1993, Figure 5.2) by (1) the use of unground soil subsamples, (2) the replacement of the final digestion step (H_2O_2/H_2SO_4) digestion step by tri-acid attack ($HF/HNO_3/HClO_4$), (3) a duration of 20 h (instead of 16 h) for each extraction step. The choice of unground samples over ground samples was made following the indications of Lajtha and Schlesinger (1988) and Potter et al. (1991) who warned that grounding overestimated the phosphorus fractions extracted in the first steps of the procedure. The final digestion step was adapted to conform to the material available in the laboratory (UCL, Louvain-la-Neuve, Belgium).

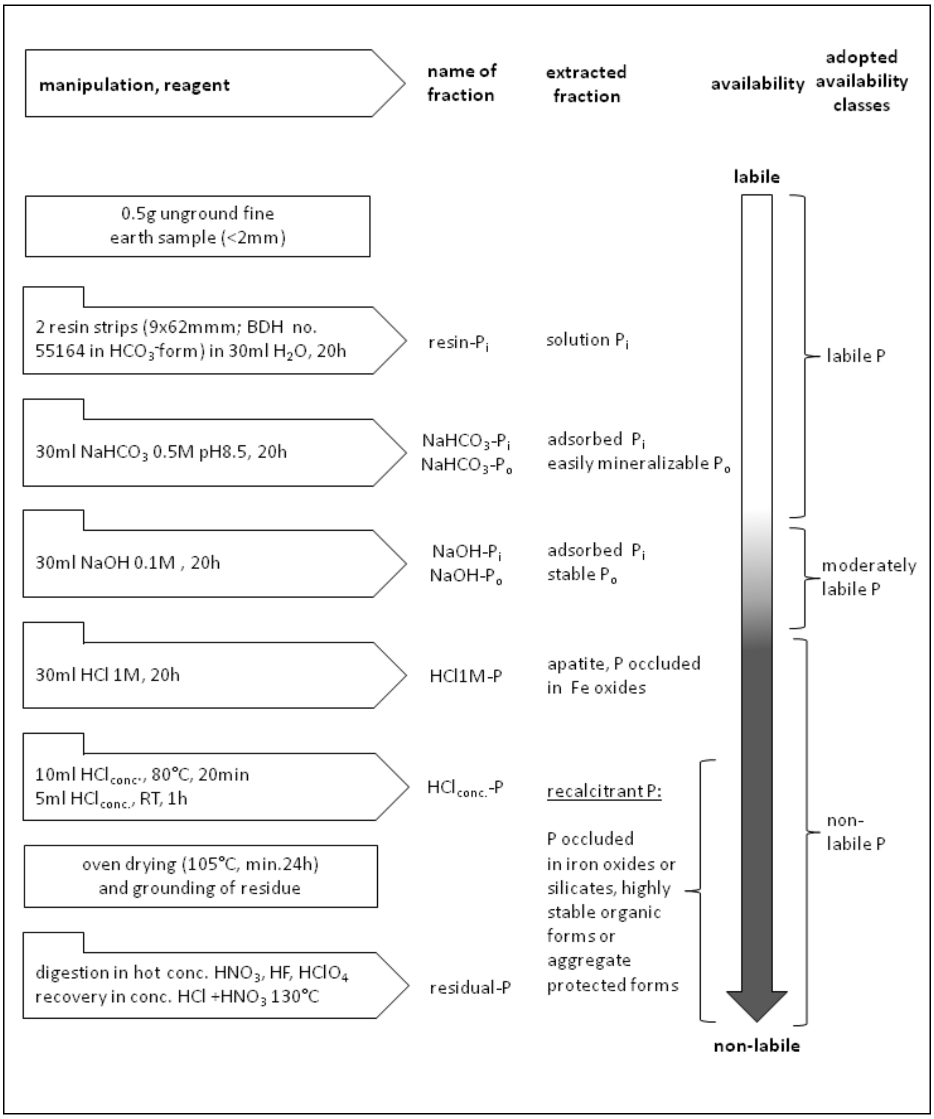

Figure 5.2. Sequential P fractionation procedure adapted from Tiessen and Moir (1993) for the final step: H_2O_2/H_2SO_4 digestion was replaced by tri-acid $HF/HNO_3/HClO_4$ digestion.

The fractionation procedure proved expensive, time-consuming and laborious. For these three reasons, only a limited number of samples were actually sequentially extracted. Only seven of them were triplicated, and one duplicated.

Review of the natures and availabilities of the P fractions

The sequential fractionation distinguishes phosphorus fractions in function of their solubilities in reagents of increasing strength. Stepping aside from the "operationally defined" ("alkaline" or "acid extractable") fractions, attempts are made to relate the chemically extracted fractions to actual phosphorus forms. Hence, resin-P_i is interpreted as freely exchangeable P forms in equilibrium with P in soil solution (Smeck, 1985; *references in* Cross and Schlesinger, 1995; Sharpley, 1995). $NaHCO_3$-P_i or NaOH-P_i are supposed to represent a continuum of P pools adsorbed to aluminium and iron oxides (Tiessen and Moir, 1993; *references in* Cross and Schlesinger, 1995). $NaHCO_3$-P_o is constituted by labile, easily mineralized forms (Bowman and Cole, 1978; *references in* Cross and Schlesinger, 1995; Solomon and Lehmann, 2000; Negassa and Leinweber, 2009). NaOH-P_o is more resistant organic phosphorus, potentially adsorbed on Al and Fe soil particles (*references in* Cross and Schlesinger, 1995; Solomon and Lehmann, 2000; Solomon et al., 2002). HCl1M-P is attributed to "apatite-like" Ca-phosphates (Beauchemin et al., 2003) or P forms occluded by Fe oxides (Syers et al., 1967; Mengel and Kirkby, 2001). He et al. (2006 *cited in* Negassa and Leinweber, 2009) indicate high concentrations of organic P in the HCl1M-extract of temperate soil samples. $HCl_{conc.}$-P and residual-P were considered "chemically or physically protected" (Tiessen et al., 1984), occluded in Fe or Al oxides (Sanchez, 1976; Tiessen et al., 1983; Smeck, 1985; Mengel and Kirkby, 2001) or silicates (Smeck, 1985). Recalcitrant phosphorus could also emanate from highly stable organic forms (*references in* Hedley et al., 1982; Smeck, 1985; Iyamuremye et al., 1996) or aggregate protected organic materials (Smeck, 1985).

Attempts are made to interpret the various P fractions in terms of plant availability. While most authors recognize resin-P_i, $NaHCO_3$-P_i and $NaHCO_3$-P_o as easily available P forms (*references in* Cross and Schlesinger, 1995; *references in* Guo et al., 2000), the availability of the other fractions is less certain (Cross and Schlesinger, 1995). NaOH-P_i and NaOH-P_o are commonly described as moderately labile forms, rendered available in the medium term (some months-years) by biological or physicochemical transformations (Tiessen et al., 1983; Sharpley et al., 1987; Cross and Schlesinger, 1995; Selles et al., 1997). Phosphorus fractions extracted by HCl 1M, concentrated HCl or $HNO_3/HF/HClO_4$ are classically labeled as recalcitrant, non-labile forms, non-available to plants (Cross and Schlesinger, 1995; Guo et al., 2000; Solomon and Lehmann, 2000; Abekoe and Sahrawat, 2003). Deviating from this commonly adopted scheme, various studies in temperate or tropical soils report that even stable phosphorus forms could be mobilized to insure plant nutrition. The labile P fraction is resplenished not only by mineralization of organic forms or by NaOH-P_i, but also by HCl1M-P (Hedley et al., 1982; Solomon and Lehmann, 2000; Abekoe and Sahrawat, 2003) or even residual-P (Hedley et al., 1982; Sharpley and Smith, 1985; Gahoonia and Nielsen, 1992). Also, the commonly adopted subdivision assumes that specific fractions extracted by the same sequential procedure have similar availabilities in all soils. Studies prove nevertheless that this assumption is not necessarily true (Guo et al., 2000).

5.2.3. Software and statistical analysis

Graphs were drawn and statistics carried out in *MATLAB 7.4.0 (R2007a)*. Normality of distributions was verified through the LillieFors-test. Paired sample *t*-tests, two sample *t*-tests, anova1-tests were executed even if the distribution was slightly skewed, since hypothesis testing proved robust to a certain violation of the assumption of normality (Smith and Wells, 2006). Medians were compared through the Wilcoxon rank sum test or the

Kruskal-Wallis nonparametric one-way analysis of variance, when (1) data-series had obvious (and suspected) non-normal distributions and when (2) usual transformations (square root, log-transformation) did not improve normality.

Paired sample *t*-test for Butare, Kibungo or Ruhengeri compared the data obtained for high potential A-plots to those for low potential B-plots of a same farm: there are 10 A-B couples for Butare, 14 for Kibungo and 20 for Ruhengeri. In Ntungamo, the data relative to subparts of the A-subplot (or B-subplot) of one farm were averaged. The averaged data for the A-subplot on one farm were compared to the averaged data of the B-subplot of the same farm. Only 10 A-B couples were available to represent the 3 soil types encountered in the Ntungamo-valley.

5.3. Results

5.3.1. Phosphorus fractions

In the descriptions of this study the common terminology of "labile" (resin-P_i + NaOH-P_{tot}), "moderately labile" (NaOH-P_{tot}) and "non labile" (HCl1M-P + $HCl_{conc.}$-P + residual-P) fractions is adopted. No data are available to actually prove that this distinction in availabilities was verified in the soils under study.

A. Evaluation of the procedure

Seven soil samples are triplicated and one duplicated when submitted to the sequential phosphorus fractionation. The replicated samples are chosen to represent soils of different areas with different textures and different total phosphorus contents. To evaluate the precision of data for one sample, the coefficients of variations are calculated ([eq.1]):

$$\text{coefficient of variation (\%)} = \frac{\text{standard deviation}}{\text{mean}} \text{ x } 100 \qquad [\text{eq. 1}]$$

The computed coefficients are summarized in Table 5.2. The small values of their coefficients of variation indicate that NaOH-P_{tot}, sum of fractions and the contributions of moderately labile and non-labile P to total phosphorus contents reproduce well. Variability is larger for resin-P_i, $NaHCO_3$-P_{tot} or HCl1M-P, $HCl_{conc.}$-P, residual-P or labile P contribution: coefficients of variations are regularly over 10%. Reproducibility is very poor for the subdivision between organic and inorganic fractions in $NaHCO_3$ and NaOH extracts. Coefficients of variation per P-fraction were not significantly (P<0.10) related to soil texture or total phosphorus content.

When comparing the sum of extracted P fractions and P by total chemical analysis, 61-157% of phosphorus is recovered. As shown in Figure 5.3, most (60%) of the samples have a P recovery between 85 and 115% (average: 94 %).

Table 5.2. Evaluation of the sequential P extraction procedure: assessment of the dispersion between replicates of a same sample.

Fraction / Sample (N replicates)	Resin $-P_i$	$NaHCO_3$			NaOH			HCl1M-P	$HCl_{conc.}$-P	Resid.-P	Sum of frac-tions	Contributions to sum of fractions		
		P_{tot}	P_i	P_o	P_{tot}	P_i	P_o					Labile	Mod. labile	Non-labile
Coefficient of variation (%) for the various fractions ($mg.kg^{-1}$) or the contributions (%) of labile (lab.), moderately (mod. lab.) labile and non-labile (non lab.)P														
B8B (N=3)	15	15	22	14	9	15	40	47	4	4	3	11	7	4
B12A (N=3)	1	10	19	26	4	22	66	4	14	15	3	7	5	8
B12B (N=3)	7	7	12	10	8	17	65	16	5	12	6	6	4	7
B67B (N=2)	9	0	4	10	9	8	11	11	5	6	7	2	2	0
K35A (N=3)	23	24	29	4	12	18	73	35	8	21	9	19	9	7
F10M13H1 (N=3)	48	6	20	33	2	9	64	23	13	17	8	14	8	5
F10M11H3B (N=3)	7	14	30	20	11	12	112	18	19	6	8	15	15	6
F7M7H5 (N=3)	13	4	4	8	2	6	30	6	1	3	2	0	1	0

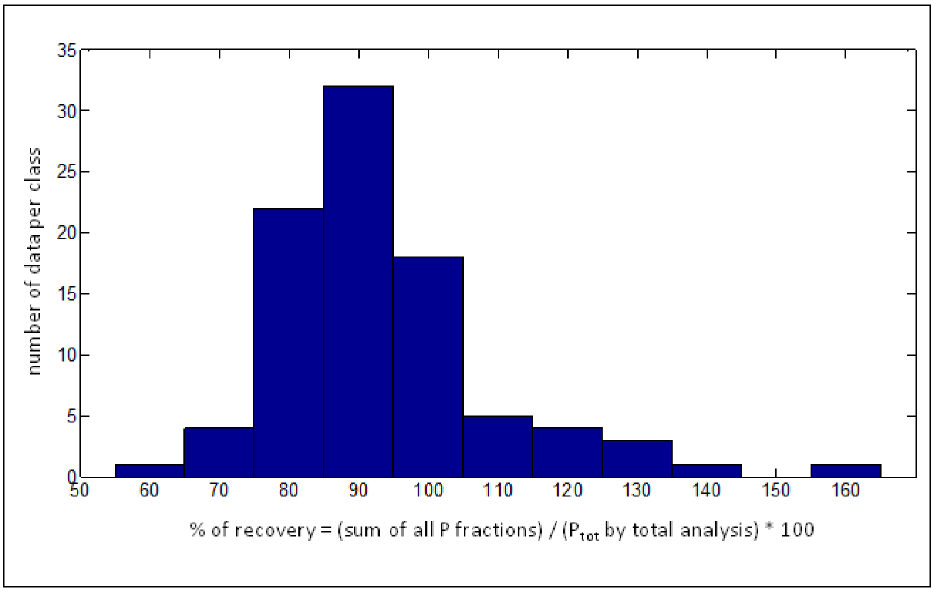

Figure 5.3. Evaluation of the sequential P extraction procedure: recovery (%) when comparing sum of P-fractions and total P contents by alkaline digestion.

B. Surface samples vs. samples from deeper horizons

Data gathered during four campaigns are available to this study (Table 5.1). The diagnostic survey in Rwanda (Butare, Kibungo, Ruhengeri; campaign 1) and the monitoring in Ntungamo (campaign 3) provide chemical data on surface samples (0-25 or 0-30 cm) of different farms (lateral distribution). During campaigns 2 (Butare, Kibungo) and 4 (Ntungamo), some farms previously studied are revisited. Both campaigns bring information on entire soil profiles (vertical distribution). The different horizons constituting the soils are described and sampled. The surface horizon widths do not correspond exactly to the 0-25cm or 0-30cm sections used in former campaigns. Data on surface horizons of soil profiles are nevertheless assimilated under those depth indications in Table 5.3. Data for Ntungamo are subdivided in three groups to conform to the observed soil heterogeneity: deep soils on micaschists in farms 2+4+5+7+8, soils on quartzite in farms 6+9+10, shallow soils on micaschists in farms 1+3 on steep slopes. Data of Table 5.3 are graphically represented in Figures 5.4 and 5.5.

Figure 5.4 represents the total phosphorus contents as distributed over the soil profiles or surface samples analyzed in Butare, Kibungo, Ntungamo (farms 1+3, farm 2+4+5+7+8, farms 6+9+10) and Ruhengeri. Total soil phosphorus contents vary widely in the surface samples of all the regions or subregions: 306-1560 $mg.kg^{-1}$ (N=35) in Butare, 535-2121 $mg.kg^{-1}$ (N=41) in Kibungo, 422-1036 $mg.kg^{-1}$ (N=66) in Ntungamo farms 2+4+5+7+8, 412-1501 $mg.kg^{-1}$ (N=40) in Ntungamo farms 6+9+10, 558-4013 $mg.kg^{-1}$ (N=28) in Ntungamo farms 1+3 and 1118-5598 $mg.kg^{-1}$ (N=40) in Ruhengeri. At depth, phosphorus contents are seemingly constant in Butare (450 $mg.kg^{-1}$) and Kibungo (780 $mg.kg^{-1}$). In Ntungamo farm 7 (Figure 5.4.C), total phosphorus contents tend to increase in the deepest parts of the soil profiles (300 $mg.kg^{-1}$ at 50-200 cm depth; 660-780 $mg.kg^{-1}$ at 250 cm). Tendencies are less clear in Ntungamo farms 6+9+10 (Figure 5.4.D), but may be similar. The total phosphorus content of the parent micaschists encountered at less than 1 m depth in Ntungamo farm 3 is 400 $mg.kg^{-1}$ (Figure 5.4.E).

Table 5.3 and Figure 5.5 summarize the contents for the different P fractions determined for surface and deep soil samples, in the regions of Butare, Kibungo, Ruhengeri and Ntungamo. No data are available for the soil at depth in the Ruhengeri region. For all regions or subregions, the contents of the resin-P_i, $NaHCO_3$-P_{tot}, NaOH-P_{tot} and HCl1M-P fractions and the sum of fractions are higher in surface horizons than at depth, although not always significantly ($P<0.05$). For the $HCl_{conc.}$-P and residual-P fractions tendencies amongst regions are less clear. Non-labile fractions contribute for most of the phosphorus in the soils in Butare, Kibungo, Ntungamo farms 2+4+5+7+8 and 6+9+10, as well in surface samples (46-66%) as at depth (56-72%). Moderately labile phosphorus forms are the second best contributors to total P (23-42% in surface samples, 24-29% in deep samples) in those regions. The easily plant-available forms account for for 9-22% of total phosphorus in surface horizons, and for 3-14% in deep horizons. In Ntungamo farms 1+3, non-labile P forms dominate (41%), but moderately labile P and labile P are almost equally important (28% and 20% respectively). In Ruhengeri, the moderately labile pool is the highest contributor to total P (44% against 41% by the non-labile forms and 13% by labile P). Labile fractions always contribute more to total phosphorus contents in surface samples than at depth. Contributions by non-labile forms are on the contrary systematically higher in deep soil samples, although not always significantly ($P<0.05$) (Table 5.3). The contributions of labile, moderately labile and non-labile P to total phosphorus content in surface and deep soil samples are graphically represented in the triangular plots of Figure 5.5.

Comparing the phosphorus fractions in deep samples of the various regions and subregions, it appears that the Butare samples have high values for the resin-P_i, $NaHCO_3$-P_{tot}, NaOH-P_{tot} and HCl1M-P fractions. For the $HCl_{conc.}$-P and residual-P fractions and the sum of fractions the highest values are found for the clayey and iron-rich soils of Kibungo. The resin-P_i, $NaHCO_3$-P_{tot}, NaOH-P_{tot}, HCl1M-P of surface samples from Ruhengeri and Ntungamo farms 1+3 stand out by their high values (Table 5.3).

$NaHCO_3$-P_o represents between 0-5% of total phosphorus content in surface samples from Butare, Kibungo or Ntungamo farms 2+4+5+7+8 and 6+9+10. $NaHCO_3$-P_o takes into account between 0 and 61% of all the P extracted by $NaHCO_3$. 0-48% of P extracted by NaOH is in organic forms in those soils. NaOH-P_o represents between 0-12% of total phosphorus contents. Organic forms ($NaHCO_3$-P_o + NaOH-P_o) hence account for 0-14% of total phosphorus in surface samples. Taking into account the large uncertainties on the P_o values, values are similar for deep horizons from Butare, Kibungo or Ntungamo farms 2+4+5+7+8 and 6+9+10. Data for Ntungamo farms 1+3 are scarce, only 1 sample for surface horizon and 1 sample at shallow depth. Organic phosphorus represents 4% of total P in surface samples and 3% at depth. In the young soils of Ruhengeri, 1-2% of total phosphorus is taken into account by $NaHCO_3$-P_o and 16-27% by NaOH-P_o. Very high variability when subdividing phosphorous between its organic and inorganic forms in the $NaHCO_3$ and NaOH extracts (Table 5.2) lends little confidence in the data of that subdivision. Results on organic P are thus not considered further (not represented in any Table).

Table 5.3 (continued on next page). Phosphorus fractionation in surface (0-25cm, 0-30cm or assimilated (profile horizons more or less coinciding with these intervals)) and deep soil samples from the 6 different regions or subregions.

Region	Depth of sample (cm) (N)	Resin-P_i ($mg.kg^{-1}$)	$NaHCO_3$-P_{tot} ($mg.kg^{-1}$)	NaOH-P_{tot} ($mg.kg^{-1}$)	HCl1M-P ($mg.kg^{-1}$)	$HCl_{conc.}$-P ($mg.kg^{-1}$)
		median (range between brackets)				
Butare	"0-25"cm (N=19)	70 (b) (12-321)	66 (b) (29-299)	198 (b) (103-323)	48 (b) (13-473)	132 (a) (83-482)
	Depth>80cm (N=8)	26 (a)*(B)* (14-94)	26 (a)*(B)* (15-58)	119 (a)*(B)* (67-181)	15 (a)*(B)* (6-119)	114 (a)*(A)* (90-182)
Kibungo	"0-25"cm (N=12)	41 (b) (18-102)	49 (b) (30-97)	234 (b) (106-346)	22 (a) (0-164)	356 (b) (244-448)
	Depth>80cm (N=4)	3 (a)*(A,B)* (2-4)	18 (a)*(A,B)* (12-21)	153 (a)*(B)* (116-169)	4 (a)*(A,B)* (3-8)	283 (a)*(B)* (263-294)
Ntungamo f.7	"0-30"cm (N=6)	16 (b) (5-23)	32 (b) (22-41)	193 (b) (125-206)	13 (b) (5-21)	90 (a) (71-120)
	Depth>80cm (N=5)	1 (a)*(A)* (1-2)	7 (a)*(A)* (7-10)	59 (a)*(A)* (56-67)	2 (a)*(A)* (1-4)	67 (a)*(A)* (64-78)
Ntungamo f.9+10	"0-30"cm (N=11)	24 (a) (2-201)	38 (b) (22-109)	179 (b) (127-258)	18 (b) (7-148)	132 (a) (103-224)
	Depth>80cm (N=8)	6 (a)*(A,B)* (2-108)	17 (a)*(A,B)* (10-27)	111 (a)*(B)* (78-165)	5 (a)*(A,B)* (1-15)	146(a)*(A,B)* (113-182)
Ntungamo f.3	0-29cm (N=1)	149	175	462	284	398
	29-60 cm (N=1)	18	34	182	40	294
Ruhengeri	"0-25"cm (N=4)	184 (129-349)	198 (115-311)	1811 (532-2368)	697 (221-1420)	224 (142-258)

(a), (b): Wilcoxon ranksum-test: for each P fraction or contribution, data for <u>surface samples</u> of 1 region are compared data for <u>deep soil samples</u> from the same area. Medians followed by a different letter, are significantly ($P<0.05$) different. *(A)*, *(B)*: Kruskal-Wallis one-way analysis of variance: P fractions or contributions of deep samples are compared <u>between regions</u>. Medians followed by a different letter, are significantly ($P<0.05$) different.

Table 5.3 (continued). Phosphorus fractionation in surface (0-25cm, 0-30cm or assimilated (profile horizons more or less coinciding with these intervals)) and deep soil samples from the 6 different regions or subregions.

Region	Depth of sample (cm) (N)	residual-P (mg.kg^{-1})	Sum of fractions (mg.kg^{-1})	Labile P (%)	Moderately labile P (%)	Non-labile P (%)
		median (range between brackets)				
Butare	"0-25"cm (N=19)	110 (a) (75-184)	615 (b) (344-1637)	22 (b) (12-44)	31 (a) (16-40)	46 (a) (35-69)
	Depth>80cm (N=8)	85 (a)*(A)* (74-125)	388(a)*(A,B)* (274-760)	14 (a)*(B)* (8-20)	29 (a)*(A)* (24-34)	56 (b)*(A)* (52-64)
Kibungo	"0-25"cm (N=12)	273 (b) (157-329)	1003 (b*)* (706-1405)	9 (b) (6-14)	23 (a) (13-31)	66 (a) (59-81)
	Depth>80cm (N=4)	146 (a)*(B)* (114-170)	597 (a)*(B)* (569-630)	4 (a)*(A)* (3-4)	26 (a)*(A)* (19-27)	70 (a)*(B)* (69-78)
Ntungamo farm 7	"0-30"cm (N=6)	85 (a) (85-131)	452 (b*)* (315-482)	10 (b) (9-13)	42 (b) (40-44)	49 (a) (43-51)
	Depth>80cm (N=5)	96 (a)*(A,B)* (82-98)	238 (a)*(A)* (229-245)	3 (a)*(A)* (3-5)	24 (a)*(A)* (24-28)	72 (b)*(B)* (66-73)
Ntungamo f.+10	"0-30"cm (N=11)	88 (a) (71-124)	489(b) (379-1063)	12 (b) (7-29)	39 (b) (24-44)	48 (a) (46-60)
	Depth>80cm (N=8)	94 (a)*(A,B)* (79-108)	387(a)*(A,B)* (329-573)	6 (a)*(A,B)* (4-22)	29 (a)*(A)* (24-33)	64 (a)*(A,B)* (49-73)
Ntungamo f.3	0-29cm (N=1)	180	1647	20	28	41
	29-60cm (N=1)	84	652	8	28	51
Ruhengeri	"0-25" cm (N=4)	562 (182-822)	3677 (1321-5528)	13 (8-18)	44 (40-53)	41 (40-45)

(a), (b): Wilcoxon ranksum-test: for each P fraction or contribution, data for surface samples of one region are compared data for deep soil samples from the same area. Medians followed by a different letter, are significantly ($P<0.05$) different. *(A)*, *(B)*: Kruskal-Wallis one-way analysis of variance: P fractions or contributions of deep samples are compared between regions. Medians followed by a different letter, are significantly ($P<0.05$) different.

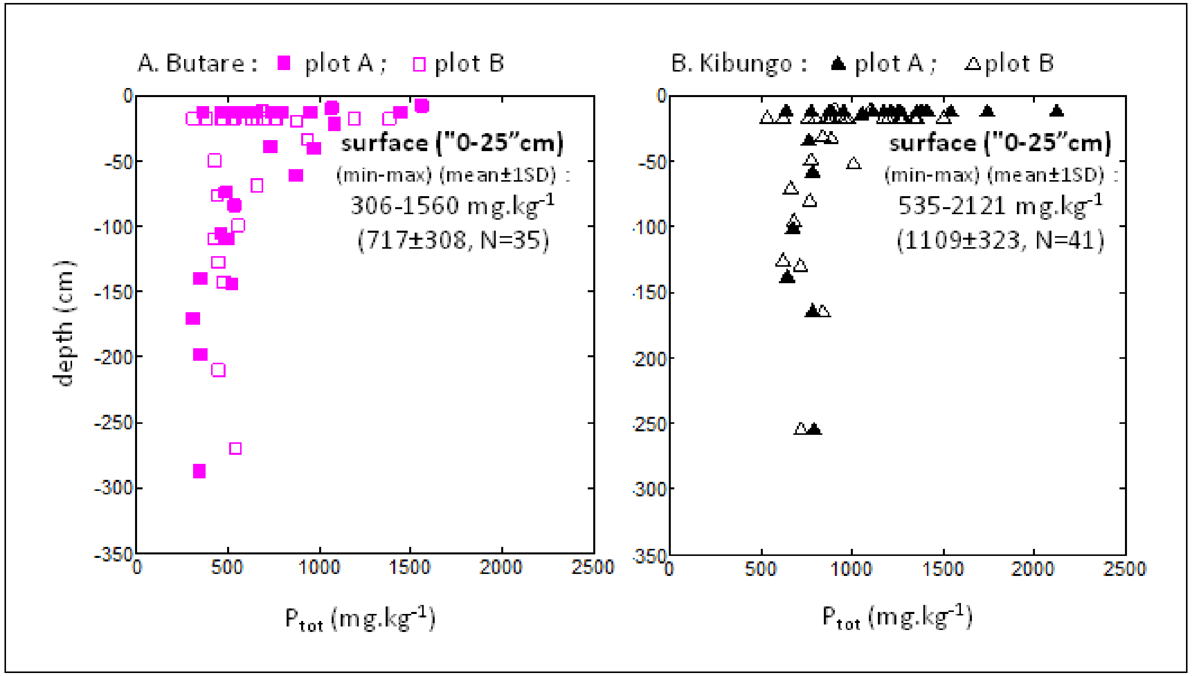

Figure 5.4. (continued on next pages) Total phosphorus contents as distributed on the entire soil profiles described in (A) Butare, (B) Kibungo, (C, D, E) Ntungamo and (F) Ruhengeri. Note different scale on X-axis in (E) and (F).

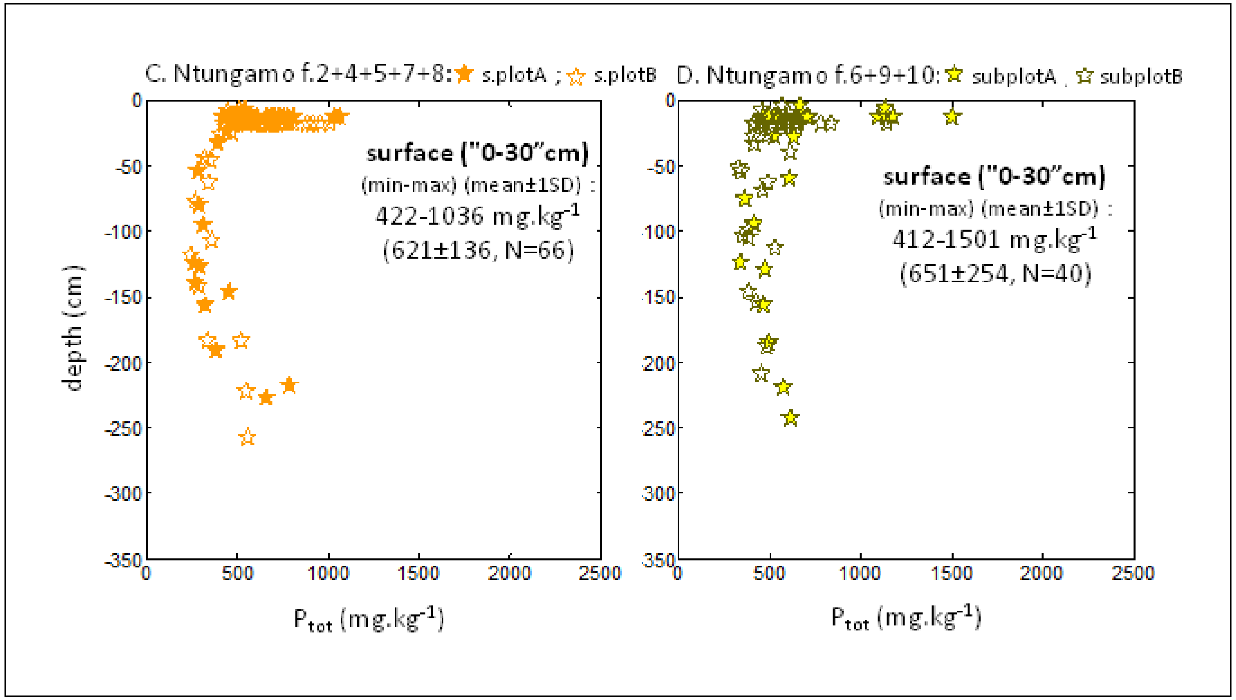

Figure 5.4. (continued) Total phosphorus contents as distributed on the entire soil profiles described in (A) Butare, (B) Kibungo, (C, D, E) Ntungamo and (F) Ruhengeri. Note different scale on X-axis in (E) and (F).

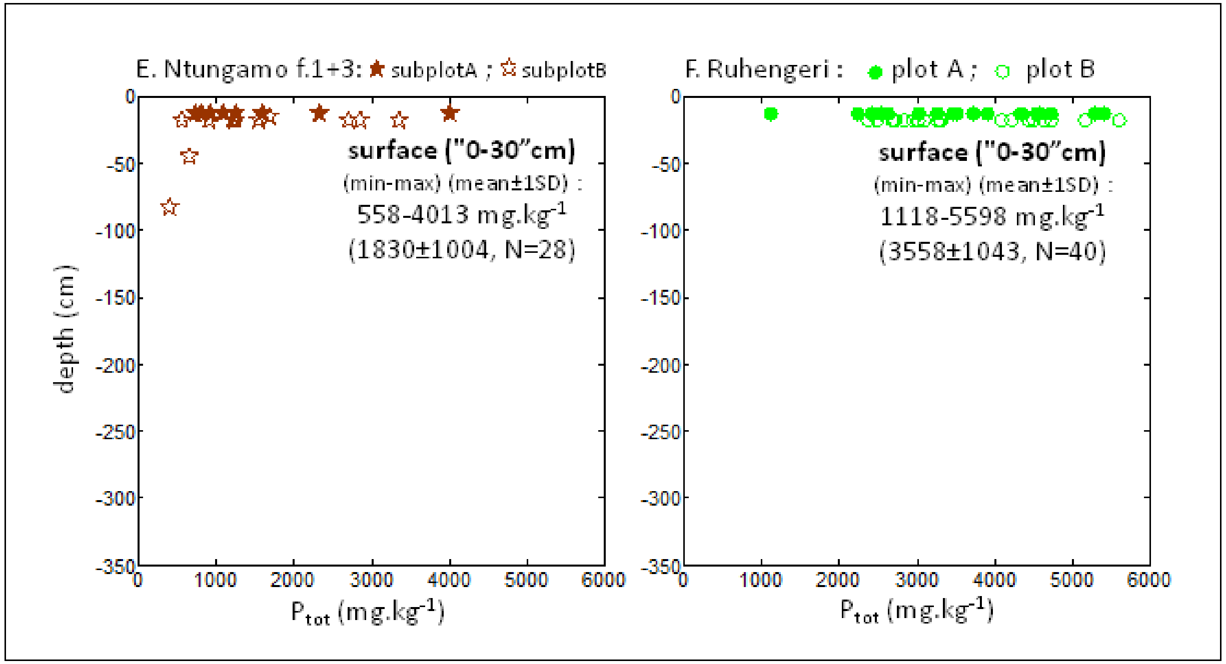

Figure 5.4. (continued) Total phosphorus contents as distributed on the entire soil profiles described in (A) Butare, (B) Kibungo, (C, D, E) Ntungamo and (F) Ruhengeri. Note different scale on X-axis in (E) and (F).

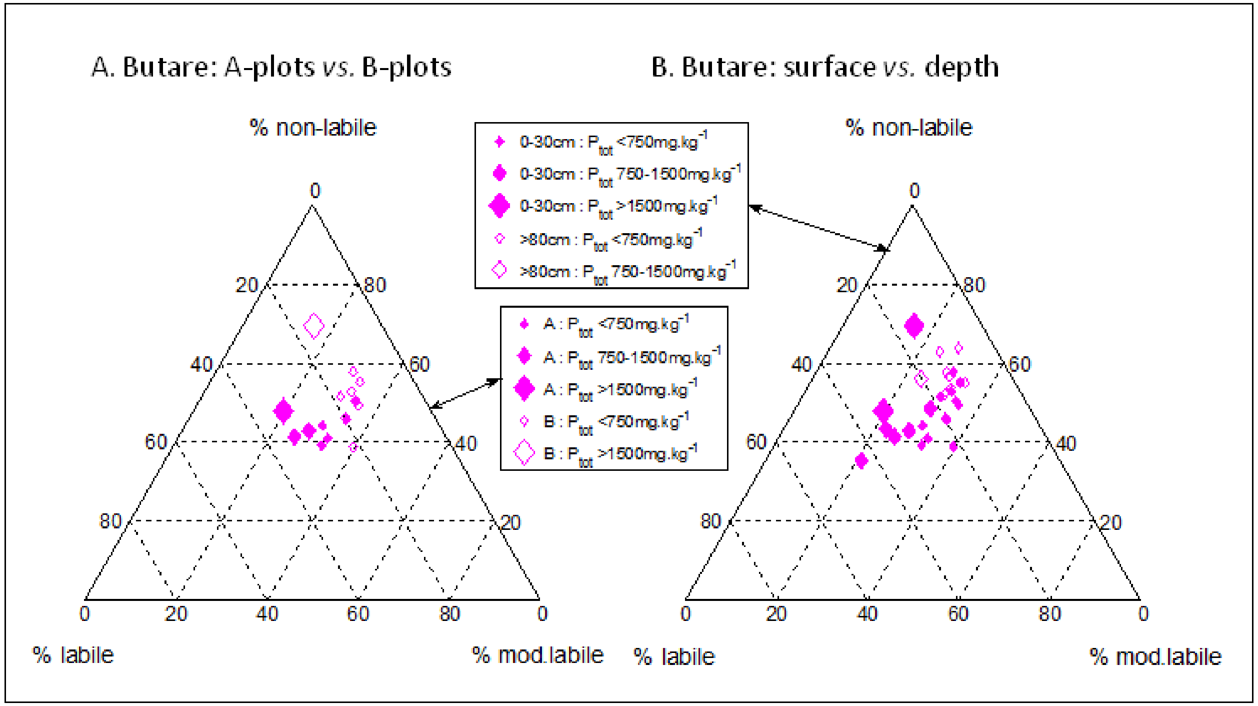

Figure 5.5 (continued on following pages). Distribution of phosphorus between labile, moderately labile and non-labile forms: (A) comparison between A- and B-plots in Butare, (B) comparison between surface and depth in Butare soils.

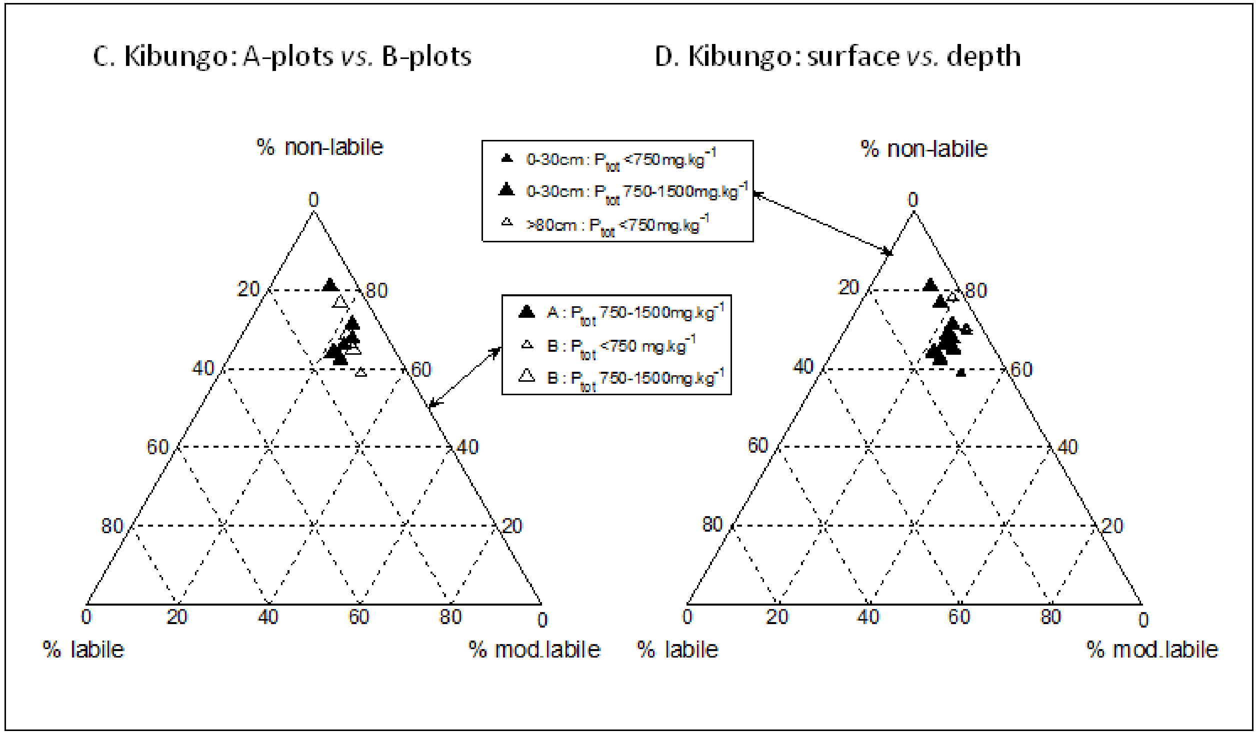

Figure 5.5 (continued on following pages). Distribution of phosphorus between labile, moderately labile and non-labile forms: (C) comparison between A- and B-plots in Kibungo, (D) comparison between surface and depth in Kibungo soils.

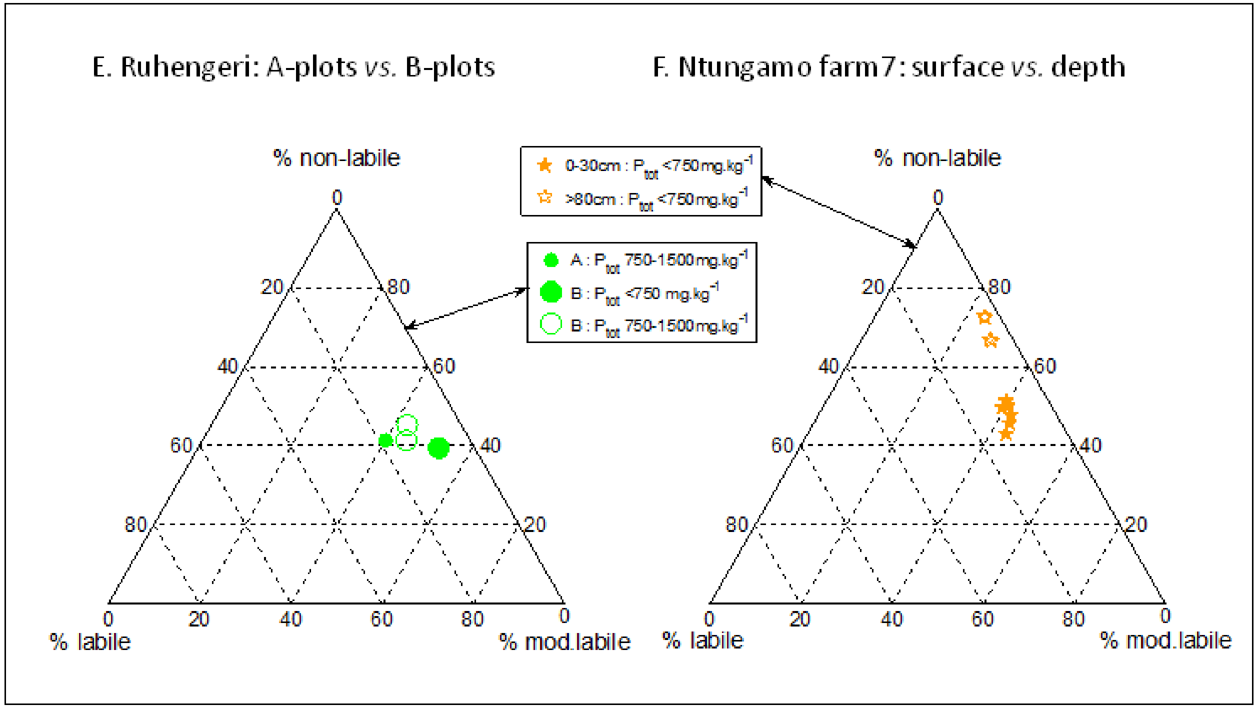

Figure 5.5. (continued). Distribution of phosphorus between labile, moderately labile and non-labile forms: (E) comparison between A- and B-plots in Ruhengeri (no data at depth), (F) comparison between surface and deep samples in Ntungamo farm 7 (A and B-plots together).

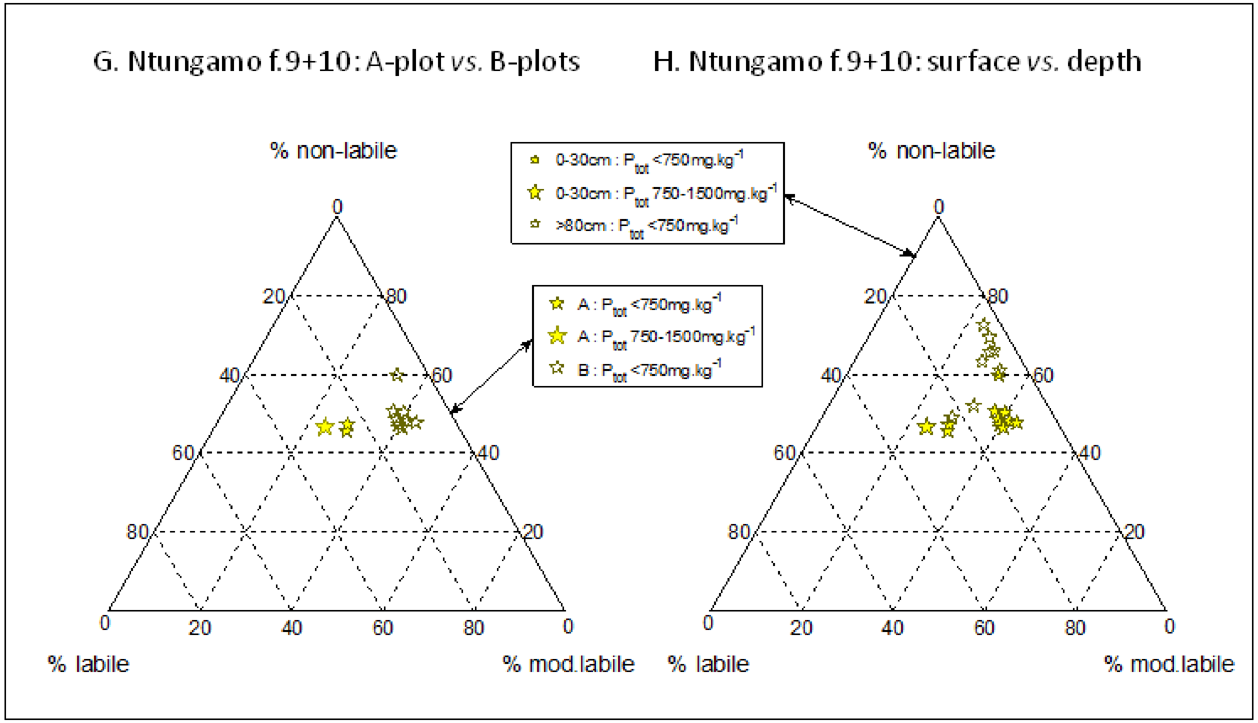

Figure 5.5. (continued). Distribution of phosphorus between labile, moderately labile and non-labile forms: (G) comparison between A- and B-plots and (H) distribution in function of depth in Ntungamo farms 9+10.

C. Within-farm variability in phosphorus quantities and forms

Table 5.4. details the P fractions and the contributions of labile, moderately labile and non-labile P to total phosphorous contents in the high (plot A) and low potential plots (plot B) of different farms in Butare, Kibungo and Ruhengeri. Paired-sample *t*-tests indicate that resin-P_i, $NaHCO_{3,tot}$, NaOH-P_{tot}, HCl1M-P, sum of fractions and contribution of labile P forms to total P are significantly (P<0.10) higher in the A-plots than in the B-plots of the farms in the Butare area. Differences between A- and B-plots in Kibungo are never significant (P>0.10) for neither of the fractions or contributions; $HCl_{conc.}$-P and sum of fractions are usually higher in A-plots compared to B-plots. In the two farms of Ruhengeri in whose samples P has been fractionated, the B-plots are richer than A-plots for the various P-fractions. This tendency observed for these two samples does not necessarily apply to the entire Ruhengeri-area. A paired-sample *t*-test on the total P contents in the A- and B-plots of 20 farms in Ruhengeri, show as a matter a fact no significant difference between plots. A-plots have an average P content of 3512 ± 1131 $mg.kg^{-1}$ (mean ± 1SD, SD = standard deviation), B-plots have P-contents averaging 3603 ± 975 $mg.kg^{-1}$ (p-value of paired sample *t*-test = 0.5830) (Table 5.6). The contributions of labile, moderately labile and non-labile P to total P contents in A- and B-plots of Butare, Kibungo and Ruhengeri farms are graphically summarized in Figure 5.5.

Table 5.4 (continued on next page). Variation in P forms and quantities between surface samples originating from different spots within farms of Butare, Kibungo or Ruhengeri: plots A and B. The three last columns represent contributions to sum of fractions. "Pval" is the P-value for paired sample *t*-tests comparing A and B-plots of a same farm (*= P<0.01, *= P<0.1).**

P / farm	Resin-P_i (mg.kg^{-1})		$NaHCO_3$-P_{tot} (mg.kg^{-1})		NaOH-P_{tot} (mg.kg^{-1})		HCl1M-P (mg.kg^{-1})		$HCl_{conc.}$-P (mg.kg^{-1})		Residual-P (mg.kg^{-1})		Sum of fract. (mg.kg^{-1})		Labile P (%)		Moderately labile P (%)		Non-labile P (%)	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Butare (surface samples: 0-25cm)																				
f.7	38	13	56	29	166	115	20	13	112	98	86	84	479	352	20	12	35	33	46	55
f.8	172	47	87	46	199	198	76	46	132	165	115	113	781	615	33	15	25	32	41	53
f.10	321	124	209	114	323	251	454	473	144	482	184	158	1637	1602	32	15	20	16	48	69
f.11	98	41	69	50	197	159	50	36	129	94	110	85	652	465	26	20	30	34	44	46
f.12	89	48	63	66	174	208	51	27	83	94	76	83	535	527	28	22	33	40	39	39
f.61	36	29	50	44	193	170	19	18	165	127	101	92	563	481	15	15	34	35	51	49
f.66	70	12	70	29	176	103	20	16	124	99	75	83	535	344	26	12	33	30	41	58
f.67	153	67	110	60	250	216	95	48	166	188	126	128	900	707	29	18	28	31	43	51
Pval	0.0078***		0.0703*		0.0703*		0.0703*		1.0000		0.7266		0.0078***		0.0703*		0.7266		0.2891	

Table 5.4 (continued). Variation in P forms and quantities between surface samples originating from different spots within farms of Butare, Kibungo or Ruhengeri: plots A and B. The three last columns represent contributions to sum of fractions. "Pval" is the P-value for paired sample *t*-tests comparing A and B-plots of a same farm (*= P<0.01, *= P<0.1).**

P / farm	Resin-P_i (mg.kg^{-1})		$NaHCO_3$-P_{tot} (mg.kg^{-1})		NaOH-P_{tot} (mg.kg^{-1})		HCl1M-P (mg.kg^{-1})		$HCl_{conc.}$-P (mg.kg^{-1})		Residual-P (mg.kg^{-1})		Sum of fract. (mg.kg^{-1})		Labile P (%)		Moderately labile P (%)		Non-labile P (%)	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Kibungo (surface samples : 0-25cm)																				
f.22	61	44	53	51	256	274	0	0	381	359	329	326	1080	1054	11	9	24	26	66	65
f.32	23	32	41	40	201	218	27	14	318	244	208	157	818	706	8	10	25	31	68	59
f.35	102	71	80	72	295	227	128	67	416	364	314	226	1334	1026	14	14	22	22	64	64
f.37	20	19	33	31	199	147	17	14	348	332	259	296	877	838	6	6	23	17	71	77
f.38	85	37	97	55	346	240	164	44	448	342	264	261	1405	979	13	9	25	24	62	66
f.40	18	47	30	46	106	252	13	60	353	406	281	283	801	1094	6	9	13	23	81	68
Pval	0.6875		0.2188		1.0000		0.3750		0.2188		0.6875		0.2188		1.0000		0.6875		0.6875	
Ruhengeri (surface samples : 0-25cm)																				
f.41	149	349	183	311	2246	2368	771	1420	207	258	706	822	4262	5528	8	12	53	43	40	45
f.46	129	220	115	212	532	1376	221	623	142	241	182	418	1321	3091	18	14	40	45	41	41

For the Ntungamo area, P-fractionation is performed on a series of samples taken at different depths from the described soil profiles. Within one farm, the widths of soil horizons and the depths at which they are encountered do not coincide from one profile to another. Direct comparison between the P-contents of samples is thus impeded; only possible tendencies can be highlighted. The data in Table 5.5 suggest that the surface samples of the A-plot in farm 9 have higher resin-P_i, $NaHCO_{3,tot}$, HCl1M-P, sum of fractions and contribution of labile P than B-plots of the same farm (see also Figure 5.5.G). The contents in the various P-fractions or contributions to total P content are quite similar in farm 7 (Table 5.5, Figure 5.5.F). No tendency appears when comparing P-fraction contents and P-contributions between the three profiles of farm 10. Data for total phosphorus contents are more numerous than those on P-fraction contents and allow further comparisons within Ntungamo subregions. Total phosphorus contents do not have a normal distribution. So, medians of total phosphorus contents in A- and B-plots are compared using the Wilcoxon rank sum test (Table 5.6). Medians of A- and B-subplots in farms 6+9+10 (643 vs. 490 $mg.kg^{-1}$, Pvalue of two sample t-test = 0.0100) are significantly ($P<0.05$) different.

D. Correlations of P-fractions with soil chemical and physical characteristics

In an attempt to understand the fractionation method and its results, correlations are considered between (1) data on some chemical and physical properties and (2) the contents in P fractions or the contributions of these fractions to total P contents. The properties under consideration are total carbon contents (C_{tot}), total aluminium and iron contents ($Al_2O_{3,tot}$, $Fe_2O_{3,tot}$), % of clay or otherwise kaolinite abundances (%clay or $\%wt_{kaolinite}$), Al and Fe extracted by dark oxalate or DCB (Al_o, Al_{DCB}, Fe_o, Fe_{DCB}), and the P-sorption capacity. The P data considered in the correlations are (1) all the data acquired, notwithstanding differences in soil type or sampling depth, (2) series per region (surface and deep soil samples). Relationships identified as significant by statistics are checked by scatterplots.

Table 5.5. Variation in P forms and quantities between surface samples originating from different spots within a same farm in Ntungamo. Farm number and mat number are indicated as "FxMy". The three last columns represent contributions of labile, moderately labile and non-labile P to sum of fractions.

Farm and mat number	Depth (cm)	Subplot potential (qualitative)	Resin-P_i ($mg.kg^{-1}$)	$NaHCO_3$-P_{tot} ($mg.kg^{-1}$)	NaOH-P_{tot} ($mg.kg^{-1}$)	HCl1M-P ($mg.kg^{-1}$)	$HCl_{conc.}$-P ($mg.kg^{-1}$)	Residual-P ($mg.kg^{-1}$)	Sum of fractions ($mg.kg^{-1}$)	Labile P (%)	Mod. labile P (%)	Non-labile P (%)
F7M4	0-20cm	A	22	41	206	16	93	93	471	13	44	43
F7M7	0-13cm	A	23	22	196	21	118	102	482	9	41	50
	13-33cm	A	9	37	168	8	71	131	424	11	40	50
F7M15	0-14cm	B	20	30	191	19	86	97	444	11	43	46
	14-35cm	B	12	34	195	10	120	89	460	10	42	48
F9M12	0-12cm	A	201	109	258	148	224	124	1063	29	24	47
	12-44cm	A	84	50	158	43	114	88	537	25	29	46
F9M6	0-19cm	B	29	38	208	21	139	99	534	12	39	49
	19-47cm	B	4	22	127	7	140	81	381	7	33	60
F9M8	0-34cm	B	2	41	214	18	135	79	489	9	44	48
F10M5	0-7cm	A	86	55	170	52	127	100	591	24	29	47
	7-48cm	A	21	37	191	13	116	86	464	12	41	46
F10M11	0-7cm	B	26	40	208	20	136	89	519	13	40	47
	7-46cm	B	10	31	160	9	119	75	404	10	40	50
F10M13	0-15cm	B	24	35	179	11	132	100	481	12	37	51
	15-40cm	B	8	31	158	8	103	71	379	10	42	48

Throughout the comparisons, significant ($P<0.05$) positive relationships recurrently appear between

- C_{tot} and (1) $NaHCO_3$-P_{tot}, (2) $NaHCO_3$-P_i, (3) NaOH-P_{tot}, (4) NaOH-P_i, (5) sum of fractions,
- $Fe_2O_{3,tot}$ and contribution of residual-P to total P-content,
- Fe_{DCB} and contribution of residual-P to total P-content,
- $\%wt_{kaolinite}$ and contribution of residual-P to total P-content.

Total carbon or iron contents, and kaolinite abundances vary, respectively, between 0.29-7.33 $\%C_{tot}$ (N=79), 1.61-16.74 $\%Fe_2O_3$ (N=79) and 5-69 $\%wt_{kaolinite}$ (N=65) and span the ranges of values observed in the entire database. Kaolinite abundances are not available for the Ruhengeri soils. Correlations with Fe_{DCB} (11.87-90.55 $g.kg^{-1}$) rely on fewer data (N=37) relating to the soil samples from Butare, Kibungo and Ntungamo. No DCB-data are available for Ruhengeri-soils. Note that Kibungo soils have significantly higher ($P<0.05$) mean kaolinite abundances (64 ± 3 $\%wt_{kaolinite}$ (mean ± 1SD)) and total iron contents (12.95 ± 0.77 $\%Fe_2O_{3,tot}$ (mean ± 1SD)) than the soils in the other regions or subregions.

5.3.2. Within-farm variations of classical fertility indicators

Some chemical data usually called upon to describe soil fertility are summarized in Table 5.6: pH_{H2O}, total carbon (C_{tot}) and phosphorus (P_{tot}) contents, total reserve in bases (TRB), exchangeable K (K_{exch}) and Ca (Ca_{exch}), sum of exchangeable K, Ca and Mg ($(K+Ca+Mg)_{exch}$) and cation exchange capacity (CEC). All data (except pH) for all the regions or subregions show wide variability (see standard deviations (SD) in Table 5.6). Because of the this wide variability for the chemical characteristics within plots or subplots of same potential (plots A or plots B), comparisons by two sample *t*-tests of all the data related to plots A to all the data of plots B may mask certain tendencies within the region. Further attempts to highlight within-farm differences are thus made by comparing data for A- and B-plots pairwise (paired sample *t*-tests in Table 5.6).

In the Butare region, two sample *t*-tests indicate significant (P<0.01) differences between A- and B-plots for pH_{H2O} (pH6.3 *vs.* 5.8) and exchangeable K (2.14 vs. 1.33 $cmolc.kg^{-1}$). Paired sample *t*-tests confirm these observations and signal further significant (P<0.05) differences for C_{tot}, P_{tot}, Ca_{exch}, $(K+Ca+Mg)_{exch}$ and CEC also. Paired samples *t*-test on the Kibungo data indicate significant (P<0.05) differences between A- and B-plots for 5 out of the 8 variables of Table 5.6: pH_{H2O}, TRB, exchangeable Ca, $(K+Ca+Mg)_{exch}$ and CEC. In Ruhengeri only pH_{H2O} differs significantly (P<0.01) between various parts of the farm according to the paired sample *t*-tests. In Ntungamo data are too scarce to allow paired sample comparisons. The following description relies thus solely on the conclusions by two sample *t*-tests. For farms 1+3 and 2+4+5+7+8, differences are not significant (P<0.05) for none of the 8 variables considered. Two sample *t*-tests indicate significantly (P<0.01) higher values for pH_{H2O}, exchangeable K and Ca, $(K+Ca+Mg)_{exch}$ in A-subplots of farms 6+9+10 of Ntungamo as compared to B-subplots.

Total phosphorus contents are strongly related to other chemical data from Butare, Kibungo, Ruhengeri and Ntungamo (Table 5.7). Positive correlation coefficients, identified as significant (P<0.05), vary between 0.49-0.89 for pH_{H2O}, 0.59-0.90 for C_{tot}, 0.69-0.99 for TRB, 0.58-0.71 for K_{exch}, 0.53-0.97 for Ca_{exch}, 0.53-0.96 for $(K+Ca+Mg)_{exch}$. For what management is concerned, statistical tests (two sample *t*-tests, paired-sample *t*-test) indicate significant (P<0.05) differences in mulch thicknesses between A- and B-plots in Ruhengeri and Ntungamo farms 1+3 (Table 5.9). In other regions or subregions, differences are not significant (P>0.05).

In the 10 farms of Ntungamo, distances between the homestead and the soil sampling places in the banana-grove are known. Possible linear relationships between the classical fertility indicators already mentioned (Y-axis) and distance to homestead (in m, X-axis) are verified. Significance of the relationship was verified by *t*-tests on the coefficients (Table 5.8) and by visual check by scatterplots (underlined slopes in Table 5.8). For farms 1 and 3, all significant relationships are positive: values for the fertility indicators increase with distance from homestead. For farms 6, 7, 9 and 10 all significant relationships are negative; values of slopes are smallest for farm 7. In farms 4, 5 and 8, significant relationships are either positive either negative. No relationship is significant in farm 2.

Table 5.6 (continued on following pages). Comparison between A- and B-plots of classical fertility indicators: total carbon or phosphorus contents (C_{tot}, P_{tot}), total reserve in bases, exchangeable K and Ca (K_{exch}, Ca_{exch}), sum of exchangeable K, Ca and Mg ($(K+Ca+Mg)_{exch}$), cation exchange capacity (CEC). Level of significance of statistical tests: ***=P<0.01, **=P<0.05, *=P<0.10. Data on K_{exch}, Ca_{exch} and CEC for Butare, Kibungo and Ruhengeri were already published in Gaidashova et al. (2009), other data are new.

	pH_{H2O} Mean ± 1SD	C_{tot} (%) Mean ± 1SD	P_{tot} ($mg.kg^{-1}$) Mean ± 1SD	TRB ($cmolc.kg^{-1}$) Mean ± 1SD	K_{exch} ($cmolc.kg^{-1}$) Mean ± 1SD	Ca_{exch} ($cmolc.kg^{-1}$) Mean ± 1SD	$(K+Ca+Mg)_{exch}$ ($cmolc.kg^{-1}$) Mean ± 1SD	CEC ($cmolc.kg^{-1}$) Mean ± 1SD
Butare								
Plots A (N=15)	6.3±0.5	1.92±0.60	659±264	40.99±18.52	2.14±0.86	6.15±3.33	10.63±4.87	12.44±3.11
Plots B (N=15)	5.8±0.41	1.68±0.54	662±287	40.56±17.39	1.33±0.58	5.50±2.85	8.76±3.71	11.66±2.66
P-value for two sample *t*-test	0.0096***	0.2491		0.9480	0.0052***	0.5705	0.2466	0.4664
P-value for rank sum test			1.0000					
P-value of paired sample *t*-test (N=10)	0.0035***	0.0172**	0.0129**	0.0879*	0.0172**	0.0130**	0.0106**	0.0074***

Table 5.6 (continued). Comparison between A- and B-plots of classical fertility indicators: total carbon or phosphorus contents (C_{tot}, P_{tot}), total reserve in bases, exchangeable K and Ca (K_{exch}, Ca_{exch}), sum of exchangeable K, Ca and Mg ($(K+Ca+Mg)_{exch}$), cation exchange capacity (CEC). Level of significance of statistical tests: ***=P<0.01, **=P<0.05, *=P<0.10. Data on K_{exch}, Ca_{exch} and CEC for Butare, Kibungo and Ruhengeri were already published in Gaidashova et al. (2009), other data are new.

	pH_{H2O} Mean ± 1SD	C_{tot} (%) Mean ± 1SD	P_{tot} ($mg.kg^{-1}$) Mean ± 1SD	TRB ($cmolc.kg^{-1}$) Mean ± 1SD	K_{exch} ($cmolc.kg^{-1}$) Mean ± 1SD	Ca_{exch} ($cmolc.kg^{-1}$) Mean ± 1SD	$(K+Ca+Mg)_{exch}$ ($cmolc.kg^{-1}$) Mean ± 1SD	CEC ($cmolc.kg^{-1}$) Mean ± 1SD
Kibungo								
Plots A (N=20)	7.3±0.5	4.70±0.43	1192±070	67.70±13.84	3.56±1.39	19.82±4.02	30.84±5.09	31.54±2.81
Plots B (N=18)	7.1±0.5	4.56±0.45	1023±266	59.69±9.11	2.82±1.44	17.42±3.82	27.56±5.44	30.41±3.59
P-value for two sample *t*-test	0.0938*	0.3424		0.0446**	0.1166	0.0673*	0.0623*	0.2827
P-value for rank sum test			0.1562					
P-value for paired sample *t*-test (N=14)	0.0338**	0.1529	0.0690*	0.0062***	0.2323	0.0178**	0.0091***	0.0342**

Table 5.6 (continued). Comparison between A- and B-plots of classical fertility indicators: total carbon or phosphorus contents (C_{tot}, P_{tot}), total reserve in bases, exchangeable K and Ca (K_{exch}, Ca_{exch}), sum of exchangeable K, Ca and Mg ($(K+Ca+Mg)_{exch}$), cation exchange capacity (CEC). Level of significance of statistical tests: ***=P<0.01, **=P<0.05, *=P<0.10. Data on K_{exch}, Ca_{exch} and CEC for Butare, Kibungo and Ruhengeri were already published in Gaidashova et al. (2009), other data are new.

	pH_{H2O} Mean ± 1SD	C_{tot} (%) Mean ± 1SD	P_{tot} ($mg.kg^{-1}$) Mean ± 1SD	TRB ($cmolc.kg^{-1}$) Mean ± 1SD	K_{exch} ($cmolc.kg^{-1}$) Mean ± 1SD	Ca_{exch} ($cmolc.kg^{-1}$) Mean ± 1SD	$(K+Ca+Mg)_{exch}$ ($cmolc.kg^{-1}$) Mean ± 1SD	CEC ($cmolc.kg^{-1}$) Mean ± 1SD
Ruhengeri								
Plots A (N=20)	7.1±0.4	3.99±1.72	3512±1131	385.63±100.9	3.56±1.69	14.09±5.89	21.53±8.76	23.60±10.21
Plots B (N=20)	6.9±0.4	4.14±1.66	3603±975	379.26±88.27	2.81±1.31	14.54±6.14	21.34±8.60	23.91±10.26
P-value for two sample *t*-test	0.1528	0.7828		0.8329	0.1303	0.8137	0.9456	0.9242
P-value for rank sum test			0.8181					
P-value for paired *t*-test (N=20)	0.0097***	0.4782	0.5830	0.5944	0.0626*	0.5908	0.8781	0.8260

Table 5.6 (continued). Comparison between A- and B-plots of classical fertility indicators: total carbon or phosphorus contents (C_{tot}, P_{tot}), total reserve in bases, exchangeable K and Ca (K_{exch}, Ca_{exch}), sum of exchangeable K, Ca and Mg ($(K+Ca+Mg)_{exch}$), cation exchange capacity (CEC). Level of significance of statistical tests: ***=P<0.01, **=P<0.05, *=P<0.10. Data on K_{exch}, Ca_{exch} and CEC for Butare, Kibungo and Ruhengeri were already published in Gaidashova et al. (2009), other data are new.

	pH_{H2O} Mean ± 1SD	C_{tot} (%) Mean ± 1SD	P_{tot} ($mg.kg^{-1}$) Mean ± 1SD	TRB ($cmolc.kg^{-1}$) Mean ± 1SD	K_{exch} ($cmolc.kg^{-1}$) Mean ± 1SD	Ca_{exch} ($cmolc.kg^{-1}$) Mean ± 1SD	$(K+Ca+Mg)_{exch}$ ($cmolc.kg^{-1}$) Mean ± 1SD	CEC ($cmolc.kg^{-1}$) Mean ± 1SD
Ntungamo farms 1+3 (only 2 plot A-plot B couples : too few data for paired sample comparison)								
Subplots A (N=8)	6.1±0.7	3.65±1.26	1237±547	96.29±16.19	1.06±0.37	4.24±2.61	9.60±5.16	ND
Subplots B (N=8)	6.3±0.7	3.89±1.51	1557±969	89.82±27.93	1.28±0.74	6.16±3.37	12.55±5.52	ND
P-value for two sample *t*-test	0.5187	0.7365		0.5797	0.4689	0.2214	0.2874	ND
P-value for rank sum test			0.5737					
P-value for paired sample *t*-test (N=2)	ND	ND	ND	ND	ND	ND	ND	ND

Table 5.6 (continued). Comparison between A- and B-plots of classical fertility indicators: total carbon or phosphorus contents (C_{tot}, P_{tot}), total reserve in bases, exchangeable K and Ca (K_{exch}, Ca_{exch}), sum of exchangeable K, Ca and Mg ($(K+Ca+Mg)_{exch}$), cation exchange capacity (CEC). Level of significance of statistical tests: ***=P<0.01, **=P<0.05, *=P<0.10. Data on K_{exch}, Ca_{exch} and CEC for Butare, Kibungo and Ruhengeri were already published in Gaidashova et al. (2009), other data are new.

	pH_{H2O} Mean ± 1SD	C_{tot} (%) Mean ± 1SD	P_{tot} ($mg.kg^{-1}$) Mean ± 1SD	TRB ($cmolc.kg^{-1}$) Mean ± 1SD	K_{exch} ($cmolc.kg^{-1}$) Mean ± 1SD	Ca_{exch} ($cmolc.kg^{-1}$) Mean ± 1SD	$(K+Ca+Mg)_{exch}$ ($cmolc.kg^{-1}$) Mean ± 1SD	CEC ($cmolc.kg^{-1}$) Mean ± 1SD
Ntungamo farms 2+4+5+7+8								
Subplots A (N=35)	6.2±0.8	1.86±0.30	616±137	60.46±8.53	0.76±0.38	2.04±1.41	4.31±2.52	ND
Subplots B (N=27)	6.1±0.9	1.90±0.32	637±139	61.93±9.78	0.67±0.35	2.18±1.37	4.40±2.43	ND
P-value for two sample *t*-test	0.6594	0.6163		0.5378	0.3256	0.6996	0.8882	ND
P-value for rank sum test			0.5322					
Pval for paired sample *t*-test (N=5)	0.5345	0.6136	0.2539	0.1298	0.4183	0.7177	0.8989	ND

Table 5.6 (continued). Comparison between A- and B-plots of classical fertility indicators: total carbon or phosphorus contents (C_{tot}, P_{tot}), total reserve in bases, exchangeable K and Ca (K_{exch}, Ca_{exch}), sum of exchangeable K, Ca and Mg ($(K+Ca+Mg)_{exch}$), cation exchange capacity (CEC). Level of significance of statistical tests: ***=P<0.01, **=P<0.05, *=P<0.10. Data on K_{exch}, Ca_{exch} and CEC for Butare, Kibungo and Ruhengeri were already published in Gaidashova et al. (2009), other data are new.

	pH_{H2O} Mean ± 1SD	C_{tot} (%) Mean ± 1SD	P_{tot} ($mg.kg^{-1}$) Mean ± 1SD	TRB ($cmolc.kg^{-1}$) Mean ± 1SD	K_{exch} ($cmolc.kg^{-1}$) Mean ± 1SD	Ca_{exch} ($cmolc.kg^{-1}$) Mean ± 1SD	$(K+Ca+Mg)_{exch}$ ($cmolc.kg^{-1}$) Mean ± 1SD	CEC ($cmolc.kg^{-1}$) Mean ± 1SD
Ntungamo farms 6+9+10 (only 3 A-B couples : too few data for paired sample comparison)								
Subplots A (N=12)	6.5±0.5	1.75±0.73	739±302	44.48±21.04	1.21±0.62	2.03±1.17	4.33±2.01	ND
Subplots B (N=21)	5.8±0.7	1.57±0.26	551±179	32.91±11.87	0.81±0.43	1.03±0.80	2.58±1.41	ND
P-value for two sample *t*-test	0.0073***	0.3388		0.0630*	0.0388**	0.0079***	0.0071***	ND
P-value for rank sum test			0.0100***					
P-value for paired *t*-test (N=3)	ND	ND	ND	ND	ND	ND	ND	ND

Table 5.7 (continued on next page). Correlation between soil chemical data and total P contents in Butare, Kibungo, Ruhengeri and the 10 farms in Ntungamo.

Farm number	Statistics	pH_{H2O}	C_{tot} (%)	TRB ($cmolc.kg^{-1}$)	K_{exch} ($cmolc.kg^{-1}$)	Ca_{exch} ($cmolc.kg^{-1}$)	$(K+Ca+Mg)_{exch}$ ($cmolc.kg^{-1}$)
Butare	Correlation	0.59	0.63	0.69	0.23	0.87	0.81
(N=30)	P-value	0.0006***	0.0002***	0.0000***	0.2317	0.0000***	0.0000***
Kibungo	Correlation	0.26	0.06	0.74	0.30	0.53	0.53
(N=38)	R^2	0.1218	0.7007	0.0000***	0.0665*	0.0007***	0.0007***
Ruhengeri	Correlation	-0.10	0.77	-0.39	0.58	0.87	0.84
(N=40)	P-value	0.5218	0.0000***	0.0135**	0.0001***	0.0000***	0.0000***
Farm 1	Correlation	0.54	0.90	0.95	-0.31	0.96	0.89
(N=15)	P-value	0.0543*	0.0000***	0.0000***	0.3021	0.0000***	0.0000***
Farm 2	Correlation	0.43	0.25	0.79	0.57	0.09	0.16
(N=15)	P-value	0.1072	0.3733	0.0004***	0.0250**	0.7444	0.5796
Farm 3	Correlation	0.49	0.76	0.48	0.22	0.78	0.74
(N=15)	P-value	0.0747*	0.0016***	0.0814*	0.4461	0.0009***	0.0027***
Farm 4	Correlation	0.66	0.63	0.69	0.13	0.88	0.88
(N=15)	P-value	0.0095***	0.0155**	0.0060***	0.6591	0.0000***	0.0000***
Farm 5	Correlation	-0.14	-0.24	-0.51	-0.06	-0.24	-0.13
(N=15)	P-value	0.6355	0.4144	0.0637*	0.8395	0.4184	0.6630

Table 5.7 (continued). Correlation between soil chemical data and total P contents in Butare, Kibungo, Ruhengeri and the 10 farms in Ntungamo.

Farm number	Statistics	pH_{H2O}	C_{tot} (%)	TRB ($cmolc.kg^{-1}$)	K_{exch} ($cmolc.kg^{-1}$)	Ca_{exch} ($cmolc.kg^{-1}$)	$(K+Ca+Mg)_{exch}$ ($cmolc.kg^{-1}$)
Farm 6	Correlation	0.32	0.07	0.99	0.35	0.18	0.23
(N=15)	P-value	0.2501	0.8160	0.0000***	0.2059	0.5219	0.4073
Farm 7	Correlation	0.84	0.59	0.75	0.65	0.71	0.81
(N=15)	P-value	0.0001***	0.0207**	0.0013***	0.0087***	0.0029***	0.0003***
Farm 8	Correlation	0.47	0.22	0.28	0.62	0.61	0.66
(N=15)	P-value	0.0742*	0.4331	0.3145	0.0146**	0.0147**	0.0077***
Farm 9	Correlation	-0.14	0.86	0.97	-0.12	0.01	-0.04
(N=15)	P-value	0.6129	0.0000***	0.0000***	0.6616	0.9723	0.9009
Farm 10	slope	0.89	0.41	0.95	0.71	0.97	0.96
(N=15)	P-value	0.0000***	0.1284	0.0000***	0.0032***	0.0000***	0.0000***

Table 5.8 (continued on next page). Relationships between soil chemical data (Y) and distance to homestead (X (in m)) for the ten farms studied in the Ntungamo area. Significance of the slope (t-statistics on the coefficients) is represented by stars: ***=P<0.01, **=P<0.05, *=P<0.1. Linear regressions are verified by scatterplots. Underlined slopes relate to linear relationships recognized as such after the visual check.

Farm number	Statistics	pH_{H2O}	C_{tot} (%)	P_{tot} ($mg.kg^{-1}$)	TRB ($cmolc.kg^{-1}$)	K_{exch} ($cmolc.kg^{-1}$)	Ca_{exch} ($cmolc.kg^{-1}$)	$(K+Ca+Mg)_{exch}$ ($cmolc.kg^{-1}$)
Farm 1	Slope	0.01	0.07***	77.76***	0.78***	-0.01	0.12***	0.15**
(N=15)	R^2	0.16	0.62	0.82	0.75	0.11	0.47	0.38
Farm 2	Slope	0.00	0.00	-0.78	-0.04	0.00	0.03	0.05
(N=15)	R^2	0.01	0.03	0.11	0.03	0.05	0.18	0.14
Farm 3	Slope	0.04***	0.05*	31.67***	0.56	0.01	0.18***	0.29***
(N=15)	R^2	0.67	0.22	0.63	0.12	0.08	0.71	0.69
Farm 4	Slope	0.00	0.00	0.26	0.07**	-0.01***	0.01*	0.01
(N=15)	R^2	0.07	0.11	0.03	0.33	0.73	0.22	0.02
Farm 5	Slope	0.00	-0.01	5.76***	-0.22**	0.00	-0.03**	-0.04**
(N=15)	R^2	0.12	0.19	0.81	0.34	0.14	0.34	0.29
Farm 6	Slope	-0.01	0.00	-14.06***	-0.88**	-0.01*	-0.01	-0.04
(N=15)	R^2	0.11	0.05	0.51	0.40	0.23	0.11	0.16

Table 5.8 (continued). Relationships between soil chemical data (Y) and distance to homestead (X (in m)) for the ten farms studied in the Ntungamo area. Significance of the slope (t-statistics on the coefficients) is represented by stars: ***=P<0.01, **=P<0.05, *=P<0.1. Linear regressions are verified by scatterplots. Underlined slopes relate to linear relationships recognized as such after the visual check.

Farm number	Statistics	pH_{H2O}	C_{tot} (%)	P_{tot} ($mg.kg^{-1}$)	TRB ($cmolc.kg^{-1}$)	K_{exch} ($cmolc.kg^{-1}$)	Ca_{exch} ($cmolc.kg^{-1}$)	$(K+Ca+Mg)_{exch}$ ($cmolc.kg^{-1}$)
Farm 7 (N=15)	Slope	-0.02***	-0.01	-4.09**	-0.14**	-0.03**	-0.03	-0.06**
	R^2	0.51	0.14	0.37	0.34	0.59	0.18	0.36
Farm 8 (N=15)	Slope	0.03***	-0.02***	0.32	-0.14***	0.00	0.04***	0.05**
	R^2	0.66	0.64	0.01	0.52	0.01	0.47	0.37
Farm 9 (N=15)	Slope	-0.03**	0.00	-2.56	-0.22	-0.02**	-0.04	-0.08*
	R^2	0.39	0.01	0.02	0.03	0.30	0.15	0.23
Farm 10 (N=15)	Slope	-0.06***	0.00	-7.06***	-0.33***	-0.04***	-0.09***	-0.16***
	R^2	0.61	0.00	0.53	0.58	0.44	0.42	0.52

Table 5.9. Mulch thicknesses in plots and subplots of variable potential in the different areas of interest to this study. Significance of mentioned statistical tests: ***=P<0.01, **=P<0.05. "ND" : not determined because of lack of data. Means for the Rwandan sites (Butare, Kibungo, Ruhengeri) are already published in Gaidashova et al. (2009); other data are new.

	Mulch thickness (cm) Mean ± 1SD
Plots A (N=15)	1.6±1.5
Plots B (N=15)	1.1±1.3
P-value for two sample *t*-test	0.3784
P-value for paired sample *t*-test (N=10)	0.1572
Plots A (N=20)	3.3±0.7
Plots B (N=18)	3.0±0.9
P-value for two sample *t*-test	0.2738
P-value for paired sample *t*-test (N=14)	0.1726
Plots A (N=20)	1.8±1.3
Plots B (N=20)	1.2±0.7
P-value for two sample *t*-test	0.0585
P-value for paired sample *t*-test (N=20)	0.0250***

	Mulch thickness (cm) Mean ± 1SD
Subplots A (N=8)	2.0±0.4
Subplots B (N=9)	2.1±0.6
P-value for two sample *t*-test	0.0.310**
P-value for paired sample *t*-test (N=2)	ND
Subplots A (N=31)	1.7±0.5
Subplots B (N=34)	1.7±0.5
P-value for two sample *t*-test	0.7574
P-value for paired sample *t*-test (N=5)	0.9390
Subplots A (N=16)	1.9±0.3
Subplots B (N=19)	1.4±0.5
P-value for two sample *t*-test	0.1157
P-value for paired sample *t*-test (N=3)	ND

5.4. Discussion

5.4.1. Phosphorus fractionation

A. Evaluation of the procedure by Tiessen and Moir (1993, Figure 5.2)

Precision of the data is verified by replicating 8 samples. While some P-fractions reproduce well, others show more variable results (Table 5.2). Variability is explained by choices made in this study and problems inherent to the fractionation scheme (or more generally to all sequential fractionation procedures).

Despite no significant ($P<0.05$) relationship is observed between variation coefficients and soil texture, it is noticed that three of the four replicates giving the more discordant results are samples having a coarse texture. The heterogeneity of coarse material and the use of unground samples influence precision. Another drawback of using unground material is the longer duration needed to attain equilibrium (Potter et al., 1991). The choice of unground samples over ground samples is justified by the demand to remain as close as possible to original soil situations. Lajtha and Schlesinger (1988) and Potter et al. (1991) report overestimations of more labile P forms in ground samples when comparing ground and unground material. The solution to avoid the drawbacks of grinding or not-grinding, is to increase the initial sample mass. Increasing sample mass as suggested by Potter et al. (1991) (1 to 5 g instead of 0.5 g) implies (1) either modification of the soil : solution ratio (2) either need to use larger flasks and possibly encounter practical problems (need of space, compatibility with centrifuge, difficulties to insure watertight sealing of larger flasks).

Another factor influencing the precision of P fractions, is the dependence of P quantities extracted upon the laboratory conditions (time, soil : solution-ratio, shaking time and speed, temperature) (Olsen et Sommers, 1982; Menon et al., 1988; Harris, 2002). While soil : solution ratio, shaking speed and temperature are held constant for all the samples, extraction time may have varied between 20 and 23 h because of practical difficulties when treating (filtrating) the samples.

A third factor influencing the precision is the huge number interventions during the procedure (details in Appendix 1) all along the sequential fractionation and the possible risks of losses or pollutions it induces. Total recovery varies between 61-157% (Figure 5.3).

The indirect determination of organic P may explain the imprecision when attempting quantification of organic P (Olsen and Sommers, 1982; Stevenson, 1982; O'Halloran, 1993; Condron et al., 2005). Indeed, Schoenau and Bettany (1987) and Tiessen and Moir (1993) mention that part of the organic P may not precipitate during the acidification step. Problems of hydrolysis of organic forms are normally avoided in the applied laboratory protocol (Potter et al., 1991).

Despite the imprecision on certain P-fractions, the results of this study remain pertinent, since the conclusions rely on the cumulated "labile", "moderately labile", "non labile" fractions and sum of fractions more than on the data for individual fractions. And data for the cumulated fractions vary far less than for fractions taken separately. The coefficients of variations vary between 0 and an exceptional 19% for the contribution of labile P to total P contents. They range between 1-15%, 0-8% and 2-9% for the moderately labile P, non-labile P and sum of fractions respectively (Table 5.2).

B. Fractions of P actually extracted

The natures of some extracted P-forms are hypothesized considering the correlations between P fractions and chemical or physical soil properties.

A recurrent positive relationship between C_{tot} and $NaHCO_3$-P_{tot}, $NaHCO_3$-P_i, NaOH-P_{tot} or NaOH-P_i is observed. Mengel and Kirby (2001) explain the positive relationship between organic carbon and phosphate adsorption by the formation of humate-Fe(Al)-P complexes reported by Gerke and Hermann (1992).

The results of this study show (1) significant ($P<0.05$) positive correlations between the contribution of residual-P to total P content and $Fe_2O_{3,tot}$, Fe_{DCB} or $\%wt_{kaolinite}$ and (2) significantly higher $HCl_{conc.}$-P and residual-P in the clayey and iron-rich Kibungo soils (Table 5.3). The results adhere to the descriptions commonly made in literature for $HCl_{conc.}$-P and residual-P: phosphate occluded under a ferric hydroxide skin (Mengel and Kirkby, 2001), phosphate occluded in iron oxides (Smeck, 1985) after diffusion beneath the adsorbing surfaces (Barrow, 1983; Bolan et al., 1985), organic matter physically protected in micro-aggregates (Smeck, 1985; Six et al., 2002).

C. Relative importance of the extracted fractions

The observed concentrations for the various fractions and the contributions of labile, moderately labile and non-labile fractions to total phosphorus contents for Butare, Kibungo, Ntungamo farms 1+3 and farms 2+4+5+7+8 are in the same ranges as those published for highly weathered tropical soils under various land-uses (Levy and Schlesinger, 1999 (review); Negassa and Leinweber, 2009 (review)). Contributions of labile, moderately labile and non-labile P to total phosphorus contents in Andosols resemble those reported by Paniagua et al. (1995) for volcanic soils in Costa Rica. Differences in total phosphorus contents and proportions of geochemical P fractions between old soils in Butare, Kibungo, Ntungamo 2+4+5+7+8, Ntungamo farms 6+9+10 and recent Andosols in Ruhengeri are explained by the difference in stage development (Smeck, 1973, 1985; Sharpley et al., 1987; Cross and Schlesinger, 1995). The same reason explains the high P contents and the high contributions of labile and moderately labile P in Ntungamo farms 1+3. Soils of farms 1+3 probably encounter rejuvenation because of erosion on the steep slopes of the hills they are developing on.

The sum of organic P determined in both $NaHCO_3$ and NaOH extracts account for 17-27% in the Ruhengeri soils (section 5.3.1.B, no Table). Those figures are similar to those of Paniagua et al. (1995) for volcanic soils in Costa Rica. In Butare, Kibungo, Ntungamo farms 2+4+5+7+8 and 6+9+10 the same fractions contribute for 0-14% to total phosphorus (section 5.3.1.B, no Table), which is far less than the 17-90% reported elsewhere for highly weathered tropical soils (Adeptu and Corey, 1976 *and references therein*; Sanchez, 1976; Sharpley et al., 1987; Sattell and Morris, 1992; Zech et al., 1997; Abekoe and Sahrawat, 2003). Bias induced by the indirect laboratory method when quantifying organic P in $NaHCO_3$ or NaOH may contribute to explain the low organic P contents observed (see section 5.4.1.B). Another reason is that part of the organic P of the soils of this study may be in more recalcitrant forms, as suggested by Hedley et al. (1982), Smeck (1985), Iyamuremye et al. (1996) or He et al. (2006 *cited in* Negassa and Leinweber, 2009). The organic fractions are not determined in the HCl1M, HCl_{conc} extracts or final digest of the Tiessen and Moir (1993) procedure.

5.4.2. Phosphorus quantities and forms highlight differential organic matter management

All the soils analyzed in this study come from banana-groves in banana-based farms. In those farms, phosphorus is returned to the soils through organic matter recycling (mostly banana residue). Nature of the soils is similar for all farms within the Butare, Kibungo and Ruhengeri areas. In Ntungamo, farms are subdivided in three groups (1+3, 2+4+5+7+8, 6+9+10) to conform to soil heterogeneity. Within a same region, climatic conditions are similar for all the farms. Tropical climatic conditions insure rapid mineralization of banana residue (Wortmann et al., 1994b; Lekasi et al., 2001; Yamaguchi and Araki, 2004) and rapid equilibrium between inputs and soils. Phosphorus liberated by mineralization is easily fixed by geochemical reactions and may transform in stable, plant unavailable forms (Sanchez, 1976; Walker and Syers, 1976; Smeck, 1985; Sharpley et al., 1987; *references in* Cross and Schlesinger, 1995; Tiessen, 2005). Losses through leaching are hence reduced, as are losses by erosion in these usually mulched systems with a permanent broad leaved canopy. Part of the phosphorus is exported with the harvested bunches (20-36% of all P accumulated in one banana-plant, Turner and Barkus, 1983b), but otherwise phosphorus accumulates in soil where it entered the soil. Same crop, same nature of recycled organic matter, same climate, limited losses and tendencies to accumulate with organic matter amendments, justify the choice of phosphorus as a tracer of cultural practices.

The higher P contents in surface samples as compared to deep samples (means 452-1647 vs. 238-652 $mg.kg^{-1}$, respectively (Ruhengeri not considered, no data for depth)), the higher contributions of labile P fractions (9-22% *vs.* 3-14%) and the lesser contributions of non-labile P (41-66% *vs.* 51-72%) to total phosphorus in surface samples (Table 5.3, Figure 5.5), underline the global influence of organic matter on P quantities and fractions. When considering lateral distributions, wide ranges of total phosphorus contents appear within surface samples of all regions or subregions (Table 5.6). Differences or tendencies emerge when comparing plots or subplots within a same farm. Total phosphorus contents and the more labile P-fractions are higher in A-plots than in B-plots in Butare farms (Table 5.4) or farm 9 in Ntungamo (Table 5.5). In Ruhengeri and Kibungo, total phosphorus contents (Table 5.6) and/or P fractions (Table 5.4) are not significantly ($P<0.05$) different.

Higher total P contents and/or higher contributions of the most labile fractions to total phosphorus contents indicate higher quantities of organic matter brought to A-plots as compared to the B-plots in Butare and Ntungamo farm 6+9+10. The absence of significant differences in total P contents and/or P fractions in A- and B-plots in Ruhengeri and Kibungo areas, would indicate more uniform management practices in those regions. Mulch thicknesses are significantly ($P<0.05$) different between A- and B-plots in Ntungamo farms 1+3 (two sample *t*-test, Table 5.9) and Ruhengeri (paired-sample *t*-test, Table 5.9). The absence of on-farm differences in mulch thickness when measured at one particular point in time does not mean that there never was differential management. Inversely, the presence of differences between A- and B-plots at one particular moment in time may be an exceptional situation in a usually uniform way of doing. Since phosphorus accumulates over time, the tracer has indeed a "memory" for present and past amendments. Banana-based farms are sometimes old. Farmers of Ntungamo estimate the ages of their farms between 21 and >100 years.

Quantities and forms of phosphorus are used elsewhere to highlight human activities. Archeologists recognize the sites of food preparation, organic refuse areas, kitchen gardens and amended cropland of century-old sites by the total phosphorus contents of soils (Eidt, 1977; Lippi, 1988; Lillios 1992; Parnell et al., 2002). To agronomists, high soil P levels are the indicators of the accumulation of biological residues (Tiessen, 2005). Patches of soils with high phosphorus contents in South Africa (Blackmore et al., 1990 *and references cited therein*; Fairhead and Leach, 2009) or Amazonia (Pre-columbian “Amazonian Dark Earths”, Sombroek, 1966; Lehmann et al. (eds), 2003; Glaser and Woods (eds.), 2004) are associated with anthropogenic soils. Human activities as crop cultivation crops, manuring or application of organic matter are recognized to modify soil P fractions towards an increased importance of more labile forms (Sharpley and Smith, 1985; Iyamuremye et al., 1996; Solomon and Lehmann, 2000; *references in* Negassa and Leinweber, 2009).

5.4.3. Management gradients parallel soil fertility gradients

Total phosphorus contents and relative fractions of P indicate that soils of the A-plots are (or have been) more amended with organic matter than are (or were) B-plots in the farms of Butare and Ntungamo farms 6+9+10. In Kibungo and Ruhengeri, management is (or was) more uniform. Phosphorus contents are positively correlated to other chemical properties usually called upon to describe soil fertility (pH, C_{tot}, TRB, K_{exch}, Ca_{exch} and $(K+Ca+Mg)_{exch}$ (Table 5.7)). The management gradient deduced from the phosphorus tracer thus parallels soil fertility gradients (Table 5.6) in Butare and Ntungamo farms 6+9+10. The comparisons of chemical data confirm the uniformity of soil fertility in Ruhengeri, Ntungamo farms 1+3 and 2+4+5+7+8 (Table 5.6). In Kibungo, paired-sample *t*-tests (Table 5.6) highlight a fertility gradient while phosphorus did not identify a management gradient.

Higher values for pH, TRB, exchangeable cations are attributed to amendments of organic matter (Prudencio, 1993; Giller et al., 1997; Baijukya and De Steenhuysen Piters, 1998; Haynes and Mokolobate, 2001; Bekunda and Manzi, 2003; Tittonell et al., 2005b; Zingore et al., 2007) and kitchen ashes (Ohno, 1992; Voundi Nkana et al., 1998; Demeyer et al., 2001; Mtambanengwe and Mapfumo, 2005; Rowe et al., 2006). Rowe et al. (2006) estimate at 5 to 10 years the duration for soil fertility gradients to install between unequally amended parts of maize fields in Zimbabwe. Mtambanengwe and Mapfumo (2005) observe slight differences in soil organic matter and fertility status between fields of a same farm after 20 years of differential management. Differences are accentuated with years of cultivation.

The Ntungamo sites allow verification whether the soil fertility gradient and soil management gradient are related to distance to homestead. The first image that comes to mind is indeed the often reported situation where plots close to homestead are more fertile and better managed than plots further away (Bekunda and Woomer, 1996; Giller et al, 1997; Wortmann and Kaizzi, 1998; Baijukya et de Steenhuijsen Piters, 1998; Tittonell et al., 2005b; Zingore et al., 2007; Okumu et al., 2011). In the Ntungamo area, things are not necessarily that simple. In farms 6, 9, 10 and less clearly in farm 7, values of fertility indicators decrease with distance from homestead. The tendency on these farms is the normal gradient already mentioned before. Farms 1 and 3 have inverse gradients: the parts furthest away from the homestead are most fertile. The farmers currently occupying the farms, indicate that they moved the location of the house when they acquired the property and that the parts furthest away from the present-day house were amended by the former owners. Farm 2 shows no gradient; all parts of the studied plot are equally poor. No clear tendency appears for farms 4, 5 and 8; isolated parts of the farm show higher values for the fertility indicators. Discussion with farmers elucidates some observations. Hence the fertile spot at the far end of farm 4 can be explained by the formerly presence of a brewery in that part of the plot. No such an explanations are available to explain the variations in soil fertility in farms 5 or 8.

5.4.4. Alternative procedures

Studies on archaeological sites (Eidt, 1977; Woods, 1977; Lillios, 1992) or on Amazonian Dark Earths (Lehmann et al., 2004) suggesting that chemical fractionation methods of phosphorus provide more reliable information on settlement history than total or available phosphorus contents, prompted us to apply a fractionation procedure in an exploratory attempt to understand past and present management practices in the African Great Lakes Region. Foregoing analysis proved that total phosphorus and its fractions could indeed be used as a tracer of human activities and that differences exist among studied soils. The comparisons of different soils and different soil depths also suggested that, in the end, only two indicators are of importance when trying to understand the human imprint on soils of the Great Lakes Region: the labile phosphorus fraction and the total phosphorus content. In areas were no fertilizer P is used, reliance on these two indicators could present simple alternatives to the laborious and expensive fractionation method, far too cumbersome to be a routine analysis. Recent amendments of organic matter could for instance be traced by (1) P extracted by anion exchange resins (Rubaek and Sibbesen, 1993; Myers et al., 2005) or iron oxide impregnated filter paper (Menon et al., 1988; Chardon et al., 2000; Myers et al., 2005), or (2) the $NaHCO_3$ extraction by Olsen et al. (1954, *cited in* Olsen and Somners, 1982) applicable to all soils having a pH superior to 5 (Pierzynski et al., 2005). Since labile P forms due to recent amendments are subfractions of the total P content, the total phosphorus content is another tracer of human activities.

5.5. Conclusions

The decision to use phosphorus as a tracer of cultural practices in farms of Butare, Kibungo, Ruhengeri and Ntungamo is justified because of

- the homogeneity of climate, soils, culture and amended organic matter within regions or subregions,
- the tendency of phosphorus to accumulate in soils, fixed by geochemical reactions,
- the rapid equilibrium between inputs and soils under tropical conditions,
- the reduced losses by leaching or erosion and export of only part of the phosphorus accumulated in plants.

Comparison of phosphorus in surface and deep soil samples, indicates that organic matter influences phosphorus in both total quantities and distribution of total phosphorus between labile, moderately labile and non-labile fractions. The input of organic matter increases total phosphorus contents and shifts distribution towards a larger proportion of the labile P fraction.

Differences in total phosphorus contents and contributions of labile and moderately labile P fractions do not only appear on a vertical transect. Indeed, differences may be significant between surface soil samples from a same region or subregion, and even between samples from different spots within a same farm. For the above-mentioned reasons, variations in total phosphorus contents and/or contributions of P-fractions in soil samples from a same farm may be interpreted in terms of differential allocation of organic matter within that farm, at present time or in the past history of the exploitation.

Differences in total phosphorus contents and P fractions in soil samples within farms of Butare and Ntungamo (at least in the farms 6+9+10), indicate that farmers allocate differentially the organic matter and kitchen ashes they gather. Other parameters related to organic matter and usually called upon as fertility indicators are influenced by this differential management. The plots or subplots of farms that show higher total P contents and/or higher contributions of labile P, have also higher pH_{H2O}, total carbon contents, TRB, exchangeable base cations and cation exchange capacity. The fertility gradient reflects the management gradient. The differential management often invoked to explain fertility gradients is hence confirmed as an explanation. The direction in which soil fertility varies within the present configuration of the farm (fertility increasing/decreasing with distance to homestead?) depends on present and past cultivation practices and on other activities taking place within the banana grove (beer brewing, for instance). The absence of differences in total phosphorus contents and P fractions, suggest uniform organic matter distributions in Kibungo and Ruhengeri. In Ruhengeri, uniformity of present and/or past organic matter distribution is confirmed by the absence of within-farm differences in values of the classical soil fertility indicators.

The phosphorus tool provides insights on the past and current organic matter management and on human imprint on soil fertility. This raises the question whether the contribution of this man-made fertility is of importance to the global soil fertility, or whether it is only a minor change against the inherent soil fertility. Understanding the influence of traditional management practices on soil fertility is a step forward when the question of sustainable management in low-input systems is raised. From a practicable point of view, routine extractions of labile P (anion exchange resins or similar, Olsen-extraction) or routine determination of total phosphorus content suffice to answer to the questions raised above for low-input systems and are, as such, alternatives to laborious and expensive chemical fractionation procedures.

6. Quantification of mineral phases in highly weathered soils by normative calculation compared to X-Ray Diffractometry

Abstract

Soil fertility is a key constraint to smallholder banana farmers in the East African highlands and use of external nutrient inputs is very limited. The impact of agriculture on soil quality and nutrient availability in the short and long term requires an understanding of the mineral composition of the soil. Pedogenetic processes and soil chemical weathering impact plant nutrient reservoirs and nutrient fluxes. Understanding these relationships requires a quantitative understanding of the soil minerals reserves. X-Ray Diffractometry (XRD) is commonly used as a tool for the identification of soil minerals. However, its ability to quantify mineral stocks is very limited because minerals deviate from their ideal chemical formulas and crystal structure. Furthermore, errors may occur during sample preparation and differential absorption by soil constituting minerals can be problematic when untangling the soil's mineral composition. In this study, we compared the XRD pattern fitting methodology of Rietveld (*SIROQUANT* software) against the less frequently used normative calculation where abundances of a series of ideal minerals are computed from chemical analysis. For this we adapted the CIPW norm developed in 1902 to include highly weathered tropical soils (Acrisols and Nitisols) composed of quartz, kaolinite, hematite, Ti-oxides (anatase, rutile), gibbsite, muscovite or sericite, vermiculite, K-feldspars (microcline, orthoclase), albite and, due to amendments by kitchen ashes, possible calcite. Applying both methods on (1) artificial samples of known composition, (2) fine earth samples (< 2000 µm) and

(3) soil textural subfractions (coarse particles > 2000 µm, sand (63-2000 µm), silt (2-63 µm), clay (<2 µm)), the normative calculation appears superior to XRD. This preference is explained by (1) the ease of calculation, (2) the time-saving compared to XRD, (3) the higher accuracy of the results when studying samples of known composition, (4) the coherence when studying fine earth samples *vs.* textural subfractions, and (5) the avoidance of errors on quantification because of grain size effects, preferred orientation, or differential absorption regularly observed with XRD. Disadvantages of the normative approach are that (1) computations of the abundances of K-feldspars and muscovite or sericite are related and depend on the distribution of potassium (K) between both minerals, and (2) gibbsite cannot be quantified when occurring in presence of kaolinite.

Keywords
Soil mineralogy; tropical soils; East-Central Africa; *SIROQUANT*; CIPW normative calculation

6.1. Introduction

The quantification of soil minerals is a key step when studying pedogenetic processes (Wilson, 1999; Mareschal et al., 2011), evaluating soil nutrient reservoirs (Andrist-Rangel et al., 2006, 2010; Barré et al., 2008) or considering chemical weathering (White et al., 1996) and nutrient fluxes (Sverdrup and Warfinge, 1988; Laclau et al., 2005).

X-Ray Diffractometry (XRD) is the most commonly used method to characterize qualitatively and quantitatively the mineral composition of soils (Weidler et al., 1998). Since its publication in 1967, the whole pattern fitting methodology of Rietveld (Rietveld, 1967, 1969) has proven to be a useful tool in quantifying mineral mixtures. The method generates a synthetic XRD pattern for each mineral constituting the multi-mineral sample, and this, considering crystal structure, diffraction optics and instrumental effects. To find the mineral abundances (%wt), the sum of the calculated patterns is fitted against the observed XRD profile of the sample by a non-linear least square iterative procedure (Weidler et al., 1998; Ward et al., 1999). *SIROQUANT* (Taylor, 1991) is a computer software that performs the XRD analysis according to the Rietveld methodology. The user can interact with the program to ask for refinement of the Rietveld parameters in order to obtain the best profile fit (Taylor and Hinczak, 2001). The XRD profiles of soil samples are difficult to refine because of variations in the diffractogram caused by deviations from the ideal chemical compositions, variations in crystallinity and lattice ordering, differential absorption of X-rays by various minerals and errors induced by sample preparation (preferred orientation and particle size effects) (Bish, 1994; Bish and Reynolds, 1989; Weidler et al., 1998; Ward et al., 1999; Alves and Omotoso, 2009).

Normative calculation of mineralogical compositions is an alternative to X-Ray Diffraction particularly when the associated quantitative interpretation of XRD proves difficult. The normative calculation requires a total chemical analysis of the sample and the qualitative knowledge of the minerals composing it. Through a formalized sequence of calculations allocating the major oxides to the expected minerals, the abundances of these minerals can be derived. Relying on the pioneering work of Cross, Iddings, Pirsson and Washington (Cross et al., 1902; Kelsey, 1965) or Niggli (Niggli, 1936; Burri, 1964) for igneous rocks, normative calculations are routine work in geology. Based on what has been done for long for magmatic rocks, the approach was adapted to extend its applicability to sedimentary rocks (Imbrie and Poldervaart, 1959; Nicholls, 1962; Metzner and Grimmeisen, 1990; Nyobe, 1991; Tarvainen et al., 1996; Ward et al., 1999; Srodon et al., 2001; Rosen and Abbyasov, 2003; Rosen et al., 2004; Posch and Kurz, 2007) and, more recently, to soils (Van der Plas and Schuylenborgh, 1970; Koljonen and Carlson, 1975; Voicu et al., 1997; Tarrah et al., 2000; Andrist-

Rangel et al., 2006; Posch and Kurz, 2007; Salminen et al., 2008; Mareschal et al., 2011).

In this study, we want to estimate the mineralogical compositions of highly weathered soils of different areas in Uganda, Rwanda and Burundi. This helps us to understand what nutrients are still available in the mineral component of the soil to better understand current and long-term fertility problems for smallholder banana growers. To achieve this, both (1) XRD-analysis and Rietveld refinement and (2) normative calculations, are performed on coarse particles (> 2000 µm), fine earth (< 2000 µm) and its sand (2000-63 µm), silt (2-63 µm) and clay (0-2 µm) fractions. The results obtained by both methods are compared and the methods further evaluated by applying them on artificial samples of known composition.

6.2. Materials and methods

6.2.1. Samples available for mineralogical analysis

A. Soil samples from Uganda, Rwanda and Burundi

The soil sampling campaigns in Ntungamo (South-West Uganda), Butare and Kibungo (Rwanda) were based on sites surveyed by Newton (2009) and Gaidashova et al. (2009). Both studies focused on the banana-production in smallholder farms. In those exploitations, crops are grown in intensively exploited banana-based systems by relying almost exclusively on traditional techniques (rudimentary tools, no machinery, no animal draft power, no or rare inorganic fertilizers) (Wortmann and Kaizzi, 1998; Clay et al., 2001; National Institute of Statistics of Rwanda, 2010). All crop-production is rain-fed.

A selection of the sites previously examined and considered as representative of their respective regions were revisited for the purpose of present study (Table 6.1). Respectively, 5, 2 and 3 farms were hence selected in the areas near Ntungamo, Butare and Kibungo. The opportunity also presented to visit the Burundian sites of Gaidashova (2009). A supplementary area known for its banana-based agriculture was thus added to this study: two farms nearby Gitega in Central Burundi were visited. The areas of interest to this study (here-after referred to by the names Ntungamo, Butare, Kibungo or Gitega) present differences in altitude (1530-1735 meters above sea-level), mean annual temperature is about 19°C and mean annual rainfall (900-1260 mm.year^{-1}) (Table 6.1). The rainfall has a bimodal distribution with rainy seasons occurring between March-May and September- December (Neel, 1983; FAO, 2005a). Soils develop on various parent materials, all of Mesoproterozoic age. Acrisols of Ntungamo form on micaschists or quartzites (Geological Survey of Uganda, 1961) and Acrisols of Butare on granites (Tahon et al., 1991). The parent materials to the Nitisols in the Kibungo area (Gérards et al., 1967) as for farm 1 in Gitega (Claessens and Theunissen, 1988) are pelitic meta-sediments. Soils of farm 2 in the Gitega area develop on granite (Claessens and Theunissen, 1988) (Table 6.1).

In all the farms, 1 to 3 pits (±1.5*1.5*1.5 m³) were excavated in the banana grove. The soil profiles at the foot of the banana-plants were described according to the FAO guidelines (FAO, 2006). Bulk soil samples were collected for each horizon of each profile. Deeper samples were recovered by augering. The soil samples were air-dried, softly ground and sieved to pass a 2 mm mesh. A selection of samples is treated further for the purpose of this study. 15, 17, 9, 10, 3, 30 and 23 samples from the various profiles in respectively Butare, Kibungo, Gitega farm 1, Gitega farm 2, Ntungamo farm 3, Ntungamo farms 2+7, Ntungamo farms 9+10, were retained for further analysis. Only 7 of the 56 samples from Ntungamo were considered.

Table 6.1. Characteristics of the agro-ecoregions of interest to this study.

Area	Farm number	Altitude (*masl*)	Mean annual rainfall (mm.year^{-1})	Mean annual temperature (°C)	Soil type
Ntungamo area (Butare village), SW Uganda			1100-1200 (*), wide variability between years 820-1300 (*)	16-20 (**)	Acrisol on
S 0°47’28’’/E 30°13’43’’	2	1540			micashist
S 0°47’15’’/E 30°13’51’’	3	1600			micashist
S 0°47’45’’/E 30°14’03’’	7	1560			micaschist
S 0°47’40’’/E 30°13’54’’	9	1555			quartzite
S 0°47’50’’/E 30°14’06’’	10	1555			quartzite
Butare area (Kikanga village), South Rwanda					Acrisol on
S 2°26’56’’/E 29°45’48’’	1	1729	1150-1260 (*)	18-21 (**)	granite
S 2°26’46’’/E 29°45’48’’	67	1735			granite
Kibungo area (Gatore village), East Rwanda					Nitisol on
S 2°16’25’’/E 30°35’34’’	32	1530	900-980 (*)	19-24 (**)	pelitic rocks
S 2°16’39’’/E 30°35’40’’	35	1543			pelitic rocks
S 2°16’15’’/E 30°36’42’’	38	1616			pelitic rocks
Gitega area (Gisuri village), central Burundi					Nitisol on
S 3°22’31’’/E 29°51’44’’	1	1658	1190 (*)	16-19 (**)	pelitic rocks
S 3°22’10’’/E 29°51’48’’	2	1645			Acrisol on granite

References: Location coordinates and altitudes were measured in the field (GPS). Soil type was ascribed in accordance with the FAO World Reference Base (IUSS, 2006). Other data were found in literature: (*) Roark and Dickson, 1986, *cited in* Byers (1990), Delepierre (1974, *cited in* Ndindahizi and Gwabije, 1991), Verdoodt and Van Ranst (2003), Smithson et al. (2004), FAO (2005b), Bouwmeester et al. (2009), Nyombi et al. (2009), Gaidashova et al. (2009), van Asten et al. (2011), Institut des Sciences agronomiques du Rwanda (online, http://www.isar.rw, (ISAR) web site, accessed on October 12th 2010). (**) FAO (2005b), Gaidashova et al. (2009). “m*asl*” stands for meters above sea-level.

On the selected samples from Butare, Kibungo, Gitega and part of those of Ntungamo, particle size distribution was determined at UCL (Louvain-la-Neuve, Belgium). Sand (63-2000 µm), silt (2-63 µm) and clay (0-2 µm) fractions were obtained through ultrasonic dispersion, sieving and prolonged dispersion with Na^{+}-resins (Rouiller et al., 1972), without preliminary destruction of organic matter. Grain size distribution was expressed as percentages (%, $g.100g^{-1}$).

B. Artificial samples of known composition

Based on the first qualitative and quantitative results concerning the mineralogical composition of the soil samples, fifteen artificial multi-mineral samples were constituted by mixing known quantities of pure mineral phases or, by default, phases of known chemical composition. Anatase, chlorite, albite, illite, hematite, kaolinite and gibbsite were available in fine powders. Powder of perthitic orthoclase and quartz were obtained by manual grinding. The purity or nature of the test minerals was verified by total chemical analysis and by acquisition of XRD-patterns of their powders. Both procedures are detailed below (section 6.2.3.A). The quantities of anatase, chlorite, albite, illite, pertitic orthoclase, hematite, kaolinite, gibbsite and quartz were added on a dry weight basis (105°C) to obtain the compositions (weight percentages, %wt) detailed in Table 6.2. Hand grinding the mineral mixtures with an agate mortar and pestle, was a first step towards the homogenization of the samples. Transferred to 20 ml glass scintillation vials, the constituted samples were placed on a dry powder reciprocal rotator (drive bar at 20°) for 4 (samples # 10-15) to 14 h (samples # 1-9) to insure a more thorough mixing. Hand grinding the mix once again afterwards constituted the final step of the homogenization-process. All samples contained hematite. The red color this mineral conferred to the mix, allowed visual appraisal of the homogeneity of the sample when smearing in out into an agate mortar.

Table 6.2. Composition (%wt) of the artificial samples constituted by the mixing of known quantities of pure mineral phases.

Mineral / Sample	Anatase (%wt)	Chlorite (%wt)	Albite (%wt)	Illite (%wt)	Orthoclase (%wt)	Hema-tite (%wt)	Kaolinite (%wt)	Gibbsite (%wt)	Quartz (%wt)
Origin of mineral	Un-known	Un-known	Un-known	Un-known	Unknown	Un-known	Zettlitz-KSB	Alcoa Inc.	Fontaine-bleau sand
#1	1.5	0.0	0.0	0.0	0.0	8.0	85.0	0.0	5.5
#2	2.0	0.0	0.0	0.0	0.0	15.0	83.0	0.0	0.0
#3	1.0	0.5	0.0	19.5	0.0	10.0	65.0	0.0	4.0
#4	2.0	0.0	2.0	1.0	5.0	2.0	6.0	0.0	82.0
#5	5.0	0.0	2.5	5.0	0.0	7.5	20.0	0.0	60.0
#6	2.0	0.0	0.0	10.0	0.0	3.0	18.0	0.0	67.0
#7	1.0	0.0	0.5	3.0	0.5	2.0	15.0	0.0	78.0
#8	2.0	0.0	0.0	0.0	1.0	12.0	71.0	4.0	10.0
#9	1.0	0.0	0.0	15.0	2.0	1.0	15.0	0.0	66.0
#10	0.5	0.5	0.0	0.0	1.5	5.5	0.0	0.5	91.5
#11	1.5	1.0	0.0	0.0	2.5	4.5	0.0	1.0	89.5
#12	2.5	2.0	0.0	0.0	3.3	3.5	0.0	1.5	87.2
#13	3.0	0.0	3.3	2.5	0.0	2.5	0.0	2.0	86.7
#14	4.0	0.0	1.5	1.5	0.0	1.5	0.0	3.0	88.5
#15	5.0	0.0	1.0	0.5	0.0	0.5	0.0	5.0	88.0

6.2.2. Mineralogical analysis by X-Ray Diffractometry

A. Identification of clay minerals relying on oriented mounts of the <2µm fraction

To identify clay minerals, fractions of the clay/water-suspensions obtained after textural analysis, underwent particular preparations. Aliquots of the clay/water-suspensions were transferred to centrifugation tubes and saturated with K or Mg using 1M KCl or 0.5M $MgCl_2$ solutions. After washing it free of the excess salt with methanol, the clay was left to dry at air. Once dry, the clay was wetted by adding a little water. Ultrasonication insured disruption of the aggregates and preparation of a homogeneous suspension. The suspension was extracted with a pipette and transferred to clean microscope glass slides resting on a level surface. The suspensions were allowed to dry before XRD analysis. The glass slides containing the K-saturated dry clay were analyzed by XRD after (1) air-drying at room temperature, (2) heating at 105°C, (3) 300°C and (4) 550°C. The glass slides containing the Mg-saturated dry clay samples were analyzed by XRD after (1) air-drying at room temperature, (2) ethylene glycol solvation, (3) spraying with an aerosol of formamide.

The diffraction patterns of the oriented mounts were collected on a Bruker D8 Advance (Bruker AXS, Madison, WI) diffractometer equipped with 9 position sampler, a theta-theta (θ-θ) goniometer and a Peltier cooled energy dispersive scintillation detector (SOL-X). The goniometer settings were 1 mm divergence slit, 1 mm antiscatter slit and 0.6 mm receiving slit. Cu Kα radiation (λ= 1.5418 Å) was used with 40 kV and 30 mA. With a 1.0 s per 0.0150°2θ step size, total scan time was 31 minutes to cover the scan range of 2 to 30°2θ. Rotation of the sample was allowed. For one clay sample, the various XRD patterns obtained because of the different treatments are superposed, compared and interpreted according to the indications of Dixon et al. (1977), Brindley and Brown (1980), Churchman et al. (1984), Theng et al. (1984), Whittig and Allardice (1986), Chamayou and Legros (1989), Velde (1992) and Dixon and Schulze (2002).

B. Identification and quantification of mineral phases by XRD and Rietveld refinement

The preparation of powder samples for X-Ray Diffractometry, the qualitative identification and quantitative evaluation of the minerals constituting them are described in the section below. We analyzed (1) fine earth samples (< 2000 µm) and (2) the soil's textural sub-fractions (coarse particles (> 2000 µm), sand, silt and clay), to (3) the pure mineral phases and (4) the artificial samples made up by mixing them. To obtain a dry powder for the clay subfraction, part of the clay/water-suspensions obtained after textural analysis, was dried at 60°C in a hot water bath. The dried clay aggregates were disrupted using an agate mortar and pestle.

All materials were (< 50 µm) ground by hand in an agate mortar. The filling of XRD front-loading sample holders with the dry, ground powders was performed with care to avoid preferred orientation of minerals. The powder, in large excess relatively to the place in the sample holder, was deposited in the circular (diameter = 25 mm; depth = 2 mm; grooves on the bottom surface) sample holder. The powder was distributed in the holder by vigorously tapping it against the table surface, then by gently pressing the powder. To produce a flat surface, the excess material was removed by cutting it away using a razor-blade. Saw-like movements were exerted when manipulating the blade.

The diffraction patterns were collected on the diffractometer specified in section 6.2.2.A. Differences in settings compared to the acquisition of the patterns on the oriented mounts, resided in the use of a 0.2 mm receiving slit, a 2.0 s per 0.0150°2θ step size and a scan range between 2 and 90°2θ (total scan duration: 3h15min). No rotation of the sample was allowed to avoid the movement of particles during analysis because of the vibrations caused by the X-Ray Diffractometer. Not allowing rotation induces opposite effects on the quality of the acquired pattern. It reduces the background scatter, on one hand, but reduces the quality by diminishing the probability to find crystals that lie at a correct θ-angle for a diffraction peak to be formed from a given crystal reflecting plane. The qualitative interpretation of the XRD-patterns obtained was done by the EVA software package EAA2 (SOCABIM, France, 1996-2000), a program contained in the Bruker software package Diffrac^{plus} V.2.4.1 (2005). Using the same XRD pattern as for the qualitative analysis, the quantification of the mineralogical composition of samples was performed on the *SIROQUANT* V.2.5 (SIETRONICS, Australia, 2000) software. For each mineral present, except kaolinite, a Rietveld-format XRD data-file (.hkl) was prepared from the collection of crystal structures in the *SIROQUANT* standard database. For kaolinite an hkl-file was selected in the *SIROQUANT* Clay Package. A task-file was set up to detail the input data: the XRD pattern (.raw) to be analyzed, the minerals being present, and the hkl-files to rely upon in the analysis. A linear curve was fitted to the points graphically selected to represent the background. Analysis of the background-free trace was done by stepwise refinement of scale factors, instrumental zero, unit cell dimensions, halfwidth and preferred orientation parameters, following the recommendations of Taylor and Hinczak (2001). Preferred orientation was tested for kaolinite, chlorite, muscovite and feldspars but only maintained if it contributed to the amelioration of the fit. The overall goodness of fit between the computed and observed profiles was indicated by a chi-square (χ^2) value. The final output of a task in *SIROQUANT* is the fit between the observed and the calculated XRD-patterns (Figure 6.1), associated chi-square value, the weight percentages and the associated errors for every mineral composing the sample. The error was evaluated by *SIROQUANT* from the estimated standard deviation (ESD) of the relevant Rietveld factor.

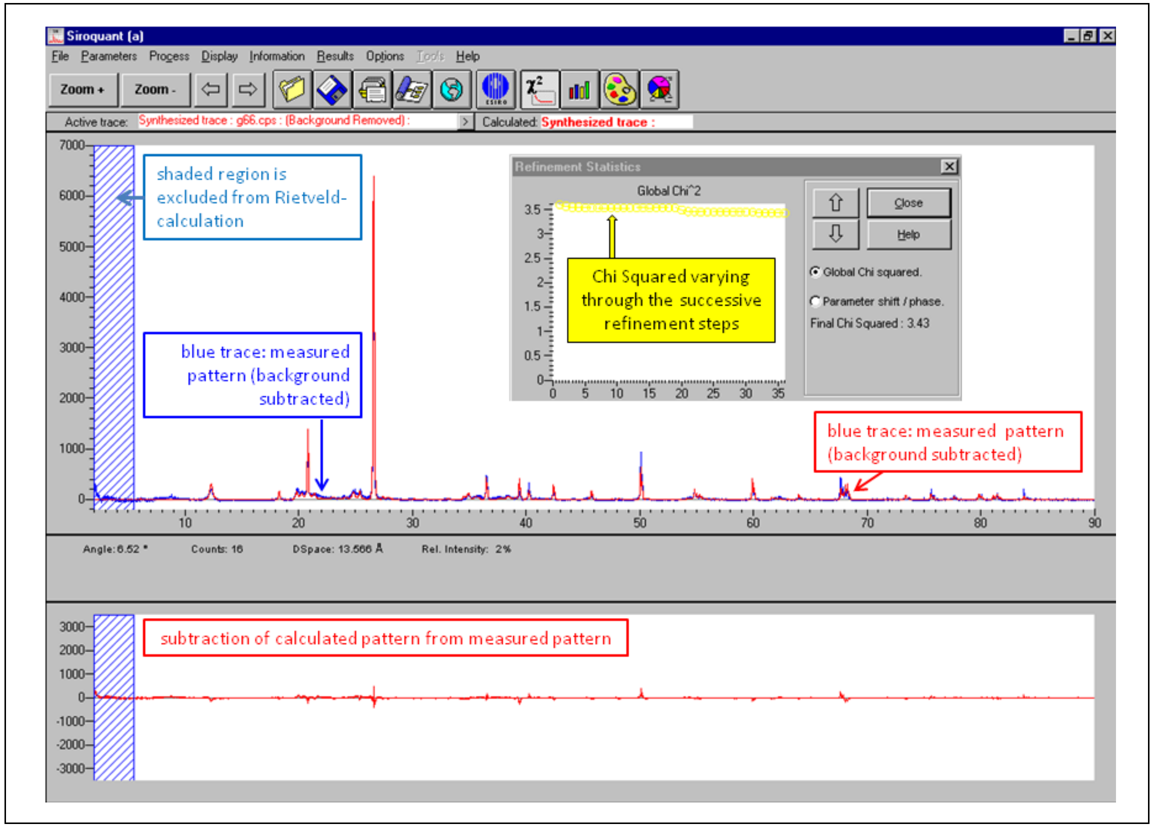

Figure 6.1. Example of the output by *SIROQUANT* when trying to quantify the mineralogical composition of one fine earth sample from Gitega farm 2.

Total error for each mineral percentage can be assessed by multiplying ESD with the square root of the global chi-square value of the analysis (Ward et al., 1999; Ruan and Ward, 2002).

6.2.3. Chemical analyses and normative calculation

All chemical analyses were done at UCL (Louvain-la-Neuve, Belgium). Total chemical analysis was a prerequisite for all normative calculation, both on fine earth samples or soil's textural sub-fractions as on isolate mineral phases or on artificial samples. Additional chemical analyses were performed on fine earth samples in order to refine and adapt the normative calculation.

A. Total chemical analysis

For total chemical analysis all samples were ground (<50 µm) by hand and mineralized at 950°C for 72 h. The choice of the method for total chemical analysis depended on the expected SiO_2 content of the samples.

Total chemical analyses on fine earth samples (< 2000 µm), silt, isolate mineral phases (except anatase and quartz) and artificial mixtures, were performed by digesting the ground mineralized powder in a mixture of lithium tetra- and metaborate at 950°C. The cooled digestion beads were dissolved in hot (100°C) 2M nitric acid (Chao and Sanzolone, 1992). Clay fractions underwent the same tetra-/metaborate digestion, but needed saturation with Sr prior to chemical digestion. Elemental (Si, Al, Fe, Mn, Mg, Ca, Na, K, Ti, P and for clay samples: Sr) contents in 2M HNO_3 were determined by inductively coupled plasma – atomic emission spectrometry (ICP-AES).

- Quantification of mineral phases by normative calculation and XRD -

Samples where quartz was the sole or quasi exclusive mineral phase (pure quartz sample, coarse particles (> 2000 µm) and sand fractions) were digested in a mix of hot concentrated acids (HNO_3, HF and $HClO_4$). The digest was recovered by concentrated HNO_3 and HCl at 130°C (Voïnovitch, 1988; Sahwney and Stilwell, 1994). Elemental (Si, Al, Fe, Mn, Mg, Ca, Na, K, Ti, P) contents in the acid mix were determined by ICP-AES.

Elemental contents were expressed as percentages of respective oxides in their most common form (SiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, TiO_2, P_2O_5). All data were expressed against dry soil weight (105°C).

B. Additional chemical analysis on fine earth samples (< 2000 µm)

pH was measured in a 1 : 5 soil : water-suspension after 1 hour of contact.

Iron oxide content and crystallinity of the oxides in the fine earth soil samples were evaluated by dark oxalate and Dithionite-Citrate-Bicarbonate (DCB) extractions according to, respectively, the Blakemore et al. (1981) and Mehra and Jackson (1960) procedures. Fe and Al contents in the extracts were determined by ICP-AES. Data were expressed against dry soil weight (105°C).

To evaluate the non-mineral K, Na, Ca and Mg, fine earth soil samples (< 2000 µm) were extracted with 0.5M $CuCl_2$ (initial pH=3) according to the procedure advocated by Juo and Kamprath (1979) and Aitken (1992) for aluminum. An extraction with 1M ammonium acetate buffered at pH7, was performed, in parallel and under the same conditions, on another subsample of the same fine earth. The procedure, for both $CuCl_2$ and ammonium acetate, consisted in a 16 h contact between 3 g of fine earth (< 2000 µm) and 30 ml of solution, under continuous reciprocal horizontal shaking. K, Na, Ca and Mg contents in the extractant solutions were determined by atomic absorption spectrophotometry (AAS). Data were expressed against dry soil weight (105°C).

C. Sequence of computations in the normative calculation procedure

Outline of the procedure

A spreadsheet allowed calculation of mineralogical compositions (%wt) when supplying elemental compositions determined by total chemical analysis, loss on ignition (LOI, %) and specification of the minerals present in the samples, as input data. Ti-oxides (rutile and/or anatase), vermiculite or chlorite, albite, a micaceous component (illite or muscovite or sericite), K-feldspar (microcline and/or orthoclase), hematite, kaolinite, gibbsite and quartz were integrated in the calculation scheme detailed below (Table 6.3). No Mn, Ca or P minerals were identified in the XRD-patterns. Occasional carbonates (calcite) were nevertheless suspected in soil samples having pH_{H2O} superior to 7, probably amended with kitchen ashes. Except maybe in the shallow soils on micaschist in the Ntungamo region, phosphate minerals were considered absent in view of the results of Chapter 6. As in the calculation procedures proposed by others (Tarrah et al., 2000), MnO and P_2O_5 were systematically neglected.

To calculate mineral abundances form oxide weight percentages, standard chemical formulas were adopted for the various minerals present (Table 6.3). The selected formulas were found in reference manuals for mineralogy (Deer et al., 1992; Klein and Hurlbut, 1999) or a theoretical paper on clays (Garrels, 1984). The formulas were reinterpreted in terms of contributions of LOI and elemental oxides, to the global formula of the mineral ([mol/mol x 100]). For each mineral, one chemical element was indicated as the “control” element. It is an element that characterizes the mineral and that limits the abundance calculated for that mineral. When there is no more of the control element, no more of the associated mineral could be created.

When a mineral was present in a sample, its amount was calculated as the difference between (1) a former sum of LOI and oxide percentages and (2) a newly calculated sum of LOI and oxide percentages. The newly calculated sum was computed from the former sum, by subtracting the oxide percentages attributed to the considered mineral. Oxide percentages were attributed to a mineral by the rules in equation 1 ([eq.1]):

$$SiO_{2,new} = SiO_{2,former} - \left[\left(\begin{array}{c}\text{\%oxide of control}\\ \text{element yet available}\\ \text{in present sample}\end{array}\right) \text{ x } \left(\frac{\begin{array}{c}\text{contribution of } SiO_2\\ \text{to the global formula of mineral}\end{array}}{\begin{array}{c}\text{contribution of oxide of control}\\ \text{element to the global formula of mineral}\end{array}}\right)\right]$$

$$Al_2O_{3,new} = Al_2\,O_{3,former} - \left[\left(\begin{array}{c}\text{\%oxide of control}\\ \text{element yet available}\\ \text{in present sample}\end{array}\right) \text{ x } \left(\frac{\begin{array}{c}\text{contribution of } Al_2O_3\\ \text{to the global formula of mineral}\end{array}}{\begin{array}{c}\text{contribution of oxide of control}\\ \text{element to the global formula of mineral}\end{array}}\right)\right]$$

$$\vdots$$

$$LOI_{new} = LOI_{former} - \left[\left(\begin{array}{c}\text{\%oxide of control}\\ \text{element yet available}\\ \text{in present sample}\end{array}\right) \text{ x } \left(\frac{\begin{array}{c}\text{contribution of LOI}\\ \text{to the global formula of mineral}\end{array}}{\begin{array}{c}\text{contribution of oxide of control}\\ \text{element to the global formula of mineral}\end{array}}\right)\right]$$

[eq. 1]

Table 6.3 (continued on next page). Normative calculation: sequence of steps and assumed structural formulas of the minerals.

Step	Ct. el.	Fraction of elemental oxides used for calculation		Mineral	Assumed formula
		Basic calculation	Adapted calculation		
1	Ti	$TiO_{2,tot}$ (%)	$TiO_{2,tot}$ (%)	Ti-oxides (anatase, rutile)	TiO_2
2a	Mg	MgO_{tot} (%), CaO_{tot} (%), $Fe_2O_{3,tot}$ (%)	MgO_{min} (%), CaO_{min} (%), $Fe_2O_{3,aluminosilicates}$	Vermiculite	$(Mg_{0.3}Ca_{0.3})(Mg_{4.7}Fe_{0.65}Al_{0.65})(Al_{2.4}Si_{5.6})O_{20}(OH)_4.8H_2O$ (Deer et al., 1992)
2b	Mg	MgO_{tot} (%), $Fe_2O_{3,tot}$ (%)	MgO_{min} (%), $Fe_2O_{3,aluminosilicates}$ (%)	Chlorite	$(Mg_{0.73}Fe_{4.27}Al)(AlSi_3)O_{10}(OH)_8$ (Deer et al., 1992)
3	Ca	CaO_{tot} (%)	CaO_{min} (%)	Calcite	$CaCO_3$ (when $pH_{H2O} > 7$)
4	Na	Na_2O_{tot} (%)	Na_2O_{min} (%)	Albite	$NaAlSi_3O_8$
5a	K	α x K_2O_{tot} (%), MgO_{tot} (%), $Fe_2O_{3,tot}$ (%)	α x K_2O_{min} (%), MgO_{min} (%), $Fe_2O_{3,aluminosilicates}$(%)	Illite	$(K_{0.8}, (H_3O)_{0.2})(Al_{1.5}Fe_{0.25}Mg_{0.25})(Al_{0.5}Si_{3.5})O_{10}(OH)_2$ (Garrels, 1984)
5b	K	α x K_2O_{tot} (%)	α x K_2O_{min} (%)	Muscovite, sericite	$KAl_2(AlSi_3O_{10})(OH)_2$
5c	K	(1-α) x K_2O_{tot} (%)	(1-α) x K_2O_{min} (%)	K-feldspar (microcline, orthoclase)	$KAlSi_3O_8$

Table 6.3 (continued). Normative calculation: sequence of steps and assumed structural formulas of the minerals.

Step	Ct. el.	Fraction of elemental oxides used for calculation		Mineral	Assumed formula
		Basic calculation	Adapted calculation		
6	Fe	$Fe_2O_{3,tot}$ (%)	$Fe_2O_{3,cryst.ox.}$ (%), $Al_2O_{3,cryst.ox}$ (%)	Hematite	In basic calculation: Fe_2O_3 In adapted calculation ([eq.3]): $(Al_{2x}Fe_{2-2x})O_3$ where $x=Al_{cryst.ox}/(Al_{cryst.ox}+Fe_{cryst.ox})$ [mol/mol] ≤ 0.18
7a	Al	$Al_2O_{3,tot}$ (%)	$Al_2O_{3,alumniosilicates}$ (%)	Kaolinite	$Al_2Si_2O_5(OH)_4$
7b	Al	$Al_2O_{3,tot}$ (%)	$Al_2O_{3,aluminosilicates}$ (%)	Gibbsite	$Al(OH)_3$
8	Si	$SiO_{2,tot}$ (%)	$SiO_{2,tot}$ (%)	Quartz	SiO_2

Ct. el. = Control element. In steps 5a,b,c : $\alpha = 2 \times (CIA-50)/100$ (Voicu et al., 1997) where CIA is the Chemical Index of Alteration $CIA = [Al_2O_3 / (Al_2O_3 + CaO + Na_2O + K_2O)] \times 100$ (see [eq.5]) Nesbitt and Young, 1982; Fedo et al., 1995; Price and Velbel, 2003). $(oxide)_{tot}$, $(oxide)_{min}$, $(oxide)_{aluminosilicates}$, $(oxide)_{cryst.ox.}$ represent the total elemental oxide contents or its subfractions attributed to, respectively, minerals (see [eq.4]), aluminosilicates and crystalline iron oxides (see [eq.2]). LOI = loss on ignition.

During the calculation, no negative values for either elemental oxides or LOI were allowed.

Particularities of the calculation procedure

1. The basic normative calculation can be refined and adapted if additional chemical data are available.

Herein, Fe_2O_3 and Al_2O_3 were more precisely distributed between aluminosilicates and crystalline oxides by submitting the fine earth samples to extraction by oxalate and Dithionite-Citrate-Bicarbonate (DCB) (Campbell and Schwertmann, 1984; Jeanroy et al., 1984; Darke and Walbridge, 1994; Poresbska and Mulder, 1996; Huang et al., 2002; Garcia-Rodeja et al., 2004). In the adapted normative calculation scheme (Table 6.3), the following subdivisions in $Al_2O_{3,tot}$ and $Fe_2O_{3,tot}$ contents were made ([eq.2]):

Fraction of $Fe_2O_{3,tot}$ (%wt) attributed to crystalline Al-hematite:

$$\mathrm{Fe_2O_{3,cryst.ox.}(\%wt) = Fe_2O_{3,DCB} - Fe_2O_{3,oxalate}}$$

Fraction of $Fe_2O_{3,tot}$ (%wt) allocated to aluminosilicates:

$$\mathrm{Fe_2O_{3,aluminosilicates}(\%wt) = Fe_2O_{3,tot} - Fe_2O_{3,DCB}}$$

Fraction of $Al_2O_{3,tot}$ (%wt) attributed to crystalline Al-hematite:

$$\mathrm{Al_2O_{3,cryst.ox.}(\%wt) = Al_2O_{3,DCB} - Al_2O_{3,oxalate}}$$

Fraction of $Al_2O_{3,tot}$ (%wt) allocated to aluminosilicates:

$$\mathrm{Al_2O_{3,aluminosilicates}(\%wt) = Al_2O_{3,tot} - Al_2O_{3,DCB}}$$

[eq.2]

The formula of hematite is adapted to account for the possible Al-substitution in its structure ([eq.3]):

$$\text{formula for Al substituted hematite}: (Al_{2x}Fe_{2-2x})O_3$$

$$\text{where } x = \frac{Al_2O_{3,cryst.ox.}}{Fe_2O_{3,cryst.ox.} + Al_2O_{3,cryst.ox.}} \left[\text{units: } \frac{mol}{mol}\right] \leq 0.18$$

[eq. 3]

Cu^{2+} cations have a high affinity for the exchange sites on organic matter (Juo and Kamprath, 1979; Stevenson, 1982; Oates and Kamprath, 1983). $CuCl_2$ is classically used to extract exchangeable and weakly organically bound Al (Porebska and Mulder, 1996; Drabek et al., 2003). In here, $CuCl_2$ (pH3) was called upon to extract exchangeable Na, K, Ca, Mg and organically bound Ca and Mg. Hence, in the adapted normative calculation procedure (Table 6.3), the fractions of Na_2O_{tot}, K_2O_{tot}, CaO_{tot} and MgO_{tot} effectively attributed to minerals were ([eq.4]):

$$Na_2O_{min}(\%wt) = Na_2O_{tot} - Na_2O_{CuCl2} \quad ; \quad K_2O_{min}(\%wt) = K_2O_{tot} - K_2O_{CuCl2}$$

$$CaO_{min}(\%wt) = CaO_{tot} - CaO_{CuCl2} \quad ; \quad MgO_{min}(\%wt) = MgO_{tot} - MgO_{CuCl2}$$

[eq. 4]

In this study, the adapted calculation was used when computing the mineralogical composition of fine earth samples (Table 6.3). The mineralogical compositions of coarse particles (> 2000 µm), sand (2000-63 µm), silt (63-2 µm) and clay (2-0 µm) subfractions were calculated through the basic calculation procedure (Table 6.3).

2. When gibbsite and kaolinite were simultaneously present in a same sample, the procedure did not allow distinction of the Al_2O_3 allocated to kaolinite and the Al_2O_3 attributed to Al-oxides. In this case all Al_2O_3 is conferred to kaolinite and gibbsite is not considered further.

3. K_2O was allocated to either a micaceous component (muscovite, illite, sericite) or K-feldspar through the mineralogical index of alteration (α) of Voicu et al. (1997).

The fractions attributed

- to the micaceous component were : ($\alpha \times K_2O_{tot}$) or ($\alpha \times K_2O_{min}$) (step 5.b in Table 6.3).

- to K-feldspars were : ($(1-\alpha) \times K_2O_{tot}$) or ($(1-\alpha) \times K_2O_{min}$) (step 5.c in Table 6.3).

where K_2O_{tot} is the total K_2O,
K_2O_{min} is the K_2O content specifically attributed to minerals ([eq.4]).

The calculation of the Mineralogical Index of Alteration α implied the Chemical Index of Alteration (CIA) of Nesbitt and Young (1982), Fedo et al. (1995), Kim and Park (2003), Price and Velbel (2003) ([eq.5]). CIA values range practically between 50 and 100 and measure the extent of the conversion of feldspars to clays during pedogenetic weathering (Nesbitt and Young, 1982) or metasomatic alteration (Fedo et al., 1995). The

Mineralogical Index of Alteration (α) is a modification of CIA, allowing its incorporation in normative calculation. The Mineralogical Index of Alteration α evaluates the transformation ratio of a primary mineral into its equivalent weathering mineral. For K-bearing minerals, the primary mineral / weathering mineral pair comprises orthoclase and sericite (Voicu et al., 1997). By using the mineralogical index of alteration (α) in the calculation procedure detailed here, we did not want to imply that there was any filiation between K-feldspar and muscovite or illite. It was solely a circumvented way to evaluate what maximum fraction of K_2O to allocate to K-feldspars under the degree of weathering estimated by CIA.

$$\text{Mineralogical Index of Alteration}, \alpha = 2 \text{ x } (\text{CIA} - 50)/100$$

$$\text{where Chemical Index of Alteration, CIA} = \left[\frac{\text{Al}_2\text{O}_3^*}{\text{Al}_2\text{O}_3^* + \text{CaO}^* + \text{Na}_2\text{O}^* + \text{K}_2\text{O}^*}\right] \text{ x } 100$$

$$[\text{eq. } 5]$$

in which Al_2O_3^*, CaO^*, Na_2O^* and K_2O^* are

- in the basic normative calculation: the total elemental contents (%wt) determined for the samples. Here-after they are referred to by $Al_2O_{3,tot}$, CaO_{tot}, Na_2O_{tot} and K_2O_{tot}.

- in the adapted calculation (see below, point 3 of present section): Al_2O_3^* is the total Al content (%wt) determined for the sample ($Al_2O_{3,tot}$), and CaO^*, Na_2O^* and K_2O^* are the contents specifically attributed to minerals ([eq.4], CaO_{min}, Na_2O_{min}, K_2O_{min}).

6.2.4. Computer software

All calculations were performed in *Microsoft Office Excel 2007*. Statistical tests were carried out in *MATLAB 7.4.0 (R2007a)*. Graphs were drawn in either *Excel* or *MATLAB*.

6.3. Results

6.3.1. Some physical and chemical characteristics of soil samples and artificial mixtures

A. Soil samples

Texture and constituting minerals

The triangular plots in Figure 6.2 summarize the soil texture established on fine earth (< 2000 µm) samples from the different regions of interest. Inside a same triangular plot, the sizes of the symbols change to highlight textural variation with depth. In all the regions the clay fraction increases with depth. According to the USDA textural classification, soils of Butare are sandy clay or sandy clay loams becoming clays at depth. Coarse particles (> 2000 µm) constitute 7-38 % of the bulk soil samples of surface horizons (0-50cm). In deeper horizons the coarse fraction (> 2000 µm) represents only 1-2 %. Kibungo soils are clayey; the gravelly fraction is as good as non-existent. Soils of farm 1 in Gitega are sandy clays, becoming clays in deeper horizons. The gravel (> 2000 µm) content varies widely: between 0 and 50 % depending on depth in the soil profile. The soils of Gitega farm 2 are sandy clays, becoming slightly more clayey at depth. The coarse fraction (> 2000 µm) represents a relative constant 0-2 % of bulk soil samples and increases (10 %) only at 2m depth. Soils of Ntungamo are heterogeneous. Soils of farm 3 develop on steep slopes, the parent micaschists are encountered at less than 1 m depth. Soils are very gravelly: coarse fragments (> 2000 µm) represent 55 % of the bulk soil sample. Fine earth (< 2000 µm) is sandy clay loam. In farms 2+7, deep soils formed on micaschists. Coarse particles represent 2-5 % of the bulk soil samples to 2.5 m depth, where the coarse fraction increases to 15%. Fine earth (< 2000 µm) is sandy clay loam becoming clay loam below 50 cm depth. In farms 9+10, the fraction superior to 2000 µm accounts for 5-10 % of the bulk soil sample. Four of the 6 profiles dug into these soils where limited at about 1.5 m depth by large masses of quartz. Fine earth samples belong to the USDA sandy loam or sandy clay loam textural classes. In horizons deeper than 50 cm, texture is sandy clay or clay.

The XRD patterns of the fine earth samples show the presence of quartz, Ti-oxides (mostly anatase, sometimes rutile), Fe-oxides (hematite), kaolinite in all the samples analyzed, whatever the region of origin of the sample, the parent material of the soil or the depth of the sample in the soil profile. Doubts on the presence of halloysite-7Å are annihilated by the formamide test on oriented clay mounts: the absence of rapid expansion (to 10Å) of the mineral structure by formamide intercalation, infirmed the presence of halloysite (Churchman et al., 1984; Joussein et al., 2005, 2007). Gibbsite is often identified in the soils of Gitega and Kibungo, but only occasionally in Butare. None of the 7 samples from Ntungamo shows presence of Al-oxides. Muscovite or sericite is a recurrent component of the soils of Gitega and Ntungamo, but it is virtually absent in the soil samples from Kibungo. In Butare, muscovite is detected in the soil sampled in one of the studied farms (farm 1) but not in the fine earth of the second farm (farm 67).

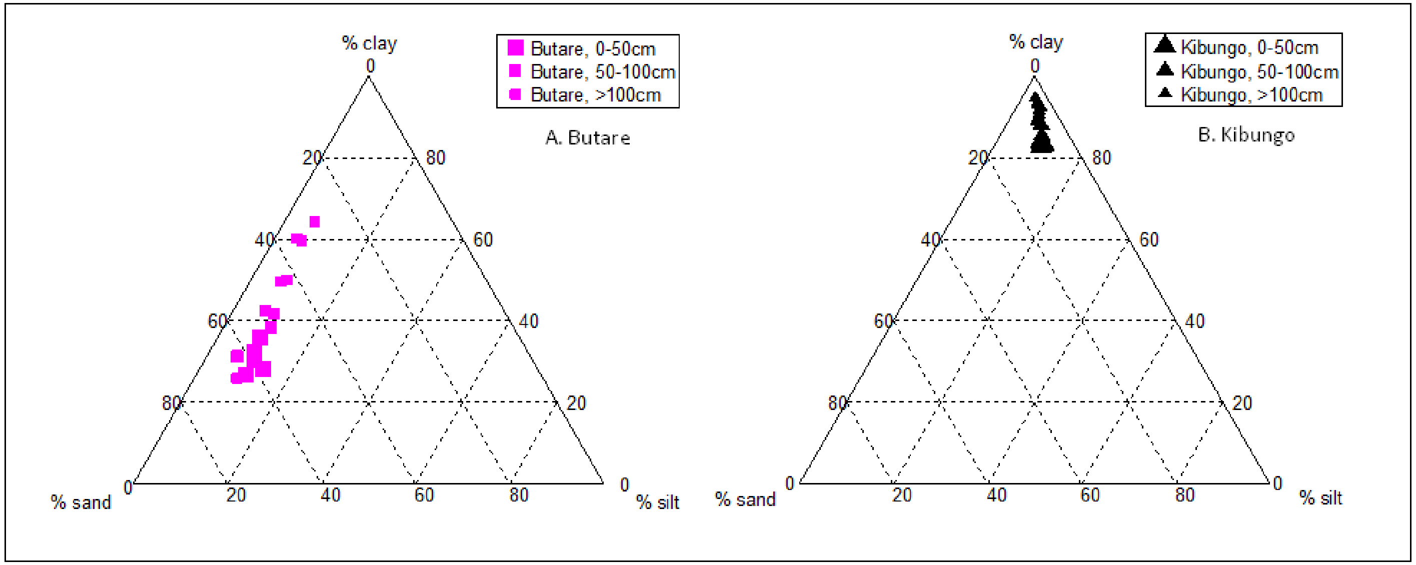

Figure 6.2 (continued on next page). Textural triangles for the successive fine earth samples recovered from the soil profiles in (A) Butare, (B) Kibungo, (C) Gitega and (D) Ntungamo. Symbols of different sizes report data for different depths (0 to ±50 cm, ±50 to ±100 cm, > 100 cm).

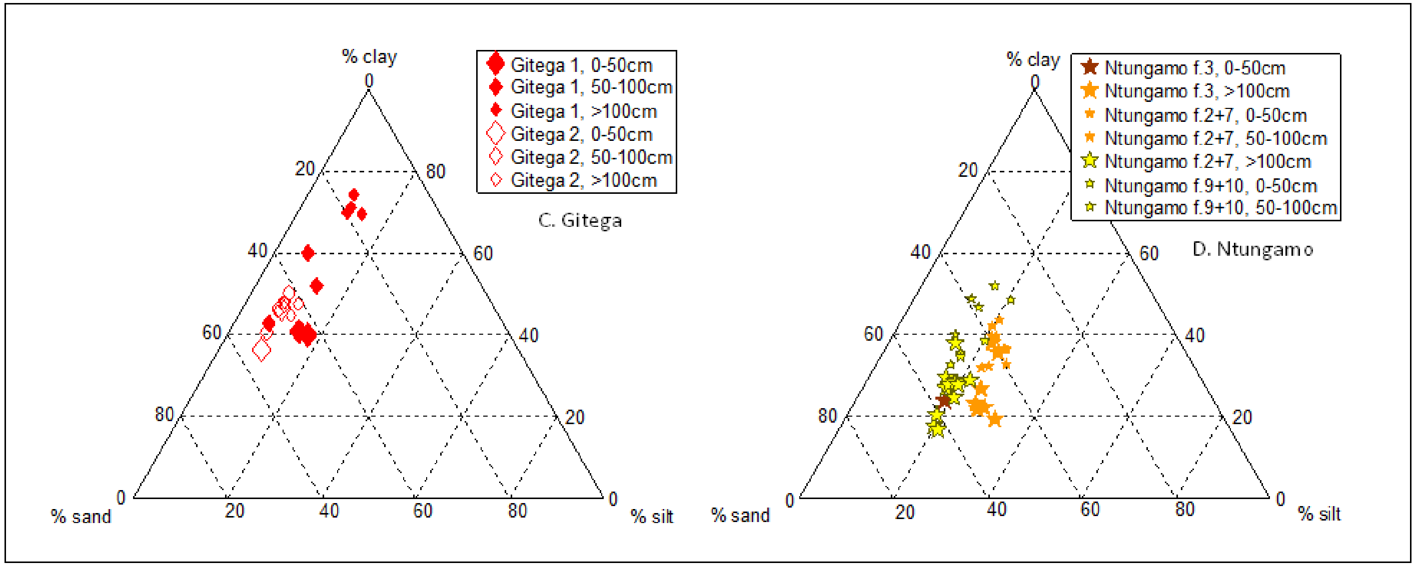

Figure 6.2 (continued). Textural triangles for the successive fine earth samples recovered from the soil profiles in (A) Butare, (B) Kibungo, (C) Gitega and (D) Ntungamo. Symbols of different sizes report data for different depths (0 to ±50 cm, ±50 to ±100 cm, > 100 cm).

A mineral having a peak at 14 Å is regularly (but not systematically) observed in the XRD patterns of soil samples from the different regions of interest. The different treatments performed on oriented clay mounts, allow the identification of that particular mineral. The mineral is thought to be (contracted or interlayered) vermiculite, because of (1) the appearance of a peak at 14 Å when the clay is Mg-saturated, (2) the presence of peaks at 10 or 14 Å when the clay is K-saturated and (3) their disappearance under heating. The presence of feldspars (K-feldspars and albite) in fine earth samples could neither be ascertained neither rejected. Indeed, the most intense peaks of K-feldspar are shoulder peaks to the most intense quartz peak and suffer overlap with the most intense peak of rutile. For both K-feldspar and albite, the recognition of tiny irregularities as possibly the most intense peaks of feldspars depends on the subjective visual appraisal of the background noise. The presence of carbonates could be suspected in samples having pH_{H2O} superior to 7. Alkaline pH values are observed for some surface samples in profiles closest to the homestead. High pH values could be explained by the amendment of the soil by kitchen ashes. In their description of the mineralogy of kitchen ashes, Eteigni and Campbell (1991), Ohno (1992), Demeyer et al. (2001) indicate calcite as the major compound.

The minerals constituting the fine earth samples distribute between the various textural fractions composing it. The clay fractions of the soils of all the regions of interest comprise kaolinite, Fe- and Ti-oxides. Vermiculite is identified in all the regions, but not systematically in all the samples. Quartz is present in the clay fractions of all the soils except in those of Kibungo. Al-oxides are present in the clay fractions of the Gitega and Kibungo soils. Muscovite or sericite is identified in the clay fractions of Butare farm 1 and Ntungamo. Iron- and Ti-oxides, kaolinite, quartz and muscovite make up the silt fractions in all the regions. Al-oxides are identified in the silt fraction of samples from Gitega. Albite and/or K-feldspar are occasionally identified in the silt fraction of Butare, Kibungo and Gitega. The sand fractions comprise Fe-oxides, quartz and muscovite.

Ti-oxides are recognized in the sand fractions of all regions but Butare. Gravel (> 2000 µm) is constituted by quartz and iron oxides. Ti-oxides are identified in > 2000 µm-soil fraction of Butare and Kibungo, and muscovite in Gitega and Kibungo. The occasional presence of feldspars in the coarse particles from Kibungo soils could not be excluded.

The Chemical Indices of Alteration (CIA, [eq.5], Table 6.6 at the end of the chapter) calculated with $Al_2O_{3,tot}$, CaO_{min}, Na_2O_{min} and K_2O_{min}, are significantly ($P < 0.05$) higher in Kibungo (98.35 ± 0.36, N=11) than in the other regions. The means of CIA for Butare (94.19 ± 1.70, N=15), Gitega farm 1 (94.56 ± 2.55, N=9) and farm 2 (95.28 ± 1.11, N=10) are significantly ($P < 0.05$) higher than CIA in Ntungamo. In Ntungamo, CIA for farms 3 (85.78 ± 4.35, N=3) and farms 2+7 (85.98 ± 1.32, N=30) are significantly ($P < 0.05$) lower than CIA in farms 9+10 (92.7 ± 1.13; N=33).

Additional data: oxalate and DCB extraction, cation displacement by $CuCl_2$

The ratio between iron extracted by dark oxalate and iron extracted by Dithionite-Citrate-Bicarbonate (DCB) (Fe_o/Fe_{DCB}) is, on average, 0.04 ± 0.02 (N=30) in Kibungo and Gitega and 0.09 ± 0.04 (N=81) in Butare or Ntungamo. In all the profiles, the ratio is higher in surface horizons than at depth. The proportion of the total Fe_2O_3 content allocated to crystalline iron oxides, is inferior in Ntungamo (39-44%) than in the other regions (80-88%). 1.8-7.5% of the total Al_2O_3 content of the fine earth samples is attributed to crystalline Al-substituted iron oxides. The molar ratio of $Al_{cryst.ox}/(Al_{cryst.ox.} + Fe_{cryst.ox.})$ calculated with the Al and Fe allocated to the crystalline iron oxides, ranges between 0.11 and 0.24.

In fine earth samples, ammonium acetate (pH7) extracts the same (or slightly higher) quantities of Na and K than the $CuCl_2$ (pH3) solution. The more aggressive $CuCl_2$ solution does not dissolve feldspars or muscovite more than does ammonium acetate. The difference of the Ca, Mg contents determined in the $CuCl_2$ extract and the Ca, Mg contents in the ammonium acetate solution, quantifies organically bound Ca and Mg. Total K_2O contents are highest in surface horizons and decrease at depth (Kibungo, Gitega 1+2, Ntungamo farm 3). In some profiles a new increase of total K_2O is observed in the deepest horizons (Butare, Gitega farm 2, Ntungamo farm 3, 2+7 and 9+10). Most (83-100%) of total K_2O content resides in the mineral pool. In the surface horizons of some profiles (those studied in Butare, Kibungo, Gitega farm 2, Ntungamo farm 9+10), the exchangeable pool is an important (about 10% or more) contributor to the total potassium reserve (Table6.4). In Butare, Kibungo and Gitega, total Na_2O contents are low (0.02-0.06%) and more or less constant on the entire profiles. In Ntungamo, a slight increase of the total Na_2O content is observed in the deepest horizons. In all the regions, minerals constitute the most important (72-100%) Na pool (Table 6.4). The total MgO content in fine earth samples is highest in surface horizons and decreases with depth. The only profile showing a new increase in MgO at depth is the profile in farm 3 of Ntungamo. Accounting for 57-99% of the total MgO content, minerals are an important Mg pool. The exchangeable Mg pool contributes for 12-34% to the total MgO content determined in surface horizons. The contribution of organically bound Mg varies widely, ranging from 0-10% in surface horizons (Table 6.4). The total CaO content in fine earth is highest in surface horizons and decreases with depth. The distribution of CaO between the mineral, exchangeable and organically bound pool differs when comparing the various profiles studied in the regions of interest. Two global conclusions apply to all profiles. First, all three pools are important contributors to the total CaO content in the surface horizons: 10-48% in the mineral pool, 36-55% in the exchangeable pool, 1-41% of organically bound Ca. Second, in intermediate to deep horizons, minerals and the exchangeable pool account together for the entire CaO content, the former for 34-90%, the latter for 10-59% (Table 6.4).

Table 6.4 (continued on following pages). Total K, Na, Ca and Mg contents in soil profiles and distribution between mineral (Min.), exchangeable (Exch.) and organically bound (Compl.) fractions.

Region	Depth	$\%K_2O_{tot}$	K fractions (%)	
			Min.	Exch.
Ntungamo farm 3 (1 profile)	0-29cm	1.97	97.97	2.03
	29-60cm	1.90	99.34	0.66
	60-105cm	3.94	99.40	0.60
Ntungamo farms 2+7 (4 profiles)	0-50cm	1.54	97.82	2.18
	50-100cm	1.70	99.51	0.49
	100-200cm	2.11	99.76	0.24
	>200cm	2.14	99.80	0.20
Ntungamo farms 9+10 (6 profiles)	0-50cm	0.81	90.96	8.87
	50-100cm	0.90	96.43	3.57
	100-200cm	0.98	97.65	2.35
	>200cm	1.09	97.31	2.69
Butare (4 profiles)	0-50cm	0.51	89.22	10.78
	50-100cm	0.49	93.37	6.63
	100-200cm	0.50	99.16	0.84
	>200cm	0.62	92.62	7.38
Kibungo (3 profiles)	0-50cm	0.35	88.75	11.20
	50-100cm	0.30	97.94	2.06
	100-200cm	0.34	99.25	0.75
	>200cm	0.28	98.99	0.78
Gitega 1 (2 profiles)	0-50cm	1.06	96.71	3.29
	50-100cm	0.61	98.94	1.06
	100-200cm	0.63	99.50	0.50
	>200cm	0.62	99.17	0.83
Gitega 2 (2 profiles)	0-50cm	0.62	82.61	16.37
	50-100cm	0.52	89.30	10.28
	100-200cm	0.52	96.34	3.61
	>200cm	0.83	99.70	0.30

Table 6.4 (continued). Total K, Na, Ca and Mg contents in soil profiles and distribution between mineral (Min.), exchangeable (Exch.) and organically bound (Compl.) fractions.

Region	Depth	$\%Na_2O_{tot}$	Na fractions (%)	
			Min.	Exch.
Ntungamo farm 3 (1 profile)	0-29cm	0.24	98.77	0.24
	29-60cm	0.21	99.80	0.20
	60-105cm	0.42	99.58	0.42
Ntungamo farms 2+7 (4 profiles)	0-50cm	0.18	99.69	0.21
	50-100cm	0.18	99.79	0.13
	100-200cm	0.21	99.78	0.20
	>200cm	0.23	99.76	0.17
Ntungamo farms 9+10 (6 profiles)	0-50cm	0.09	97.48	1.77
	50-100cm	0.09	98.61	1.24
	100-200cm	0.10	98.67	1.20
	>200cm	0.11	98.48	1.47
Butare (4 profiles)	0-50cm	0.04	87.18	12.23
	50-100cm	0.04	88.64	9.99
	100-200cm	0.03	91.23	4.89
	>200cm	0.03	81.79	18.21
Kibungo (3 profiles)	0-50cm	0.06	88.25	11.75
	50-100cm	0.06	89.12	10.20
	100-200cm	0.06	89.08	10.29
	>200cm	0.05	85.99	13.46
Gitega 1 (2 profiles)	0-50cm	0.05	87.63	8.30
	50-100cm	0.03	86.15	12.99
	100-200cm	0.02	77.86	19.72
	>200cm	0.02	73.52	26.48
Gitega 2 (2 profiles)	0-50cm	0.03	76.49	14.33
	50-100cm	0.02	72.66	18.10
	100-200cm	0.02	72.09	19.88
	>200cm	0.03	82.47	17.51

Table 6.4 (continued). Total K, Na, Ca and Mg contents in soil profiles and distribution between mineral (Min.), exchangeable (Exch.) and organically bound (Compl.) fractions.

Region	Depth	$\%MgO_{tot}$	Mg fractions (%)		
			Min.	Exch.	Compl.
Ntungamo farm 3 (1 profile)	0-29cm	0.33	63.80	26.48	9.72
	29-60cm	0.22	93.32	6.30	0.38
	60-105cm	0.41	96.87	3.08	0.05
Ntungamo farms 2+7 (4 profiles)	0-50cm	0.15	91.75	7.81	0.44
	50-100cm	0.15	97.70	2.30	0.00
	100-200cm	0.17	99.15	0.85	0.00
	>200cm	0.16	99.22	0.78	0.00
Ntungamo farms 9+10 (6 profiles)	0-50cm	0.15	95.82	12.39	1.82
	50-100cm	0.15	85.79	6.15	0.37
	100-200cm	0.16	93.48	5.60	0.00
	>200cm	0.16	94.40	4.18	0.00
Butare (4 profiles)	0-50cm	0.18	66.27	28.89	4.85
	50-100cm	0.15	73.35	24.34	2.31
	100-200cm	0.17	82.89	15.75	1.36
	>200cm	0.17	83.33	15.29	1.38
Kibungo (3 profiles)	0-50cm	0.36	56.93	33.71	9.36
	50-100cm	0.22	88.40	10.25	1.35
	100-200cm	0.19	92.78	6.35	0.87
	>200cm	0.16	89.09	9.82	1.09
Gitega 1 (2 profiles)	0-50cm	0.30	86.48	12.03	1.50
	50-100cm	0.23	88.42	10.84	0.74
	100-200cm	0.24	83.27	15.43	1.30
	>200cm	0.25	81.33	17.33	1.33
Gitega 2 (2 profiles)	0-50cm	0.32	72.78	20.30	6.91
	50-100cm	0.20	92.26	6.46	1.28
	100-200cm	0.19	95.97	3.81	0.22
	>200cm	0.18	97.85	2.15	0.00

Table 6.4 (continued). Total K, Na, Ca and Mg contents in soil profiles and distribution between mineral (Min.), exchangeable (Exch.) and organically bound (Compl.) fractions.

Region	Depth	$\%CaO_{tot}$	Ca fractions (%)		
			Min.	Exch.	Compl.
Ntungamo farm 3 (1 profile)	0-29cm	0.67	9.67	49.15	41.18
	29-60cm	0.08	37.73	59.42	2.84
	60-105cm	0.04	59.32	40.68	0.00
Ntungamo farms 2+7 (4 profiles)	0-50cm	0.10	48.41	50.57	1.02
	50-100cm	0.04	81.53	18.47	0.00
	100-200cm	0.04	89.84	10.16	0.00
	>200cm	0.04	90.48	9.52	0.00
Ntungamo farms 9+10 (6 profiles)	0-50cm	0.12	43.72	51.77	5.06
	50-100cm	0.05	62.77	36.64	0.59
	100-200cm	0.04	57.67	42.33	0.00
	>200cm	0.06	45.56	54.44	0.00
Butare (4 profiles)	0-50cm	0.38	25.41	55.48	19.11
	50-100cm	0.20	33.65	58.90	7.45
	100-200cm	0.23	43.83	50.29	5.89
	>200cm	0.15	43.81	53.41	2.78
Kibungo (3 profiles)	0-50cm	0.61	16.45	54.50	29.50
	50-100cm	0.24	47.92	49.55	2.53
	100-200cm	0.30	41.25	48.21	10.54
	>200cm	0.14	49.54	50.46	0.00
Gitega 1 (2 profiles)	0-50cm	0.32	31.68	36.00	32.32
	50-100cm	0.15	40.03	46.76	13.21
	100-200cm	0.09	44.56	55.44	0.00
	>200cm	0.08	41.29	58.71	0.00
Gitega 2 (2 profiles)	0-50cm	0.43	33.57	47.86	18.57
	50-100cm	0.09	70.06	29.94	0.00
	100-200cm	0.05	75.26	24.74	0.00
	>200cm	0.03	85.49	14.51	0.00

B. Artificial test samples

In an attempt to evaluate the mineral quantification methods (normative calculation and *SIROQUANT*), artificial samples of known composition are constituted. Their composition is inspired from the mineralogical composition and mineral abundances observed in real soil samples (Table 6.2): anatase, chlorite, albite, illite, perthitic orthoclase, hematite, kaolinite, gibbsite and quartz. Total chemical analysis and XRD confirmed purity and crystalline order of the selected anatase (TiO_2), albite ($NaAlSi_3O_8$), hematite (Fe_2O_3), gibbsite ($Al(OH)_3$) and quartz (SiO_2). Total chemical analysis allowed estimation of the chemical composition of the perthitic orthoclase: 77% orthoclase, 23% albite. In accordance with what is published in literature (Wilson and Jiranek, 1995; Frost et al., 2004), Zettlitz kaolinite is found to contain quartz (2.3%) and muscovite (9.3%). The choice of the standard chemical formula of chlorite ($(Mg_{4.27}Fe_{0.73}Al)(AlSi_3)O_{10}(OH)_8$) and illite ($(K_{0.8}, (H_3O)_{0.2})(Al_{1.5}Fe_{0.25}Mg_{0.25})(Al_{0.5}Si_{3.5})O_{10}(OH)_2$) is made on basis of general chemical formulas (Garrels, 1984; Deer et al., 1992) and total chemical analyses. Because of the difficulty to ground platy minerals, the fine grained material illite is preferred to muscovite when composing the artificial samples. Anatase, chlorite, albite, hematite, kaolinite are available as fine powders. Perthitic orthoclase and quartz are ground by hand.

6.3.2. Quantification of the mineral quantities in artificial test samples

The graphs of Figure 6.3 represent, for some minerals, the mineral abundances (%wt) determined by normative calculation (NC, Y-axis) or *SIROQUANT* (SQT, Y-axis) against the real compositions of the artificial samples (RL, X-axis).

Considering the error on the estimates by *SIROQUANT*, the quantities of anatase (not shown, [SQT = (0.95*RL) + 0.64; R^2=0.76; N=15]), kaolinite (Figure 6.3.D) and gibbsite (Figure 6.3.E) are correctly evaluated by *SIROQUANT*. Illite (Figure 6.3.B) is systematically underestimated by *SIROQUANT* and quartz is underestimated at low abundances (Figure 6.3.F). The amounts of orthoclase (Figure 6.3.C), albite (not shown, [SQT = (1.54*RL) + 1.37; R^2=0.36; N=6]), chlorite (Figure 6.3.A) and hematite (not shown, [SQT = (1.78*RL) + 0.74; R^2=0.99; N=15]) are, on the contrary, overestimated. Consideration of the intensities of XRD-peaks of a same mineral in function of its known abundances, allows establishment of practical detection limits. The minerals illite, hematite, gibbsite and anatase are not identified on the XRD-pattern if they are present in quantities inferior to 0.5 %wt in the sample. For albite, orthoclase and chlorite, the detection limit seems to be 1 %wt.

As deduced from the graphs of Figure 6.2, the mineral abundances determined by normative calculation are close to those expected for the minerals anatase (not shown, [NC = (0.93*RL) + 0.15; R^2=0.99; N=15]), albite (not shown, [NC = (1.01*RL) + 0.07; R^2=0.99; N=6]), hematite (not shown, [NC = (0.97*RL) - 0.00; R^2=1.00; N=15]), chlorite (Figure 6.3.A), kaolinite (Figure 6.3.D), gibbsite (Figure 6.3.E) and quartz (Figure 6.3.F). Larger deviances are observed for orthoclase (Figure 6.3.C) and illite (Figure 6.3.B). Additional annotations in the graphs of Figure 6.3 aim to highlight some problems inherent to the normative calculation. Sample #8 in Figure 6.3.E exemplifies the case where gibbsite cannot be quantified by normative calculation. Samples #4 and #9 in Figure 6.3.B and Figure 6.3.C illustrate the inadequacy of the distribution of K_2O between illite and K-feldspar. The grey bars in the graphs relative to chlorite (Figure 6.3.A) or illite (Figure 6.3.B) indicate the range of mineral amounts calculated when the chemical formulas of both minerals are allowed to change. For the purpose of this example, the chemical formulas of chlorite and illite are modified as follows:

- for chlorite (relying on the general formula by Klein and Hurlbut, 1999):
  $(Mg_{5-5x}Fe_{5x}Al)(AlSi_3)O_{10}(OH)_8$ where 5x = 0 - 4.99, to cover the range of magnesian to Fe-rich chlorites.

- for illite (relying on the general formula by Garrels, 1984):
  $(K_y(H_3O)_{1-y})(Al_{1.5}Fe_xMg_{0.5-x})(Si_2Al)_4O_{10}(OH)_2$ where x = 0 - 0.5 and y = 0.4 - 0.8, to cover the range of low- to high-K illites.

According to Rosen and Abbyasov (2003) or Rosen et al. (2004) the accuracy of normative calculation can be assessed by the variation coefficient (V_d, [eq.6]) expressed in relative percentages compared to the average. In this study, *SIROQUANT*, as well as normative calculation, are evaluated in that way.

$$V_d = \sqrt{\frac{\sum_{i=1}^{i=n}\left(\frac{d_i}{m_i} * 100\right)^2}{2n}}$$

where n = number of samples for which the paired information of (1) exact mineralogical compositions and (2) estimated compositions (determined by normative calculation or *SIROQUANT*), are available.

d_i = the absolute difference between normative mineral content (or abundances determined by *SIROQUANT*) and real composition.

m_i = the average value between normative mineral content (or abundances by *SIROQUANT*) and corresponding real composition.

[eq.6]

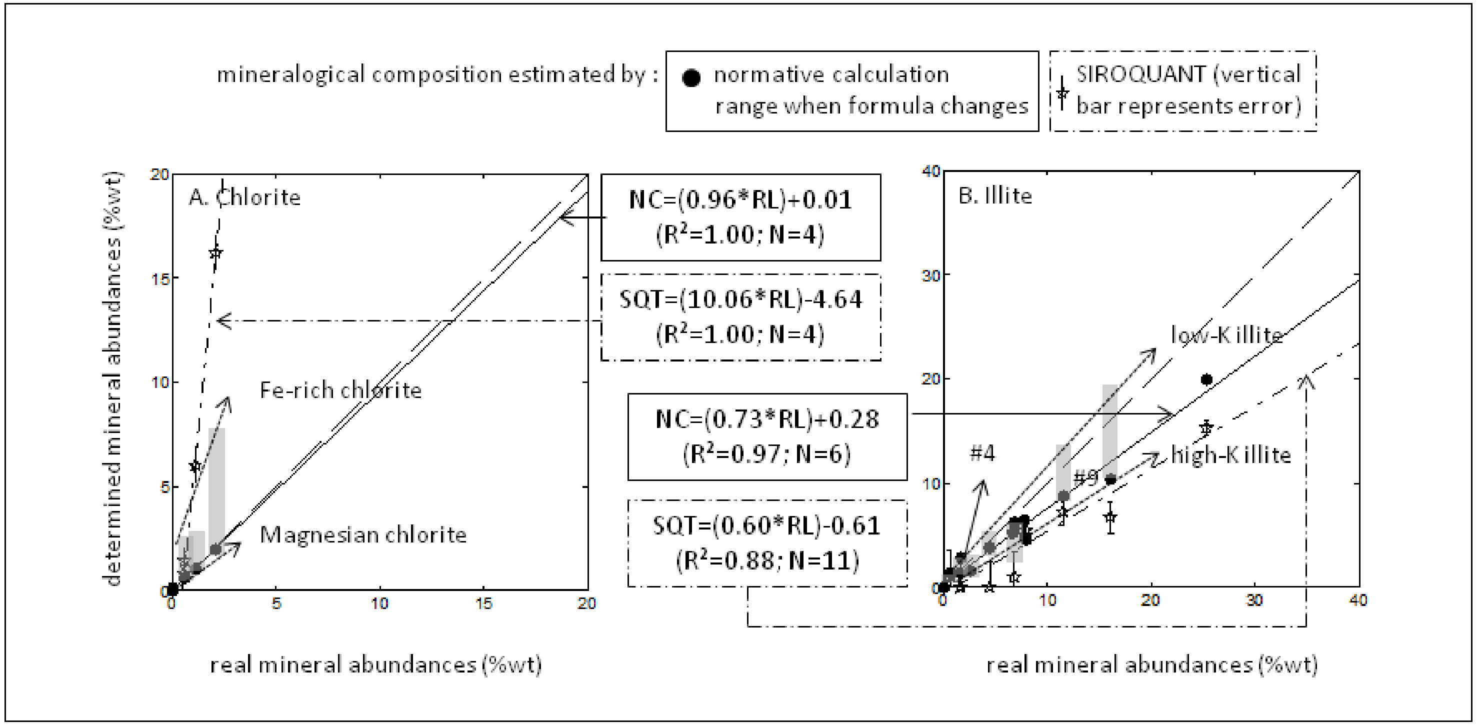

Figure 6.3 (continued on following pages). Comparison of mineral quantities determined by normative calculation (NC, filled circle) or *SIROQUANT* (SQT, open stars) and real mineral abundances (RL) of artificial samples.

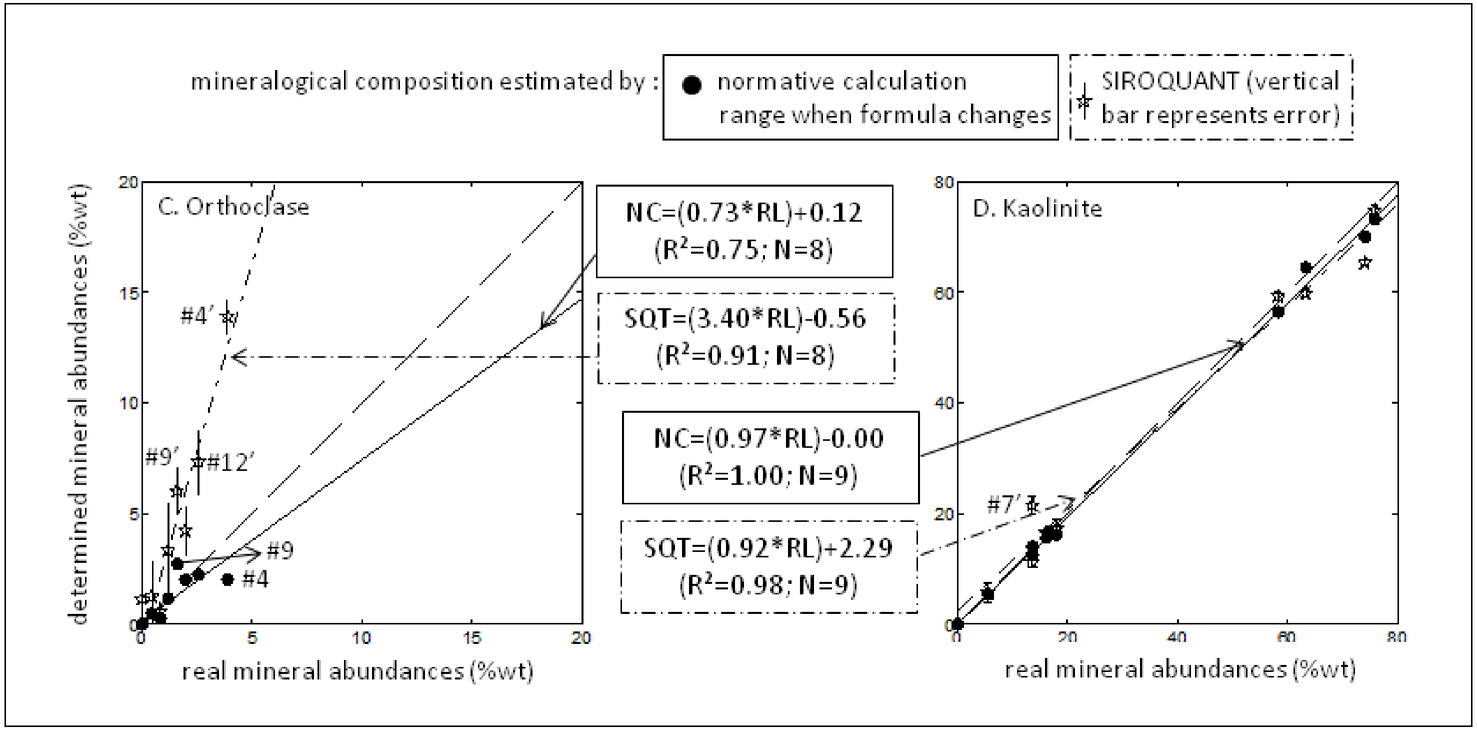

Figure 6.3 (continued). Comparison of mineral quantities determined by normative calculation (NC, filled circle) or *SIROQUANT* (SQT, open stars) and real mineral abundances (RL) of artificial samples.

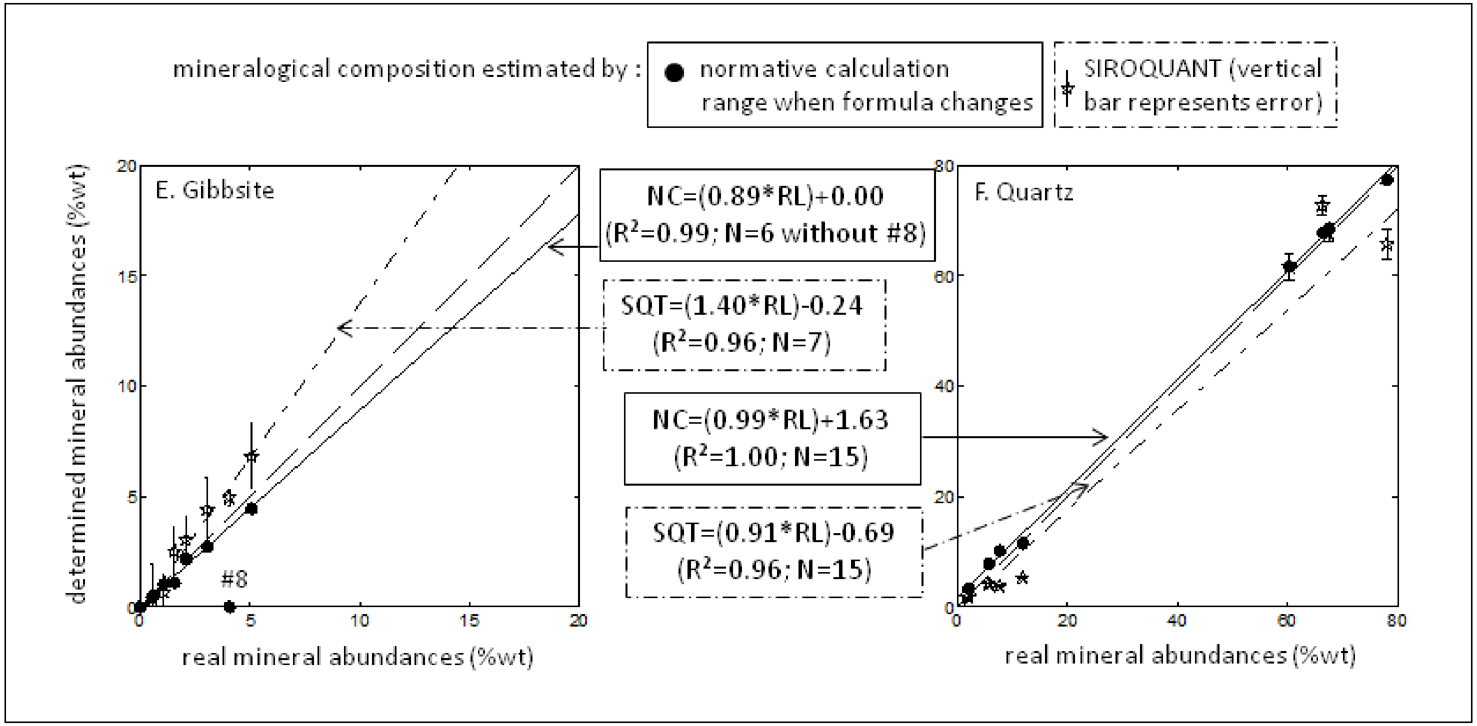

Figure 6.3 (continued). Comparison of mineral quantities determined by normative calculation (NC, filled circle) or *SIROQUANT* (SQT, open stars) and real mineral abundances (RL) of artificial samples.

Figure 6.4 summarizes the discrepancies between the quantified mineral abundances and the real compositions of the artificial samples. Except for gibbsite, *SIROQUANT* induces larger discrepancies than does normative calculation (Figure 6.4.A). For the estimates of weight percentages of muscovite, chlorite, orthoclase, albite and hematite (Figure 6.4.A) by *SIROQUANT*, discrepancies relatively to the real compositions) are superior to the 40% considered as “acceptable” by Rosen and Abbyasov (2003). For the normative calculation the largest discrepancies (relatively to the real compositions) are observed for gibbsite (55%), orthoclase (35%) and muscovite (29%). When estimating mineral compositions, normative calculation provided more accurate results than *SIROQUANT* (staircase lines in Figure 6.4.B *vs.* 6.4.C). For mineral abundances of 25-100 %wt, uncertainty was 22 % for *SIROQUANT* but only 4 % for normative calculation. Mineral quantities between 7-16 %wt, show discrepancies of 0-30 % with normative calculation, but can reach 58 % when determined by *SIROQUANT*. With uncertainties of 0-100%, minerals present in low amounts (limit is higher in *SIROQUANT*: < 7 %wt for *SIROQUANT*, < 4 %wt for normative calculation) proved most difficult to quantify correctly (Figure 6.4.B+C).

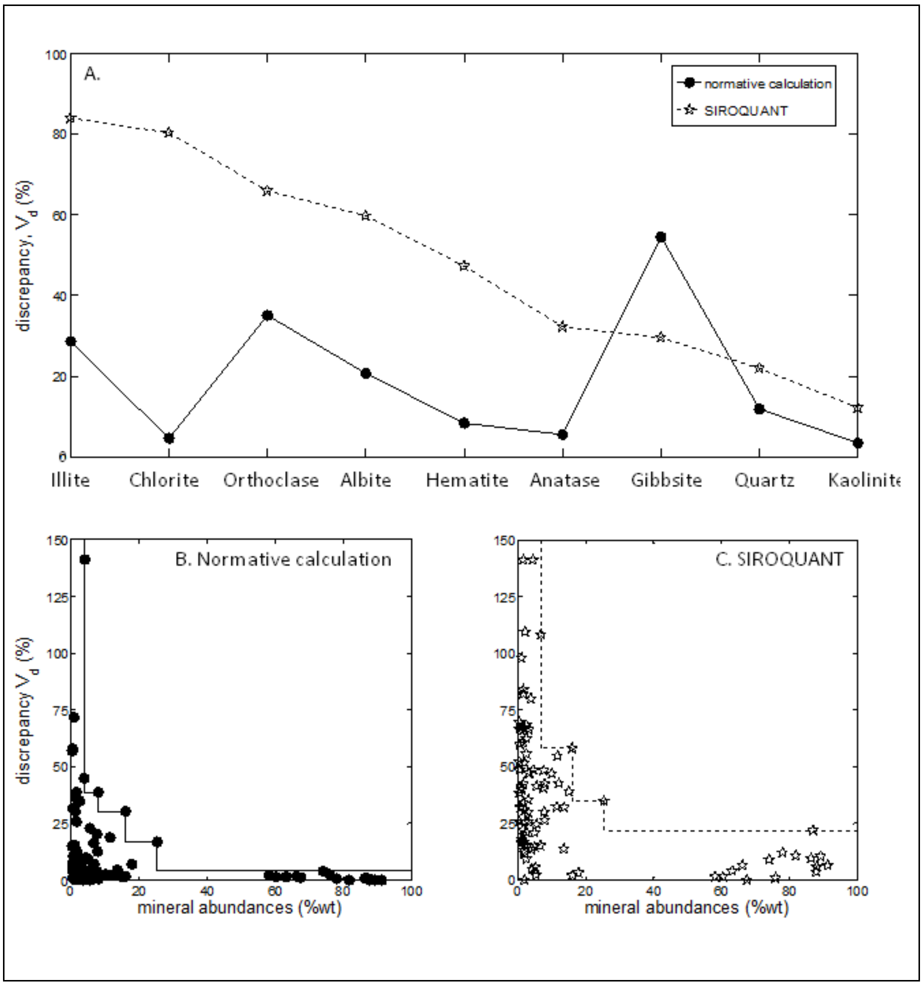

Figure 6.4. Discrepancies (V_d) between the mineral amounts determined by normative calculation or *SIROQUANT*, and real mineralogical compositions of artificial samples: (A) for minerals, (B-C) for mineral mixtures. The staircase lines in plots B and C go through the upper values of V_d within the intervals (B) 0-4, 4-8, 8-16, 16-25, 25-100 %wt and (C) 0-7, 7-16, 16-25, 25-100 %wt and indicate the maximum relative error observed within those intervals.

6.3.3. Quantifying the mineralogical composition of soil sub-fractions and fine earth samples: comparison of methods

A. Adapted normative calculation vs. basic normative calculation

Herein are compared the mineral abundances computed by the basic normative calculation and those by the calculation integrating additional chemical data on fine earth samples (oxalate, DCB, ammonium acetate and $CuCl_2$ extracts). Anatase is the only mineral phase not affected by the adaptations of the calculation. All other phases are affected, whether directly (the elemental contents allocated to those minerals change because of the complementary data) or indirectly (differences in the mineral abundances calculated in the first steps of the calculation of Table 6.3 influence the amounts calculated in the steps).

Differences in the amounts computed by the basic and the adapted calculation, are small for albite and quartz. Indeed, the relationships relating the adapted calculation ($NC_{adapted}$) to the basic normative calculation (NC_{basic}) are [$NC_{adapted} = (0.99*NC_{basic}) - 0.09$, $R^2=1.00$, N=28] for albite and [$NC_{adapted} = (0.98*NC_{basic}) + 2.54$, $R^2=1.00$, N=52] for quartz. The graphs in Figure 6.5 compare the abundances of (A) vermiculite, (B) microcline, (C) hematite and (D) kaolinite calculated by the basic (X-axis) and the adapted (Y-axis) normative calculations. The graphs illustrate that differences are small for the majority of the data, but may be more important for some samples (grey patches in Figure 6.5). For hematite the largest differences are for the samples from Ntungamo (grey patches, Figure 6.5C), for which only 36-44% of Fe_{tot} are allocated to crystalline iron oxide abundances, the rest being attributed to aluminosilicates, amorphous phases or organic complexes. For kaolinite (grey patches in Figure 6.5.D) the largest differences between basic and adapted calculation, relate to samples having the biggest differences between $Al_2O_{3,tot}$ and $Al_2O_{3,aluminosilicates}$. Important differences between K_2O_{tot} and K_2O_{min} explain the deviances between basic and adapted calculation for K-feldspar (grey patches in Figure 6.5.B). For the samples where the abundances in vermiculite calculated by the adapted normative calculation differ strongly from the abundances computed by the basic calculation (grey patches in Figure 6.5.A), the vermiculite content is limited in the adapted calculation by the CaO allocated to minerals or the Al_2O_3 attributed to aluminosilicates.

B. Normative calculation (basic or adapted computation) vs. SIROQUANT

The mineral compositions of 123 samples (fine earth and soil subfractions (coarse particles > 2000 µm, sand, silt, clay), are quantified by *SIROQUANT*. Chi-square values of the pattern fits range between 1.31 and 9.19, with most of the values (70%) being between 2.5 and 4.0.

The graphs of Figure 6.6 represent the relationships between the mineral abundances determined by normative calculation *vs. SIROQUANT*, for fine earth and soil subfractions. The Ti-oxides in real fine earth or soil subfraction proved difficult to fit in *SIROQUANT*. This difficulty explains the scatter in Figure 6.6.A. There is no clear tendency either for the rare data on vermiculite (Figure 6.6.B). *SIROQUANT* gives higher albite (Figure 6.6.C), muscovite (Figure 6.6.D) and K-feldspars (Figure 6.6.E) amounts than normative calculation. For hematite (Figure 6.6.F), kaolinite (Figure 6.6.G) and quartz (Figure 6.6.H), the mineral abundances estimated by normative calculation are relatively close to those determined by *SIROQUANT*.

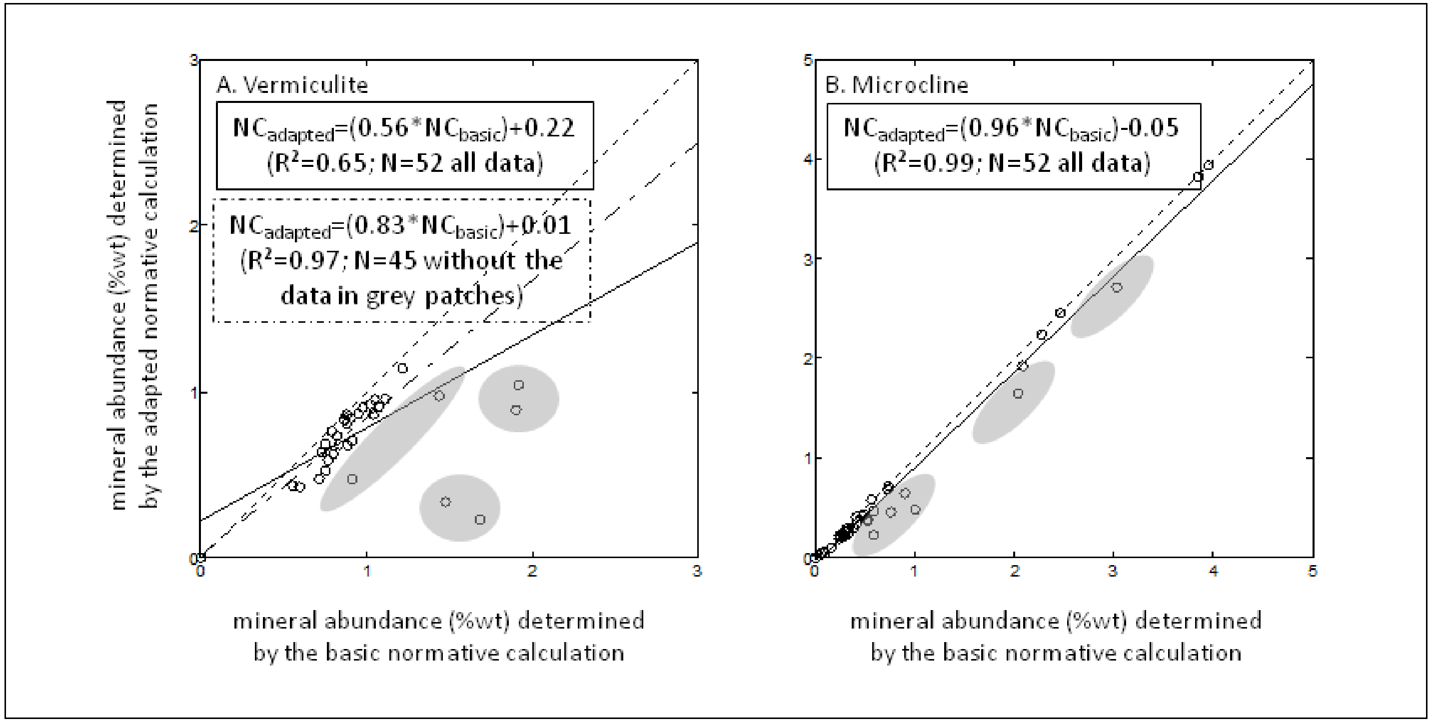

Figure 6.5 (continued on next page). Comparison of the mineral quantities in fine earth samples, as calculated by the basic or the adapted calculation. The grey patches highlight data for which differences between both calculation methods are important.

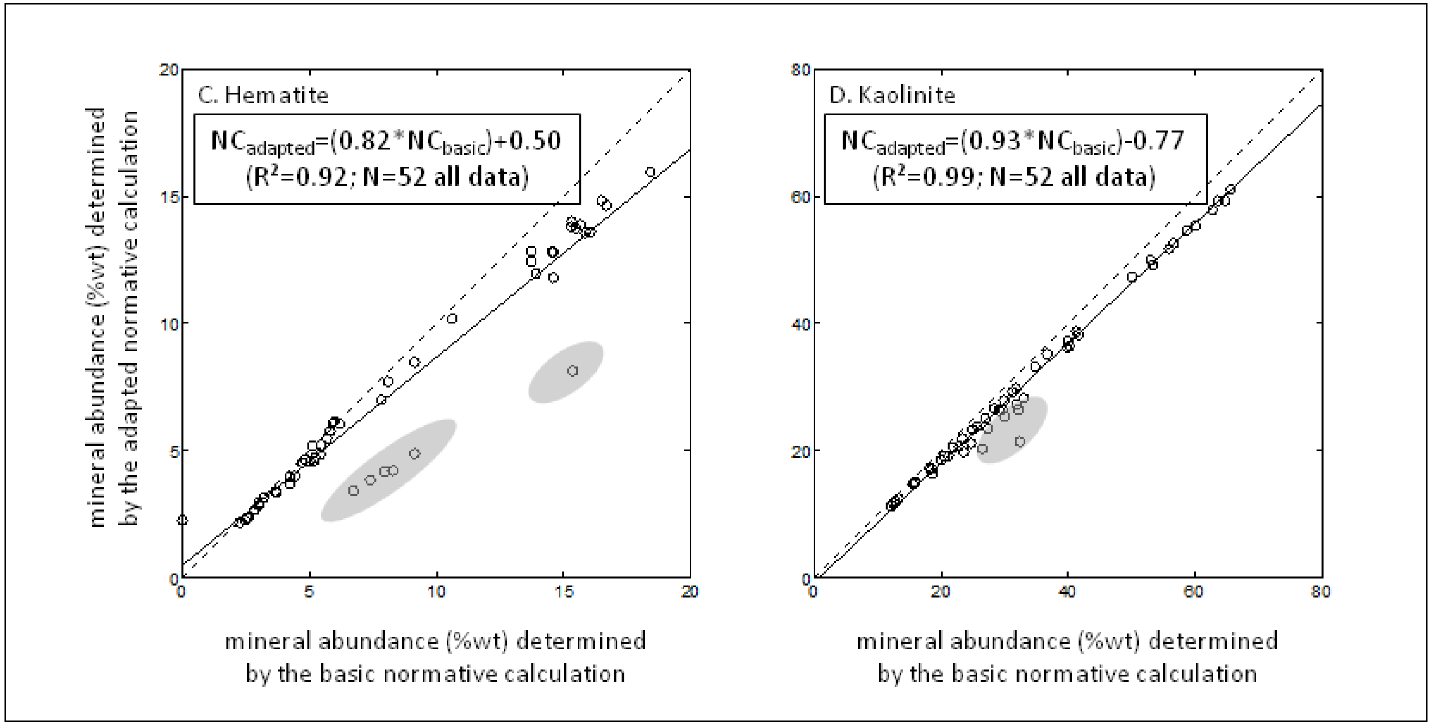

Figure 6.5 (continued). Comparison of the mineral quantities in fine earth samples, as calculated by the basic or the adapted calculation. The grey patches highlight data for which differences between both calculation methods are important.

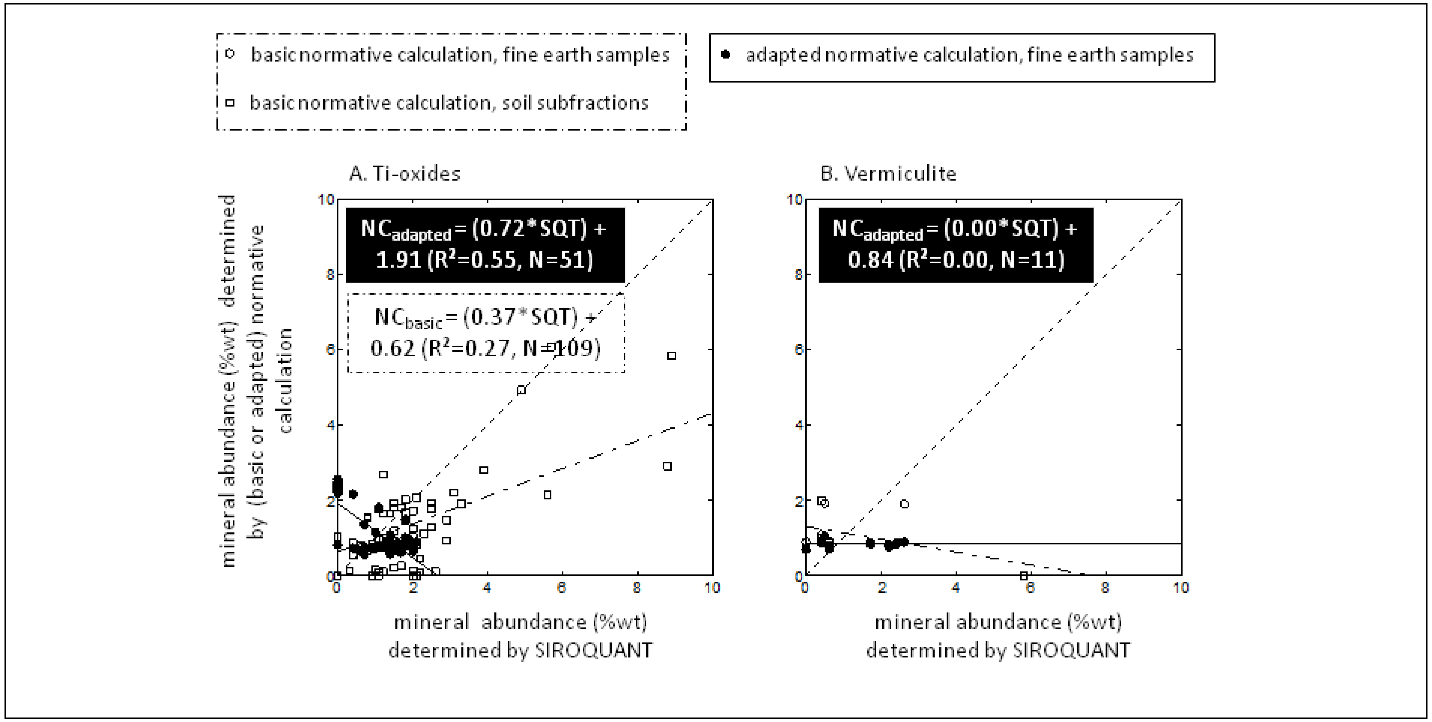

Figure 6.6 (continued on following pages). Comparison of the mineral abundances in fine earth and soil subfractions, as determined by normative calculation (basic or adapted calculation) and *SIROQUANT*.

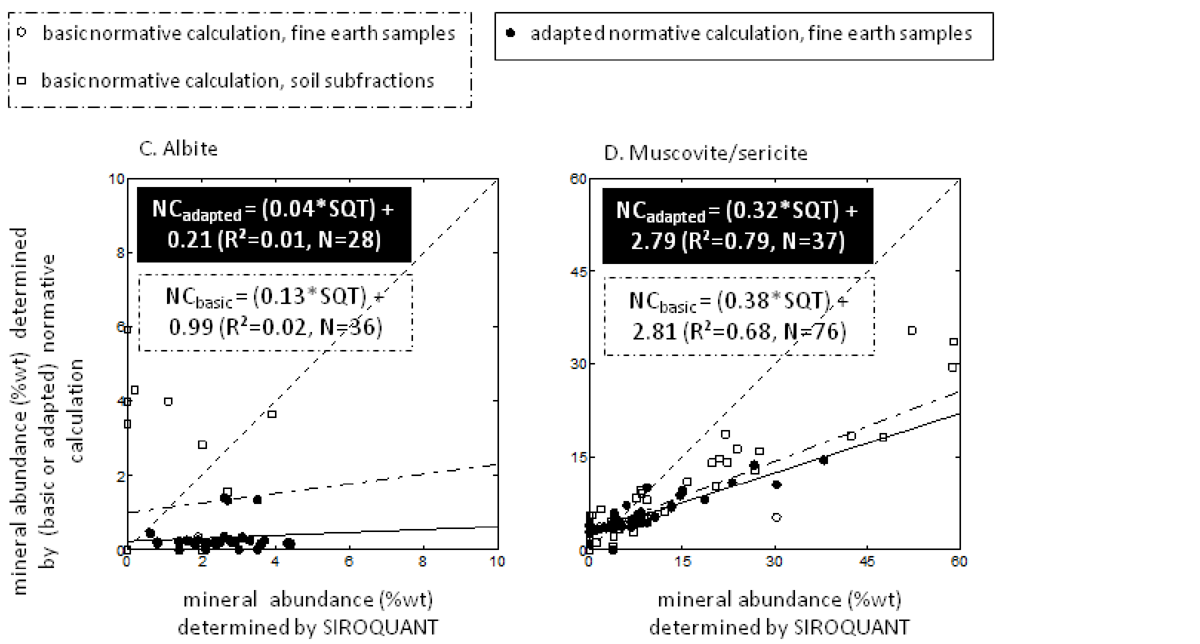

Figure 6.6 (continued). Comparison of the mineral abundances in fine earth and soil subfractions, as determined by normative calculation (basic or adapted calculation) and *SIROQUANT*.

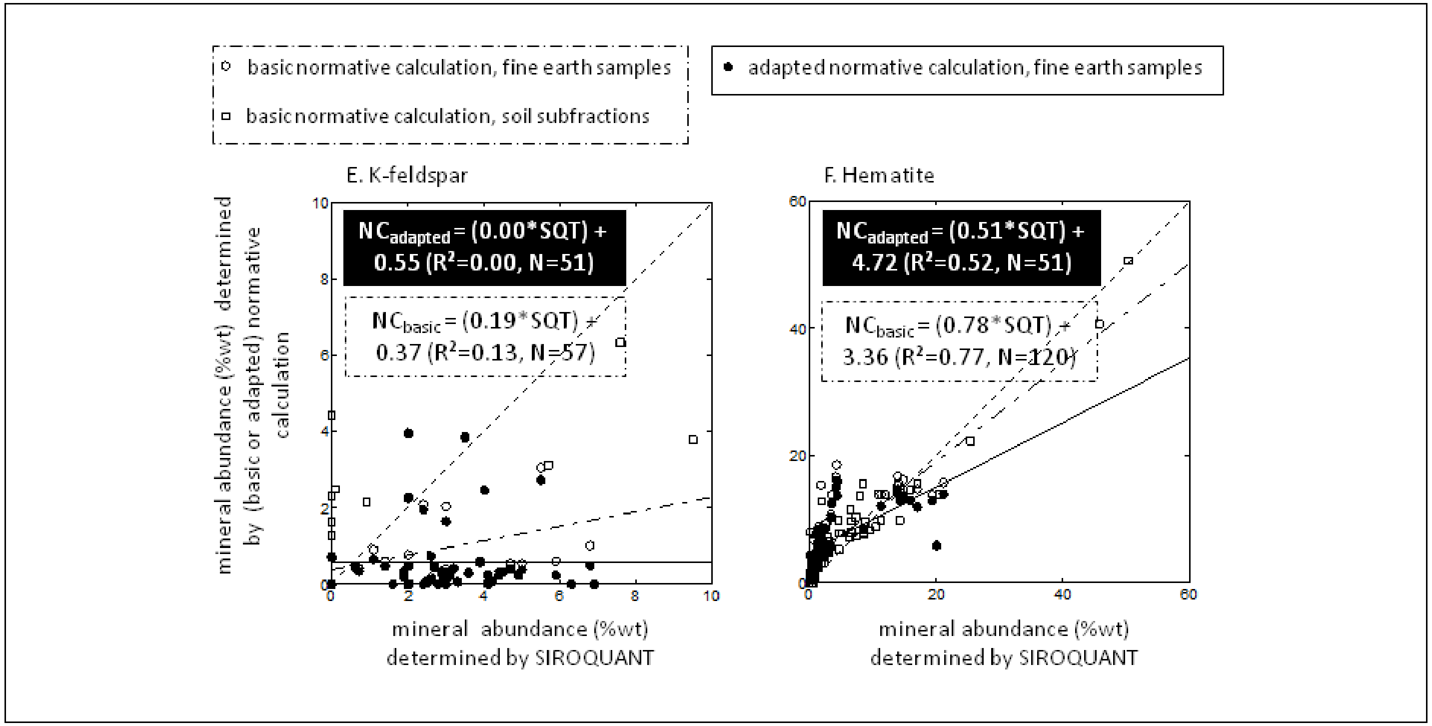

Figure 6.6 (continued). Comparison of the mineral abundances in fine earth and soil subfractions, as determined by normative calculation (basic or adapted calculation) and *SIROQUANT*.

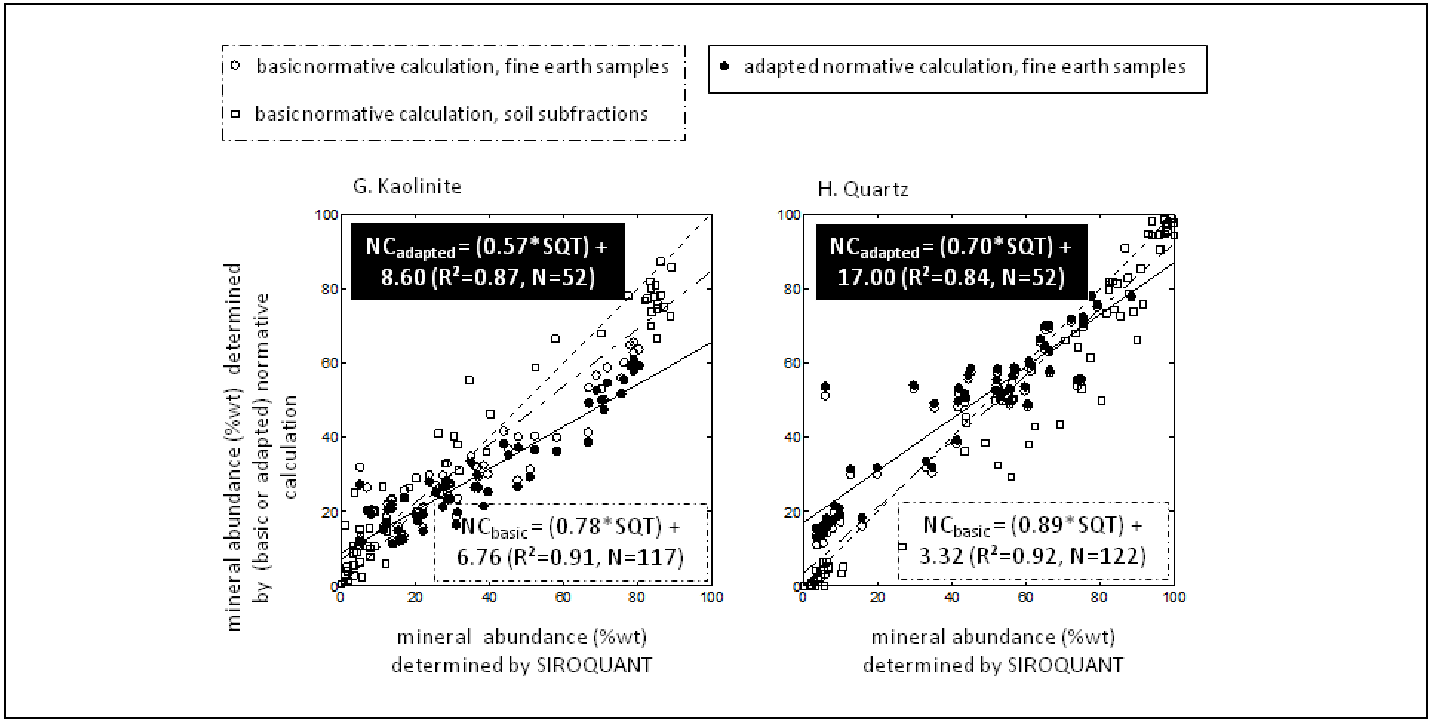

Figure 6.6 (continued). Comparison of the mineral abundances in fine earth and soil subfractions, as determined by normative calculation (basic or adapted calculation) and *SIROQUANT*.

C. Mineralogical composition of fine earth samples compared to the weighted sum of mineral abundances in sand, silt and clay subfractions

The mineralogical composition of fine earth samples can be approximated by the weighted addition of the mineralogical compositions of the textural fractions (sand, silt, clay) constituting them. In Table 6.5, this weighted sum is compared to the mineral quantities directly determined on fine earth samples. The comparison is made for both *SIROQUANT* (right column) and the normative calculation (middle column). For the latter, the comparison implies the mineral abundances computed by the adapted calculation. The adapted calculation is preferred to the basic calculation, since the pre-treatment of the clay fraction with $SrCl_2$ eliminated the exchangeable cations, in the same way as what is advocated by the adapted normative calculation (see [eq.4]).

The relationships summarized in Table 6.5 compare the weighted sum estimates to mineral abundances directly determined for fine earth samples. It seems that normative calculation gives the most coherent results (slopes closest to 1; highest coefficient of determination R-squared) for anatase, hematite, kaolinite and quartz. For albite and K-feldspar, direct determination of the mineralogical composition of fine earth samples gives higher abundances than the weighted sum calculation, and this for both quantification methods. For muscovite, the inverse is true when considering the normative calculation. For vermiculite, data are too scarce (N=1-2) to draw conclusions or make comparisons.

Table 6.5. The mineralogical composition of fine earth samples (FE) is calculated by the weighted sum of the compositions of its textural subfractions (sand, silt and clay) (∑FRACT). The Table compares these weighted sum compositions (∑FRACT) to the mineral abundances effectively determined in fine earth samples by adapted normative calculation ($FE_{adapt.NC}$) and *SIROQUANT* (FE).

Mineral(s) \ Method	Normative calculation	*SIROQUANT*
Anatase	$\sum FRACT = (0.78 * FE_{adapt.NC}) - 0.08$ ($R^2 = 0.85$; N = 17)	$\sum FRACT = (0.35 * FE) + 0.96$ ($R^2 = 0.16$; N = 17)
Vermiculite	ND	ND
Albite	$\sum FRACT = (0.46 * FE_{adapt.NC}) + 0.29$ ($R^2 = 0.78$; N = 9)	ND
Muscovite/sericite	$\sum FRACT = (1.23 * FE) - 3.26$ ($R^2 = 0.81$; N = 15)	$\sum FRACT = (0.65 * FE) - 1.52$ ($R^2 = 0.71$; N = 12)
K-feldspar	$\sum FRACT = (0.33 * FE_{adapt.NC}) + 0.19$ ($R^2 = 0.47$; N = 12)	$\sum FRACT = (0.04 * FE) + 0.35$ ($R^2 = 0.02$; N = 8)
Hematite	$\sum FRACT = (0.91 * FE_{adapt.NC}) + 0.41$ ($R^2 = 0.97$; N = 17)	$\sum FRACT = (0.35 * FE) + 4.13$ ($R^2 = 0.11$; N = 17)
Kaolinite	$\sum FRACT = (1.20 * FE_{adapt.NC}) + 6.40$ ($R^2 = 0.87$; N = 17)	$\sum FRACT = (0.25 * FE) + 29.33$ ($R^2 = 0.06$; N = 17)
Quartz	$\sum FRACT = (1.07 * FE_{adapt.NC}) - 9.08$ ($R^2 = 0.91$; N = 17)	$\sum FRACT = (0.23 * FE) + 36.35$ ($R^2 = 0.08$; N = 17)

6.3.4. Estimates of mineralogical composition of the highly weathered soils of the regions of interest

Table 6.6 (at the end of this chapter, inserted after the conclusions) details the mineralogical compositions of fine earth from soil profiles in the different areas of interest. The mineralogical compositions presented in Table 6.6, are those computed by the adapted normative calculation. For some profiles, the data are graphically represented in Figure 6.7. In both Table 6.6 and Figure 6.7, “unaccounted” stands for the weight percentages not accounted for by the minerals detailed in the description. “Unaccounted” comprises MnO, P_2O_5, but also part of the loss on ignition and MgO, CaO, K_2O if no vermiculite, chlorite, muscovite, K-feldspar are identified in the sample or calcite supposed because of pH values superior to 7.

Quartz is the prevailing mineral (30-78 %wt) in all soils at all depths, except in Kibungo (13-21 %wt quartz; 47-61 %wt kaolinite) or in the deepest horizons of Gitega farm 1 (31-34 %wt quartz; 36-39 %wt kaolinite) where kaolinite dominates (Table 6.6, Figure 6.7). In the profiles of all the regions, the proportions of kaolinite increase with depth. Hematite is more abundant in the soils of Kibungo (12-15 %wt) and Gitega farm 1 (5-16 %wt), than in the other soils (2-10 %wt) studied. Muscovite or sericite was identified in all the regions. In Kibungo muscovite abundances are small (0-3 %wt) compared to the other regions (0-17 %wt and 27 %wt in the parent micaschists at the base of the profile in farm 3 of Ntungamo) (Table 6.6, Figure 6.7). Vermiculite is encountered in small quantities in all the regions, but abundances are highest in Ntungamo farm 3 (1-2 %wt) (Table 6.6, Figure 6.7). K-feldspar abundances range between 0.0 and 1.6 %wt in Butare, Kibungo, Gitega and Ntungamo farms 9+10. Quantities are higher in Ntungamo farm 3 (1.2-4.4 %wt) and farms 2+7 (0.4-2.2 %wt), all three of them on micaschists. The computed albite quantities are 0.0-0.4 %wt in soils of Butare, Kibungo and Gitega. Slightly higher abundances were calculated for Ntungamo: 0.6 to 2.4 %wt, with an exceptional 3.6 %wt in the parent micaschists of farm 3. Calcite brought to soils with kitchen ashes represents minor fractions (max. 0.18 %wt) in some surface horizons. The unaccounted fraction represents 3 to 17 %wt; it is highest in surface horizons and decreases with depth (Table 6.6, Figure 6.7). Higher values in surface horizons are explained by higher organic matter contents than in deep soil samples.

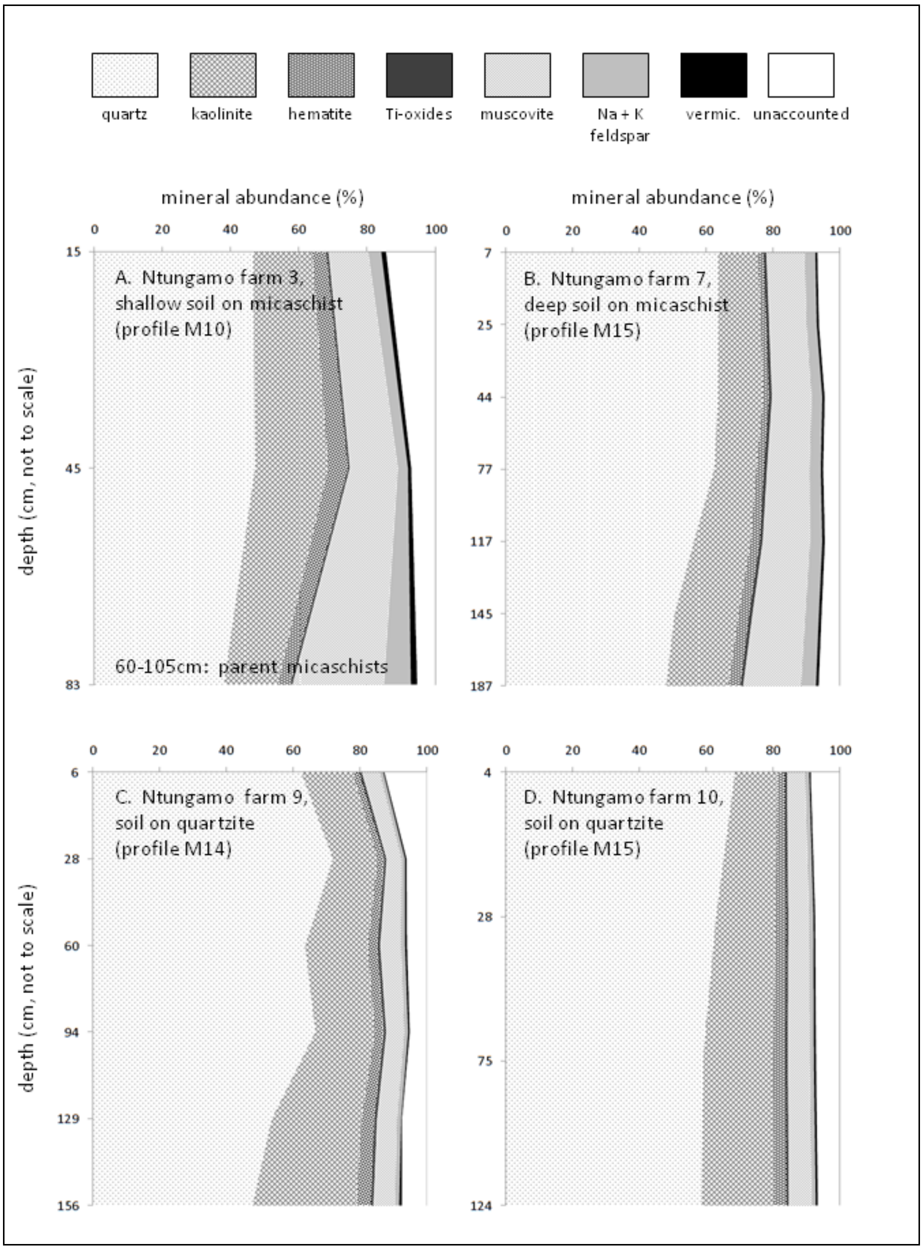

Figure 6.7 (continued on next page). Mineralogical composition (%wt) along soil profiles described in (A, B, C, D) Ntungamo, (E) Butare, (F) Kibungo, and (G, H) Gitega. "Vermic." stands for vermiculite.

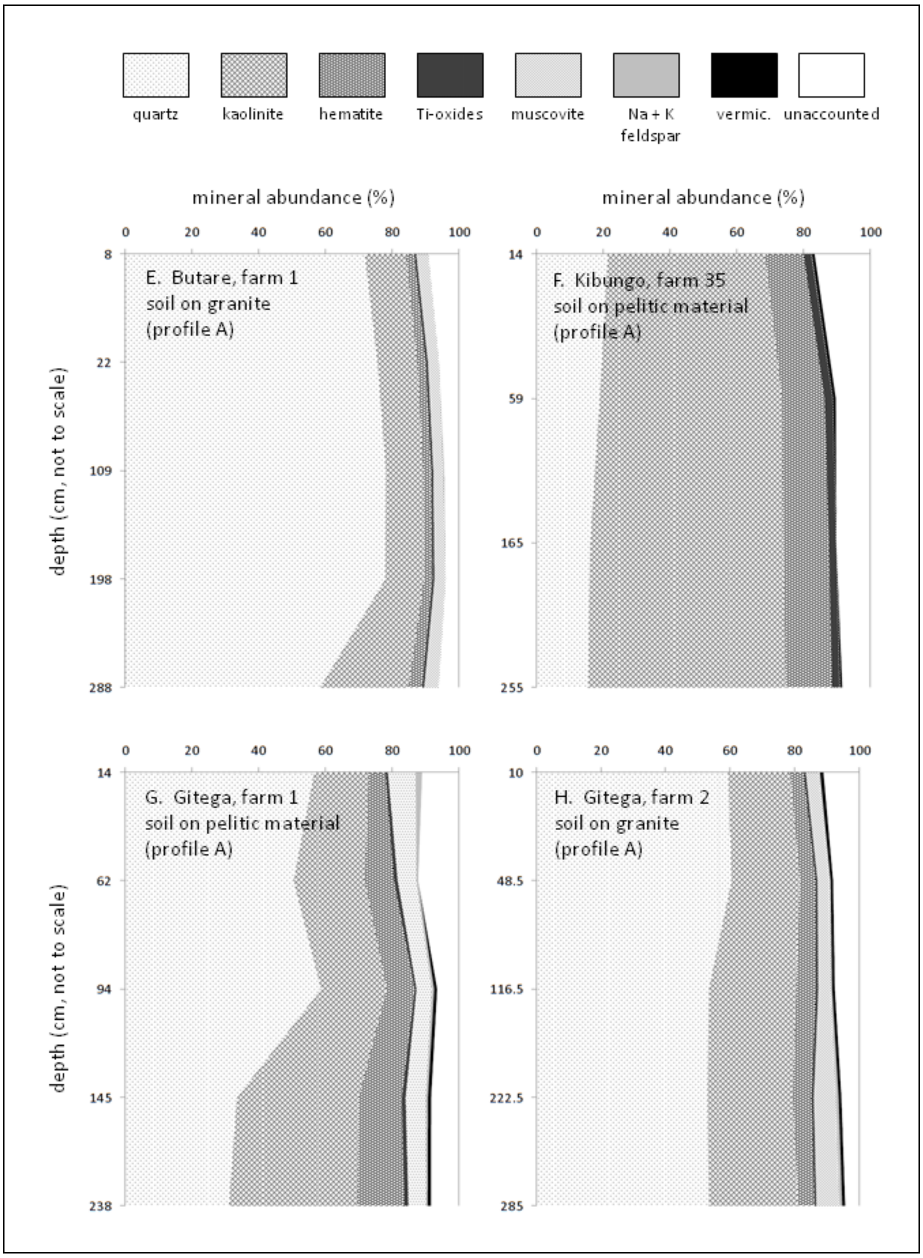

Figure 6.7. (continued). Mineralogical composition (%wt) along soil profiles described in (A, B, C, D) Ntungamo, (E) Butare, (F) Kibungo, and (G, H) Gitega. "Vermic." stands for vermiculite.

6.4. Discussion

6.4.1. Quantification of mineral quantities in powders: comparison of methods

A. SIROQUANT: X-Ray Diffractometry and Rietveld refinement

X-Ray Diffractometry is commonly used to identify and quantify soil minerals. As a quantification tool, XRD is however recognized as limited (Ruan and Ward, 2002). The method is indeed confronted to various drawbacks, appearing at the different steps of the quantifying process.

Hence, sample preparation has a strong influence on the XRD analysis. The quality of the XRD pattern and thus quantification are influenced by (1) insufficient grinding or overgrinding of the powder, (2) insufficiently wide and/or thick samples, (3) loose packing of the powder, (4) induction of preferred orientation of minerals, (5) differential absorption of X-rays by the various minerals in the mixture (Davis, 1987; Bish, 1994; Bish and Reynolds, 1989; Ward et al., 1999). In the samples used in this study, insufficient grinding and preferred orientation have affected the results. Indeed, by manual grinding it is impossible to obtain the fine (< 10 µm) grain size recommended by Bish (1994) for XRD analysis. In our samples, the problem of insufficient and differential grinding arises mainly in the artificial samples, since they are constituted by putting together minerals of different sizes and different hardness. In real soil samples, insufficient grinding affects the results for (1) the coarse textural fractions (coarse particles and sand) of the soils of all regions and for (2) the fine earth of Butare, Ntungamo and, to a lesser extent, Gitega, because of the important sand fraction it contains. The clayey samples (artificial samples #1 #2 #3 #8, fine earth of Kibungo and deep horizons of Gitega farm 1, clay textural subfractions), on the contrary, could suffer of preferred orientation because they are mainly constituted of kaolinite and non-platy minerals are scare in those samples. In the artificial samples, the relationships between the weight percentages of orthoclase and the intensities of the $(002) + (040)$ and $(\bar{1}12)$ reflexions (data not shown) for orthoclase indicate preferred orientation for the samples #9', #12' and #4' of Figure 6.3.C. For kaolinite, similar relationships for the (001) and (020) reflexions (data not shown) evidence preferred orientation for sample #7' of Figure 6.3.D. As in Rosen and Abbyasov (2003) and Rosen et al. (2004), illite is underestimated in the artificial samples. As for the artificial samples of this study, hematite is overestimated compared to quartz in the soil samples of Weidler et al. (1998). They explain this observation by the close association of quartz and hematite in the hand ground samples. The intensity diffracted by quartz is reduced by absorption of portions of the primary intensity by the hematite coating the quartz particles (Weidler et al., 1998).

Another type of difficulty with XRD is the qualitative interpretation of minor phases. According to our observations on artificial samples, the minerals illite, hematite, gibbsite and anatase are not recognized on the XRD pattern if their abundance is inferior to 0.5 %wt. For albite, K-feldspar and chlorite the detection limit is around 1 %wt. The detection limits mentioned here may be artificially low, since peak intensity of the various minerals could have been enhanced because of the coarse grain size of the minerals and/or preferred orientation. Wilson (1987, *cited in* Hodson et al., 1997) or Davis (1987) report detection limits of 1 %wt or even 5 %wt for some minerals. When even the most intense peaks of those minor phases do not stand out clearly against the background or when they suffer superposition of peaks of other mineral phases, the presence or absence of a mineral is a mere subjective interpretation. It proved particularly difficult when deciding about the possible presence of K-feldspars and albite in the real soil samples. In their interlaboratory comparison of quantification of clay minerals, Ottner et al. (2000) pinpoint the qualitative interpretation of clay minerals as causing the strongest divergences between laboratories. In this study, different treatments of the clay fraction (K- or Mg-saturation, heating, air drying, ethylene glycol solvatation, formamide spraying) allowed identification of the clay minerals present. Vermiculite is hence recognized and the presence of halloysite infirmed.

The quantification of mineral compositions by *SIROQUANT* depends on the experience of the user and the sequence of refinement steps he decides to apply (Taylor et al., 2008). When working with real soil samples, the diffractogram may show changes because of (1) ionic substitution in the mineral structure, (2) departure from its ideal chemical composition or (3) variations in crystallinity (Weidler et al., 1998; Ruan and Ward, 2002). The requirement of an adequate structural model of a mineral calls for the specialized intervention to adapt the pre-registered hkl-files. Weidler et al. (1998) or Alves and Omotoso (2009) hence modify the hkl-file for hematite to take into account the Al-substitution in the mineral lattice. And to quantify disordered kaolinite in Lixisols of Mali, Weidler et al. (1998) adapted the corresponding hkl-file. No such adaptations are done in present study and could explain the difficulties encountered to fit the hematite, anatase, muscovite (or illite) and vermiculite peaks.

B. Normative calculation

Normative calculation is an alternative to X-Ray Diffractometry and Rietveld refinement. There are some drawbacks inherent to this second method as well.

First, the normative calculation needs qualitative information on the minerals present in the sample. Information can be obtained by various means or a combination of methods (microscope observation, chemical extraction, thermogravimetry, XRD, …) (e.g. Imbrie and Poldervaart, 1959).

Second, total elemental analyses allow estimations of mineralogical compositions, but additional chemical data are needed for more accurate work. As indicated by the grey patches in Figure 6.5, the abundances computed by the adapted calculation of this study differ sometimes notably from the abundances by the basic calculation. Subtraction of the exchangeable K, Na, Ca and Mg of the total contents of these elements, is the least to be done when evaluating the abundances of remaining weatherable minerals. The contributions of exchangeable K, Mg and Ca to total cation contents (resp. 2-10%, 12-34%, 36-55%) are indeed significant in the surface horizons of the studied soils. Since determination of exchangeable cations is routine work in soil sciences, the required adaption of total cation contents is not constraining. An even more accurate, but less usual, adaptation of total cation contents is the subtraction of cations determined by $CuCl_2$ extraction, in order to eliminate exchangeable K, Na, Ca, Mg and organically bound Ca and Mg.

The third drawback of normative calculation is the need to distribute a chemical element between different minerals (Table 6.3). This demand raises problems when allocating Al and K. Indeed, without complementary information it is impossible to know what fractions of Al are due to Al-oxides and what to kaolinite (see also Nyobe, 1991). A similar problem arises when allocating K to K-feldspars or the micaceous component (muscovite, sericite, illite). This issue is also encountered by Fanning and Keramidas (1977), Tarvainen et al. (1996) or Ward et al. (1999). Complementary analyses as alkaline chemical extraction, thermogravimetry, differential thermal analysis to quantify gibbsite (Mendelovici et al., 1979; Hsu, 1989; Amonette, 2002), or preferential chemical dissolution of muscovite (Kiely and Jackson, 1964) would alleviate unknowns. To avoid supplementary analyses requiring sometimes specialized equipment, simplifications are adopted. Visual appraisal of the XRD-patterns indicates that Al-oxides are minor phases in the studied samples. It is thus decided to allocate all Al_2O_3 to kaolinite when both Al-oxides and kaolinite are identified. Sample #8 of Figure 6.3.E exemplifies the situation where gibbsite cannot be quantified when associated to. This impossibility explains the large discrepancy for the mineral gibbsite in the artificial samples (Figure 6.4.A). For K, the cation is artificially distributed between a micaceous component (muscovite, sericite, illite) and K-feldspars by relying on the Chemical Index of Alteration (CIA) (Nesbitt and Young, 1982; Fedo et al., 1995) and the Mineralogical Index of alteration (α) (Voicu et al., 1997). This circumvented way to estimate K-feldspar and muscovite abundances is appreciated for its ease of use and the fact that it does not require additional analyses.

Also, the computation of the abundances of minerals in the first steps of the calculation procedure (Table 6.3) influences the calculations in the subsequent steps. As illustrated in Figure 6.3.B+C for artificial samples, the overestimation/underestimation (resp. #4 and #9) of illite, leads to an underestimation/overestimation of the abundances of K-feldspar calculated subsequently.

Finally, the abundance calculated for a mineral depends on the chemical formula retained for that mineral (Koljonen and Carlson, 1975; Metzner et Grimmeisen, 1990; Ruan and Ward, 2002). The cases of chlorite and illite in Figure 6.3.A+B exemplify this dependence. Since most of the iron oxides in soils are Al-substituted (Schwertmann and Taylor, 1989), the adapted normative calculation adopts ($Al_{2x}Fe_{2-2x}O_3$) as the chemical formula for hematite. The maximum value allowed for x is 0.18, since further Al-substitution is not observed (Schwertmann et al., 1979) because of the structural instability it would induce (Schwertmann and Kämpf, 1985).

Normative calculation generates globally more accurate results than *SIROQUANT* for the amounts of anatase, chlorite, albite, hematite, kaolinite, gibbsite and quartz in artificial samples (Figure 6.4.A). Discrepancies when evaluating the compositions of mineral mixtures are smaller by normative calculations than by *SIROQUANT* (Figure 6.4.B *vs.* C). Uncertainties range between 50 and 100% (Figure 6.3.B+C) for minerals in low amounts (4 % for normative calculations, 7 % for *SIROQUANT*). Normative calculation gives more coherent results than *SIROQUANT* for anatase, hematite, kaolinite and quartz (Table 6.5), when the mineralogical composition of fine earth is compared to the weighted sum of the compositions of its textural subfractions.

6.4.2. Mineral composition of highly weathered soils in the African Great Lakes Region

The high CIA values underline the weathered nature of the soils. Soils on pelitic rocks in Kibungo and Gitega farm 1 have CIA values around 98 and 95 while CIA for fresh pelitic rocks is about 75 (Nesbitt and Young, 1982). While fresh granites have CIA values between 45 and 55 (Nesbitt and Young, 1982), CIA values for soils on granite are notably higher: 94 in Butare and 95 in Gitega farm 2. In Ntungamo, the highest CIA values (96) are observed for the soils of farms 9+10 on quartzite, the lowest ones for the shallow soils of farm 3 (86). The lowest values for this latter is explained by rejuvenation of soil by erosion on steep slopes. The parent micaschists appear at less than 1 m depth.

The minerals quartz, kaolinite, Ti-oxides, Fe-oxides are present in all the samples analyzed. Al-oxides and muscovite are often identified, although not always. Vermiculite is regularly observed. The occasional presence of feldspars could not be excluded. Low to moderate values for Fe_o/Fe_{DCB} (1-21%) indicates the dominance of crystalline forms of iron oxide, but highlights also the presence of “amorphous” forms. The XRD-patterns do not show any humps, characteristic of non-diffracting material as ferrihydrite. The unnoticeable but nevertheless possible effect of non-diffracting material is subtracted from the XRD pattern along with the background level. Amorphous oxides are not considered further neither in XRD analysis nor in normative calculations. Fe_o/Fe_{DCB} is highest in surface horizons since adsorption of organic components on amorphous oxides impedes further crystallisation (Schwertmann, 1966; Fitzpatrick and Schwertmann, 1982; Schwertmann et al., 1982; Tuhela et al., 1992). Hematite is the sole representative of crystallline oxides effectively identified in the soil. The red color of most of the soils (2.5-5YR) is another indication of the presence of hematite (Esawaran and Sys, 1970; Schwertmann, 1993), although other factors than just the nature of the oxides determine the color of the soil (Schwertmann, 1993). The presence of vermiculite seems plausible, since it is reported as a weathering product of mica (Tardy, 1993 *and references cited therein*; Muggler et al., 2007).

The results by the adapted normative calculation are preferred to the results by *SIROQUANT* (Table 6.6 and Figure 6.7) because of (1) the higher accuracy and (2) coherence of the results in normative calculation, (3) minerals (feldspars or muscovite or sericite) possibly fall below the detection limits by *SIROQUANT*, (4) the abundances of platy or cleaved minerals may be overestimated by XRD because of size effects or preferred orientation.

From qualitative point of view, the observation of this study concord with general descriptions of mineralogy for Acrisols or Nitisols (FAO, 2001). The mineralogy detailed in this report corresponds to the mineralogy of Oxisols in Brazil (Alves and Omotoso, 2009) or Acrisols on biotite gneiss in Nigeria (Okusami et al., 1997). For the Butare area (Rwanda), Schlichting (1983) details the mineralogical composition of soils on granite as determined by microscope counting: 80-85% of quartz, <1% feldspars, <1% muscovite, <1% biotite, <1% rutile. Pyroxene, tourmaline and opaque minerals are also mentioned. The amounts of quartz are higher and those of muscovite lower than the quantities calculated here by normative calculation, but for feldspars and Ti-oxides abundances concord. Biotite, pyroxene, tourmaline and opaque minerals are not identified in our samples and thus not considered. Opdecamp and Sottiaux (1983) detail the minerals in soils on micaceous acid rock in Gitega (Burundi): muscovite or illite, chlorite, kaolinite, gibbsite, goethite and hematite. Mathieu (1985) describes a soil profile on pelitic rocks or granite in Gitega. Both soils contain kaolinite, gibbsite, montmorillonite, vermiculite and iron oxides (hematite or magnetite). Presence of trace quantities of biotite and K-feldspars are reported for the soil on granite. In both soils, the clay fraction is analyzed by differential thermal analysis: kaolinite makes up ±50% of the clay in both soils, gibbsite ±15% in the soil on pelitic rock and ±5% in the soil on granite. The amounts of kaolinite calculated in present study for the clay subfraction, are about 20% higher than those reported by Mathieu (1985). For Gitega, the abundances in kaolinite we determined by normative calculation are overestimates, since in the calculation all Al_2O_3 is allocated to the sole mineral kaolinite, notwithstanding the presence of gibbsite. In the clay fractions of the Gitega samples of this study, gibbsite represented maximum 8 %wt of the soils, according to XRD analysis.

In some surface soil samples of profiles near the homestead, pH is superior to 7. High pHs (max observed: pH 9 in Gitega farm 2) could be explained by carbonates in kitchen ashes disseminated over the soils. Since calcite is the major compound in kitchen ashes (Eteigni and Campbell, 1991; Ohno, 1992; Demeyer et al., 2001), this mineral was anecdotally considered in this study.

6.5. Conclusions

X-Ray Diffractometry and normative calculation were compared in order to quantify the mineralogical compositions of highly weathered Acrisols and Nitisols. To do so the abundances of quartz, kaolinite, Ti-oxides (anatase or rutile), hematite, gibbsite, illite or muscovite or sericite, chlorite or vermiculite, albite, K-feldspars and calcite were determined in artificial samples, fine earth samples (< 2000 µm) and soil textural subfractions (coarse particles (> 2000 µm), sand (63-2000 µm), silt (2-63 µm), clay (0-2 µm)).

Relying on routine chemical analyses, the adapted normative calculation proves a rapid and easily adaptable tool to estimate soil mineral contents. Despite the simplifications inherent to the computation, the adapted normative calculation gives more accurate and coherent results than the commonly X-Ray Diffractometry.

The calculation allows estimation of mineral abundances in highly weathered soils for which mineral contents are scarce or inexistent. In highly weathered soils dominated by quartz and kaolinite, weatherable minerals (feldspars, Al-vermiculite), possible calcite) are present in low amounts. K-feldspars abundances are max. 0.4 %wt in Butare, Kibungo and Gitega; higher values are calculated for Ntungamo (1.7%wt for farms 2, 9; 4%wt in parent micaschist of farm 3). Albite amounts for max. 0.5% wt in upper parts of soil profiles in Butare, Kibungo, Gitega farm 2 and Ntungamo farm 9. Albite abundances are max 1.6 %wt in Gitega farm 1 and Ntungamo farm 2 and 4 %wt in micaschists of Ntungamo farm 3. Vermiculite contents are inferior to 1 %wt in all regions and subregions except in the parent micaschists of Ntungamo farm 3 (5 %wt). For soils with pH superior to 7 in surface horizons, calcite (max. 0.18 %wt) is supposedly present, brought to soils through amendments with kitchen ashes. In the upper 1 m of soil profiles of weathered soils from Butare, Kibungo and Gitega farm 1 muscovite contents are max. 4 %wt. Abundances are higher in Gitega farm 1 and Ntungamo farm 9 (8 %wt) and farm 2 on micaschist (13 %wt). Muscovite makes up 27 %wt of the parent micaschists in Ntungamo farm 3. The results of this study hence confirm the accepted but rarely quantified image of highly weathered soils with small amounts of weatherable minerals and thus a limited capacity to supply plant nutrients. In highly weathered soils with low weatherable mineral contents and clay fraction dominated by low-activity clays, organic matter has a key role in maintaining soil fertility.

Table 6.6 (continued on following pages). Mineral abundances computed by the adapted normative calculation for various profiles in highly weathered soils of the Great Lakes Region. "Un-acc. (unaccounted)" stands for the elemental oxides or LOI remaining at the end of the calculation procedure: MnO, P_2O_5, CaO, but possibly also parts of LOI, MgO, CaO, K_2O. CIA values are calculated with $Al_2O_{3,tot}$, CaO_{min}, K_2O_{min}, Na_2O_{min}.([eq.4+5]).

Region (profile)	Horizon	Depth (cm)	CIA	Quartz (%wt)	Kaoli-nite (%wt)	Al-hema-tite (%wt)	Anatase (%wt)	Musco-vite (%wt)	Albite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Un-acc. (%wt)
Ntunga	1	0-16	87.97	58.09	16.65	2.90	0.87	10.08	1.31	0.96	0.00	0.63	8.50
mo	2	16-35	87.95	56.38	17.60	3.25	0.88	10.89	1.29	1.04	0.00	0.66	8.02
Farm 2	3	35-56	87.85	55.97	18.34	3.35	0.99	11.59	1.34	1.12	0.00	0.63	6.67
(profile	4	56-69	88.39	55.27	19.47	3.35	0.92	11.41	1.30	1.05	0.00	0.63	6.61
M6)	5	69-145	87.78	53.27	19.51	3.74	0.87	12.58	1.40	1.22	0.00	0.67	6.73
	augered	150-173	87.82	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	178-195	87.59	44.43	23.02	4.71	0.86	15.06	1.49	1.46	0.00	0.86	8.10
	augered	200-216	88.04	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	221-228	87.97	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	233-248	87.95	44.44	21.49	6.10	0.69	14.42	1.55	1.43	0.00	0.71	9.17
	augered	253-267	87.85	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Table 6.6 (continued). Mineral abundances computed by the adapted normative calculation for various profiles in highly weathered soils of the Great Lakes Region. "Un-acc. (unaccounted)" stands for the elemental oxides or LOI remaining at the end of the calculation procedure: MnO, P_2O_5, CaO, but possibly also parts of LOI, MgO, CaO, K_2O. CIA values are calculated with $Al_2O_{3,tot}$, CaO_{min}, K_2O_{min}, Na_2O_{min}.([eq.4+5]).

Region (profile)	Horizon	Depth (cm)	CIA	Quartz (%wt)	Kaoli-nite (%wt)	Al-hema-tite (%wt)	Anatase (%wt)	Musco-vite (%wt)	Albite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Un-acc. (%wt)
Ntungamo Farm 7 (profile M4)	1	0-20	85.33	63.07	13.30	1.76	0.80	11.31	1.57	1.36	0.08	0.61	4.84
	2	20-45	84.95	60.70	14.41	2.09	0.95	12.87	1.73	1.59	0.00	0.72	4.93
	3	45-115	85.37	60.48	14.91	2.14	0.84	12.73	1.73	1.52	0.00	0.75	4.89
	4	115-133	85.96	59.90	15.68	2.55	0.88	12.59	1.76	1.44	0.00	0.74	4.46
	5	133-145	86.02	56.30	17.26	2.80	0.87	13.68	1.94	1.55	0.00	0.75	4.84
	augered	150-167	85.70	50.47	19.19	3.33	0.88	15.86	2.37	1.85	0.00	0.83	5.23
	augered	172-184	85.83	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	189-198	85.63	49.21	19.45	3.88	0.74	16.08	2.19	1.85	0.00	0.69	5.91
	augered	203-210	85.97	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	215-225	85.33	41.31	18.75	6.92	0.66	16.26	2.29	1.91	0.00	0.77	11.13
	augered	227-229	84.95	38.74	20.80	7.83	0.73	17.24	2.31	1.97	0.00	0.75	9.62
Ntungamo Farm 7 (profile M7)	1	0-13	85.27	63.72	13.15	1.62	0.86	10.92	1.58	1.32	0.00	0.70	6.12
	2	13-33	85.09	62.40	12.22	1.63	0.94	10.76	1.57	1.32	0.00	0.68	8.49
	3	33-75	86.30	60.25	16.45	2.02	0.95	12.43	1.64	1.38	0.00	0.71	4.18
	4	75-115	83.43	60.22	12.55	2.25	0.85	14.45	1.81	2.00	0.00	0.82	5.04
	5	115-139	85.02	55.20	16.49	2.89	0.89	15.10	2.06	1.86	0.00	0.79	4.72
	augered	139-153	85.33	42.22	19.39	5.56	0.71	17.33	2.28	2.08	0.00	0.73	9.69

Table 6.6 (continued). Mineral abundances computed by the adapted normative calculation for various profiles in highly weathered soils of the Great Lakes Region. "Un-acc. (unaccounted)" stands for the elemental oxides or LOI remaining at the end of the calculation procedure: MnO, P_2O_5, CaO, but possibly also parts of LOI, MgO, CaO, K_2O. CIA values are calculated with $Al_2O_{3,tot}$, CaO_{min}, K_2O_{min}, Na_2O_{min}.([eq.4+5]).

Region (profile)	Horizon	Depth (cm)	CIA	Quartz (%wt)	Kaoli-nite (%wt)	Al-hema-tite (%wt)	Anatase (%wt)	Musco-vite (%wt)	Albite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Un-acc. (%wt)
Ntungamo Farm 7 (profile M15)	1	0-14	84.25	63.73	11.96	1.63	0.84	11.52	1.73	1.50	0.00	0.56	6.51
	2	14-35	84.98	63.80	12.80	1.64	0.80	11.25	1.68	1.39	0.00	0.62	6.03
	3	35-53	85.16	63.69	13.62	1.72	0.82	11.95	1.69	1.46	0.00	0.70	4.34
	4	53-100	84.34	62.57	12.62	2.30	0.88	12.81	1.69	1.66	0.00	0.68	4.79
	5	100-136	85.67	56.49	16.99	2.77	0.79	14.29	1.95	1.67	0.00	0.76	4.28
	augered	139-150	85.71	50.72	19.07	3.28	0.89	15.99	2.16	1.86	0.00	0.77	5.25
	augered	155-167	84.77	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	170-174	92.97	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	179-194	92.97	48.18	18.44	3.71	0.78	17.46	2.35	2.19	0.00	0.78	6.11
Ntungamo Farm 9 (profile M6)	1	0-19	93.45	61.47	19.85	2.96	0.65	5.45	0.62	0.29	0.00	0.62	8.08
	2	19-47	95.42	53.69	24.70	4.24	0.63	6.98	0.74	0.37	0.00	0.67	7.97
	3	47-90	85.27	46.54	29.97	4.83	0.66	7.81	0.76	0.38	0.00	0.74	8.30
	4	90-120	85.09	29.81	43.73	9.94	0.52	7.54	0.74	0.25	0.00	0.62	6.85

Table 6.6 (continued). Mineral abundances computed by the adapted normative calculation for various profiles in highly weathered soils of the Great Lakes Region. "Un-acc. (unaccounted)" stands for the elemental oxides or LOI remaining at the end of the calculation procedure: MnO, P_2O_5, CaO, but possibly also parts of LOI, MgO, CaO, K_2O. CIA values are calculated with $Al_2O_{3,tot}$, CaO_{min}, K_2O_{min}, Na_2O_{min}.([eq.4+5]).

Region (profile)	Horizon	Depth (cm)	CIA	Quartz (%wt)	Kaoli-nite (%wt)	Al-hema-tite (%wt)	Anatase (%wt)	Musco-vite (%wt)	Albite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Un-acc. (%wt)
Ntungamo Farm 9 (profile M8)	1	0-34	92.96	56.72	22.77	3.32	0.64	6.28	0.70	0.33	0.00	0.67	8.58
	2	34-45	92.97	53.66	24.61	3.56	0.62	6.81	0.71	0.36	0.00	0.65	9.01
	3	45-80	93.82	40.11	35.17	5.05	0.60	8.45	0.81	0.39	0.00	0.85	8.58
	4	80-145	93.55	38.56	34.38	5.58	0.51	8.92	0.75	0.43	0.00	0.81	10.05
Ntungamo Farm9 (profile M12)	1a	0-12	91.77	62.47	15.40	2.20	0.67	5.41	0.67	0.34	0.00	0.30	12.55
	1b	12-44	91.45	72.06	13.45	1.88	0.66	4.64	0.62	0.30	0.06	0.48	5.16
	2	44-75	91.88	63.68	18.78	2.92	0.76	6.40	0.69	0.40	0.05	0.57	5.42
	3	75-113	92.26	66.78	17.86	2.56	0.76	5.57	0.68	0.33	0.05	0.51	4.52
	4	113-145	93.82	53.72	26.86	3.93	0.71	6.16	0.83	0.28	0.00	0.22	7.30
	augered	150-167	94.30	47.91	31.14	4.38	0.70	6.61	0.86	0.28	0.00	0.81	7.30
	augered	172-179	94.52	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	184-191	94.44	44.65	33.43	5.02	0.68	6.77	0.90	0.27	0.00	0.76	7.52
	augered	195-217	93.53	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	220-222	89.84	40.98	35.19	5.40	0.69	7.33	0.94	0.30	0.00	0.77	8.40
	augered	227-236	91.58	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	240-249	92.41	38.76	34.66	6.27	0.66	9.10	0.88	0.44	0.00	0.62	8.59

Table 6.6 (continued). Mineral abundances computed by the adapted normative calculation for various profiles in highly weathered soils of the Great Lakes Region. "Un-acc. (unaccounted)" stands for the elemental oxides or LOI remaining at the end of the calculation procedure: MnO, P_2O_5, CaO, but possibly also parts of LOI, MgO, CaO, K_2O. CIA values are calculated with $Al_2O_{3,tot}$, CaO_{min}, K_2O_{min}, Na_2O_{min}.([eq.4+5]).

Region (profile)	Horizon	Depth (cm)	CIA	Quartz (%wt)	Kaoli-nite (%wt)	Al-hema-tite (%wt)	Anatase (%wt)	Musco-vite (%wt)	Albite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Un-acc. (%wt)
Ntunga mo F10 (profile M5)	1	0-7	92.44	68.76	12.72	2.19	0.65	5.44	0.81	0.43	0.00	0.42	8.58
	2	7-48	92.96	62.98	17.97	3.10	0.65	6.38	0.74	0.41	0.00	0.54	7.23
	3	48-102	92.97	59.05	21.21	3.61	0.70	6.64	0.76	0.38	0.00	0.66	6.98
	4	102-145	93.82	58.66	21.82	3.69	0.69	6.94	0.69	0.40	0.0	0.69	6.43
Ntunga mo Farm 10 (profile M11)	1	0-7	91.58	64.45	16.28	2.94	0.60	5.79	0.68	0.37	0.00	0.52	8.37
	2	7-46	92.29	60.25	19.94	3.41	0.69	6.35	0.72	0.37	0.00	0.61	7.66
	3A	46-63	92.88	58.87	22.36	3.52	0.70	6.33	0.74	0.34	0.00	0.63	6.51
	3B	63-143	92.78	59.18	22.10	3.81	0.72	6.30	0.76	0.34	0.00	0.66	6.12
	4	143-160	93.58	47.22	29.80	4.81	0.68	7.59	0.79	0.36	0.00	0.71	8.05
Ntunga mo Farm 10 (profile M13)	1	0-15	92.08	65.23	16.09	4.69	0.68	5.29	0.68	0.32	0.00	0.53	6.49
	2	15-40	92.03	64.67	17.84	2.54	0.67	5.78	0.73	0.35	0.00	0.55	6.87
	3	40-63	92.03	62.90	19.19	3.28	0.72	6.27	0.80	0.38	0.00	0.60	5.86
	4	63-134	91.19	59.16	20.66	3.34	0.72	7.58	1.10	0.51	0.00	0.63	6.31
	augered	139-157	91.94	60.39	21.15	3.24	0.75	6.85	1.01	0.42	0.00	0.60	5.58
	augered	162-177	92.39	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	182-200	92.26	53.74	25.09	3.97	0.79	7.80	0.94	0.45	0.00	0.67	6.53
	augered	205-217	91.58	55.04	24.59	3.76	0.77	7.82	0.94	0.46	0.00	0.70	5.92
	augered	222-228	92.29	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

Table 6.6 (continued). Mineral abundances computed by the adapted normative calculation for various profiles in highly weathered soils of the Great Lakes Region. "Un-acc. (unaccounted)" stands for the elemental oxides or LOI remaining at the end of the calculation procedure: MnO, P_2O_5, CaO, but possibly also parts of LOI, MgO, CaO, K_2O. CIA values are calculated with $Al_2O_{3,tot}$, CaO_{min}, K_2O_{min}, Na_2O_{min}.([eq.4+5]).

Region (profile)	Horizon	Depth (cm)	CIA	Quartz (%wt)	Kaoli-nite (%wt)	Al-hema-tite (%wt)	Anatase (%wt)	Musco-vite (%wt)	Albite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Un-acc. (%wt)
Ntungamo F.3 (profile M10)	1	0-29	86.65	46.84	16.82	4.22	0.57	12.41	1.97	1.34	0.00	1.45	14.39
	2	29-60	89.63	47.18	21.45	5.80	0.54	14.16	1.80	1.15	0.05	0.99	6.58
	3, parent material		81.07	15.74	37.99	3.94	0.51	26.81	3.57	4.38	ND	1.88	5.18
Butare Farm 1 (profile A)	Ap1	0-15	92.17	71.89	12.43	2.39	0.65	3.65	0.00	0.47	0.03	0.00	7.57
	Ap2	15-28	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	AB1	28-52	91.89	75.73	12.05	2.36	0.71	3.35	0.00	0.45	0.10	0.00	4.61
	AB2	52-70	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	B1	70-98	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	B2	98-120	92.09	78.26	11.31	2.21	0.64	2.94	0.00	0.39	0.12	0.43	3.23
	B3	120-160	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Bs	160-80	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	180-215	91.88	78.07	11.71	2.33	0.69	3.41	0.00	0.46	0.00	0.00	3.33
	augered	215-255	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	255-275	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	275-300	95.14	58.55	26.58	3.90	0.72	4.45	0.00	0.34	0.00	0.00	5.46

Table 6.6 (continued). Mineral abundances computed by the adapted normative calculation for various profiles in highly weathered soils of the Great Lakes Region. "Un-acc. (unaccounted)" stands for the elemental oxides or LOI remaining at the end of the calculation procedure: MnO, P_2O_5, CaO, but possibly also parts of LOI, MgO, CaO, K_2O. CIA values are calculated with $Al_2O_{3,tot}$, CaO_{min}, K_2O_{min}, Na_2O_{min}.([eq.4+5]).

Region (profile)	Horizon	Depth (cm)	CIA	Quartz (%wt)	Kaoli-nite (%wt)	Al-hema-tite (%wt)	Anatase (%wt)	Musco-vite (%wt)	Albite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Un-acc. (%wt)
Butare	Ap	0-22	93.09	72.37	14.81	2.72	0.61	3.66	0.00	0.00	0.00	0.42	5.41
Farm 1	AB	22-45	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
(profile	Bt1	45-93	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
B)	BtG1	93-105	93.85	70.52	17.24	3.29	0.75	3.80	0.00	0.00	0.06	0.47	3.39
	BtG2	105-150	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	160-190	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	200-220	96.16	50.96	33.19	4.83	0.74	4.26	0.00	0.00	0.00	0.58	5.44
	augered	230-255	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	260-280	96.26	49.01	35.20	5.03	0.73	4.31	0.00	0.00	0.11	0.63	4.43
Butare	Ap1	0-18	94.88	70.23	14.70	2.98	0.57	2.79	0.32	0.22	0.00	0.00	8.19
Farm 67	Ap2	18-60	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
(profile	AB	60-88	94.75	66.37	23.34	3.58	0.75	0.00	0.00	0.29	0.00	0.00	5.67
A)	Bt1	88-123	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	2A	123-165	95.95	58.44	29.77	4.24	0.83	0.00	0.00	0.22	0.62	0.00	5.87

Table 6.6 (continued). Mineral abundances computed by the adapted normative calculation for various profiles in highly weathered soils of the Great Lakes Region. "Un-acc. (unaccounted)" stands for the elemental oxides or LOI remaining at the end of the calculation procedure: MnO, P_2O_5, CaO, but possibly also parts of LOI, MgO, CaO, K_2O. CIA values are calculated with $Al_2O_{3,tot}$, CaO_{min}, K_2O_{min}, Na_2O_{min}.([eq.4+5]).

Region (profile)	Horizon	Depth (cm)	CIA	Quartz (%wt)	Kaoli-nite (%wt)	Al-hema-tite (%wt)	Anatase (%wt)	Musco-vite (%wt)	Albite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Un-acc. (%wt)
Butare	Ap	0-38	92.99	69.92	18.50	3.10	0.55	0.00	0.27	0.37	0.58	0.00	6.72
Farm 67	Bt1	38-61	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
(profile	BtG1	61-92	95.71	64.65	25.09	3.56	0.72	0.00	0.00	0.21	0.00	0.00	5.77
B)	BtG2	92-126	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	BtG3	126-160	96.00	49.56	37.25	4.88	0.76	0.00	0.23	0.26	0.68	0.00	6.39
Kibungo	Ap1	0-22	98.37	18.18	52.58	11.96	2.44	0.00	0.00	0.05	0.98	0.00	13.82
Farm 32	AB	22-40	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
(profile	B1	40-58	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
B)	B2	58-103	98.61	18.02	55.44	12.80	2.55	0.00	0.00	0.04	0.87	0.00	10.29
	B3	103-150	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	150-180	98.90	14.08	59.40	14.01	2.16	0.00	0.00	0.02	0.73	0.00	9.59
	augered	185-210	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	215-240	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	245-265	98.63	13.01	61.08	13.59	2.29	0.00	0.00	0.04	0.00	0.00	9.98

Table 6.6 (continued). Mineral abundances computed by the adapted normative calculation for various profiles in highly weathered soils of the Great Lakes Region. "Un-acc. (unaccounted)" stands for the elemental oxides or LOI remaining at the end of the calculation procedure: MnO, P_2O_5, CaO, but possibly also parts of LOI, MgO, CaO, K_2O. CIA values are calculated with $Al_2O_{3,tot}$, CaO_{min}, K_2O_{min}, Na_2O_{min}.([eq.4+5]).

Region (profile)	Horizon	Depth (cm)	CIA	Quartz (%wt)	Kaoli-nite (%wt)	Al-hema-tite (%wt)	Anatase (%wt)	Musco-vite (%wt)	Albite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Un-acc. (%wt)
Kibungo Farm 35 (profile A)	Ap	0-28	97.96	21.43	47.04	11.81	2.27	0.00	0.00	0.00	0.00	0.88	14.73
	BA	28-41	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	B1	41-76	98.25	19.02	54.66	12.82	2.46	0.00	0.00	0.00	0.00	0.86	10.18
	B2	76-127	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	B3	127-150	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	150-180	98.69	16.18	57.82	13.76	2.21	0.00	0.00	0.00	0.00	0.00	10.03
	augered	185-210	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	215-240	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	245-265	98.50	15.49	59.35	13.80	2.37	0.00	0.00	0.05	0.00	0.68	8.25
Kibungo Farm 38 (profile B)	Ap	0-21	98.18	15.93	49.88	12.84	2.23	2.69	0.00	0.00	0.00	1.00	15.43
	AB	21-45	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	BA	45-60	97.69	20.85	49.20	13.89	2.41	0.00	0.00	0.10	0.00	0.95	12.61
	B1	60-82	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	B2	82-110	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	B3	110-150	98.09	17.38	51.69	14.64	2.31	2.71	0.00	0.00	0.00	0.84	10.43

Table 6.6 (continued). Mineral abundances computed by the adapted normative calculation for various profiles in highly weathered soils of the Great Lakes Region. "Un-acc. (unaccounted)" stands for the elemental oxides or LOI remaining at the end of the calculation procedure: MnO, P_2O_5, CaO, but possibly also parts of LOI, MgO, CaO, K_2O. CIA values are calculated with $Al_2O_{3,tot}$, CaO_{min}, K_2O_{min}, Na_2O_{min}.([eq.4+5]).

Region (profile)	Horizon	Depth (cm)	CIA	Quartz (%wt)	Kaoli-nite (%wt)	Al-hema-tite (%wt)	Anatase (%wt)	Musco-vite (%wt)	Albite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Un-acc. (%wt)
Gitega	Ap1	0-27	88.80	56.78	16.40	5.05	0.71	8.15	0.42	1.64	0.00	0.00	10.85
Farm 1	Ap2	27-54	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
(profile1	AB	54-70	93.45	50.59	21.40	8.75	1.08	5.51	0.00	0.58	0.00	0.00	12.09
A)	B1	70-82	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	2B2	82-105	94.16	58.84	19.72	8.20	0.67	4.62	0.23	0.43	0.00	0.92	6.38
	3B3	105-130	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	130-160	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	160-200	95.50	33.62	36.50	12.90	1.15	6.06	0.21	0.42	0.00	0.95	8.20
Gitega	Ap	0-25	93.27	55.19	20.24	7.19	0.95	5.91	0.30	0.64	0.00	1.23	8.36
Farm 1	B1	25-61	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
(profile	2B2	61-88	96.54	51.62	25.19	10.80	0.85	3.57	0.15	0.19	0.00	0.79	6.84
B)	2B3	88-110	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	130-165	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	165-195	96.41	31.96	38.17	14.98	1.49	4.91	0.16	0.27	0.00	0.00	8.06
	augered	195-210	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	210-240	96.67	31.62	36.25	16.15	1.81	4.40	0.14	0.22	0.00	0.00	9.40

Table 6.6 (continued). Mineral abundances computed by the adapted normative calculation for various profiles in highly weathered soils of the Great Lakes Region. "Un-acc. (unaccounted)" stands for the elemental oxides or LOI remaining at the end of the calculation procedure: MnO, P_2O_5, CaO, but possibly also parts of LOI, MgO, CaO, K_2O. CIA values are calculated with $Al_2O_{3,tot}$, CaO_{min}, K_2O_{min}, Na_2O_{min}.([eq.4+5]).

Region (profile)	Horizon	Depth (cm)	CIA	Quartz (%wt)	Kaoli-nite (%wt)	Al-hema-tite (%wt)	Anatase (%wt)	Musco-vite (%wt)	Albite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Un-acc. (%wt)
Gitega Farm 2 (profile A)	Ap1	0-20	94.10	59.55	19.12	4.23	0.70	4.02	0.25	0.00	0.18	1.15	9.04
	Ap2	20-35	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Ap3	35-62	95.42	60.54	21.18	4.82	0.68	3.81	0.17	0.00	0.00	0.80	7.99
	BA	62-80	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	B1	80-103	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	B2	103-130	96.27	53.48	27.08	6.11	0.80	3.86	0.16	0.22	0.00	0.86	7.43
	B3	130-170	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	170-185	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	195-250	93.72	53.10	26.39	5.81	0.77	6.81	0.19	0.68	0.00	0.86	5.39
	augered	260-270	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	270-300	93.65	53.46	27.78	4.96	0.68	7.07	0.23	0.72	0.00	0.90	4.20

Table 6.6 (continued). Mineral abundances computed by the adapted normative calculation for various profiles in highly weathered soils of the Great Lakes Region. "Un-acc. (unaccounted)" stands for the elemental oxides or LOI remaining at the end of the calculation procedure: MnO, P_2O_5, CaO, but possibly also parts of LOI, MgO, CaO, K_2O. CIA values are calculated with $Al_2O_{3,tot}$, CaO_{min}, K_2O_{min}, Na_2O_{min}.([eq.4+5]).

Region (profile)	Horizon	Depth (cm)	CIA	Quartz (%wt)	Kaoli-nite (%wt)	Al-hema-tite (%wt)	Anatase (%wt)	Musco-vite (%wt)	Albite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Un-acc. (%wt)
Gitega Farm 2 (profile B)	Ap1	0-22	95.85	56.54	23.39	5.21	0.78	3.64	0.19	0.23	0.00	0.91	9.11
	Ap2	22-51	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	AB	51-77	96.62	52.55	26.49	6.15	0.84	3.33	0.13	0.00	0.00	0.90	9.61
	BA	77-91	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	B1	91-109	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	B2	109-128	96.39	52.12	28.22	6.05	0.89	4.01	0.11	0.22	0.00	0.83	7.55
	B3	128-160	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	160-190	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	195-220	95.65	55.43	26.48	6.08	0.73	4.33	0.18	0.29	0.00	0.83	5.64
	augered	225-250	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	255-260	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	augered	265-290	95.10	53.92	29.24	5.22	0.72	5.33	0.17	0.40	0.00	0.76	4.23

7. Importance of organic matter for the nutrient supply of bananas grown on highly weathered soils of the African Great Lakes Region

Abstract

The aim of this study is to evaluate the importance of organic matter and soil minerals as plant nutrient sources and contributors to the cation exchange capacity of the soil. The study areas in Rwanda, Burundi and Uganda represent different agro-ecoregions, at different altitudes, under various climatic conditions and with soils on contrasting parent materials. All soils are highly weathered. They are constituted of various proportions of quartz, kaolinite, Fe-oxides, Al-oxides, Ti-oxides, muscovite, small quantities of vermiculite and occasional K-feldspars and albite. Calcite may be present in surface horizons having pH superior to 7. The release rates of Na, K, Ca and Mg by weathering of albite-plagioclase, K-feldspars, muscovite, calcite and vermiculite are evaluated by the data-intensive geochemical model *PROFILE*. The study searches for ranges of release rates more than for absolute values. Various parameters of the model are thus allowed to vary within realistic ranges, as deduced from measurement or literature surveys. Amongst the input data, a stable self-sufficient system is hypothesized to make *PROFILE* run. All scenarios and all regions considered together, the release rates by mineral weathering reach maximum 5.9 $kg.ha^{-1}.year^{-1}$ for Na, 32.5 $kg.ha^{-1}.year^{-1}$ for K and 12.5 $kg.ha^{-1}.year^{-1}$ for Mg. When calcite is brought to soils through amendments with kitchen ashes, Ca release rates may reach 155.4 $kg.ha^{-1}.year^{-1}$ but are otherwise close to zero. Inputs by banana leaves, pseudostems and bunches are estimated at 653-1326 $kg.ha^{-1}.year^{-1}$ for K, 47-93 $kg.ha^{-1}.year^{-1}$ for Mg and

93-193 kg.ha^{-1}.year^{-1} for Ca. Mineralization of recycled banana residues insures nutrient fluxes at least one order of magnitude higher than the mineral weathering rates. Organic matter is in the meantime an important contributor to the cation exchange capacity (CEC) of the soils. It accounts for 60-98% of the CEC in surface horizons and 20-50% at depth. Minerals are the other contributors to CEC. Their contribution increases with depth (40-2% in surface samples, 80-50% in deep horizons). Because of its importance as nutrient source and contributor to CEC, organic matter has a central role in insuring the sustainability of the banana cultivation in traditional small-holder farms of the African Great Lakes Region. Minerals may be limited as nutrient sources, but keep an importance as contributors to CEC.

Keywords
Tropical soils; East African Highlands; *PROFILE*; nutrient fluxes; organic matter

7.1. Introduction

The soil is the major reservoir for plant-available water and nutrients. Physicochemical (weathering, absorption, desorption, precipitation/ condensation) and biochemical (mineralization, immobili-zation) processes control the availability of nutrients in soils (Comerford, 2005). Related to these physicochemical processes, the long-term delivering capacity of plant nutrients by weathering is a measure of inherent soil fertility (Holmqvist et al., 2003).

The model *PROFILE* is a steady-state soil chemical model which includes a submodel for the release of base cations and phosphorous by mineral weathering (Sverdrup and Warfinge, 1993). Originally developed to address soil acidification problems, the model is commonly used to estimate the soil's vulnerability to acid deposition (Hodson and Langan, 1999; Koptsik et al., 1999) or to calculate weathering rates (Duan et al., 2002; Holmqvist et al., 2003; Laclau et al., 2005; Nzila et al., 2004; Ouimet and Duchesne, 2005; Koseva et al., 2010). It is most widely used through Europe (e.g. Sverdrup and Warfinge, 1993; Koptsik et al., 1999; Holmqvist et al., 2003) and North America (e.g. Ouimet and Duchesne, 2005; Koseva et al 2010), with more occasional uses in tropical or subtropical environments (Duan et al., 2002; Laclau et al., 2005; Nzila et al., 2004).

PROFILE provides the weathering rates of 14 common minerals and the chemistry of soil solution and surface waters. The model relies on mass balances, solution equilibrium reactions and kinetic rate equations for its calculations, and hence combines theoretical analysis of laboratory data and field conditions (Sverdrup and Warfinge, 1988; Jönsson et al., 1995; Sverdrup, 1996). The input data required by *PROFILE* cover various fields: climate (temperature, precipitation), vegetation (uptake of base cations, ammonium and nitrate, percentage of uptake per horizon), inputs to the soil (wet and dry deposition, litter fall, canopy fall, mineralization), mineralogy and soil physics (exposed reactive surface area, texture, density), soil hydrology (soil water content, percolation), soil solution and stream water chemistry (CO_2 pressure, Dissolved Organic Carbon, solubility product of gibbsite).

In the areas of interest to this study, most of the soils are old and weathered. Ferralsols, Acrisols, and to a lesser extent, Nitisols, are the dominant soil types found around the African Great Lakes (Eledu et al., 2004; Bouwmeester et al., 2009). Under the advanced weathering stages, weatherable minerals contents are variable ("relatively high" in Nitisol, inexistent in Ferralsols) and low-activity clays dominate the clay assemblages (IUSS, 2006). Soil organic matter has thus a key role as a reservoir and a source of plant nutrients in weathered tropical soils (Tiessen et al., 1994; Zech et al., 1997; Craswell and Lefroy, 2001). Soil organic matter also impacts nutrient supply through its influence on the exchange capacities of soils (Klamt and Sombroek, 1986; Asadu et al., 1997; Craswell and Lefroy, 2001; Oorts et al., 2003; Soares and Alleoni, 2008).

The present study aims to evaluate the supply in base cations (K, Ca, Mg, Na) to East African Highland Bananas (Musa spp. AAA-EA) grown on highly weathered soils in the banana-based systems of Rwanda, Burundi and Uganda. The contribution of soil minerals to the nutrient supply is estimated through the *PROFILE* model and is compared to the nutrient supply that organic matter recycling brings about. The importance of soil organic matter and soil minerals for nutrient supply is also considered through their contribution to the cation exchange capacity of the studied soils.

7.2. Materials and methods

7.2.1. Study sites

The areas of interest to this study are situated between the latitudes S 00°46' – S 3°22' and the longitudes E 29°38 – E 30°37'. More specifically, they are located near the towns of Butare and Kibungo in Rwanda, Gitega in Central Burundi, and Ntungamo in the south-western part of Uganda. The study areas represent different agro-ecoregions, varying in altitude, climate and/or soil type (Table 7.1). Land is fragmented between numerous smallholder farmers who grow their crops in intensively exploited banana-based systems. Farmers rely almost exclusively on traditional techniques (rudimentary tools, no machinery, no animal draft power, no or rare inorganic fertilizer) to manage their fields (Oduol and Aluma, 1990 ; Roose and Ndayizigiye, 1994 ; Wortmann and Kaizzi, 1998 ; Aniku et al., 2001 ; Clay et al., 2001 ; National Institute of Statistics of Rwanda, 2010). All crop-production is rain-fed.

Table 7.1. Characteristics of the studied agro-ecoregions.

Area	Altitude (m*asl*)	Mean annual rainfall (mm.year^{-1})	Mean annual temperature (°C)	Soil type
Rwanda				
Butare	1675-1763	1150-1260 (*)	19.2 (**)	Acrisol (**), on granite
Kibungo	1498-1623	900-980 (*)	19-20.6 (**)	Nitisol (**) on pelitic rocks
Burundi				
Gitega Farm 1 Farm 2	1645-1658	1190 (*)	19 (**)	Acrisol (**), on pelitic rock on granite
Uganda				
Ntungamo Farms 1+3 F.2+4+5+7+8 Farms 6+9+10	1535-1611	1100-1200 (*) wide variability between years : 820-1300 (*)	19 (**)	Acrisol, on micaschist on micaschist on quartzite
References: Location coordinates and altitudes were measured in the field (GPS). Other data were found in literature: (*) Roark and Dickson, 1986, *cited in* Byers, 1990 ; Delepierre, 1974, *cited in* Ndindahizi and Gwabije, 1991 ; Smithson et al., 2004; *New_LocClim* (FAO, 2005b); IUSS, 2006 ; Bouwmeester et al., 2009; Nyombi et al., 2009 ; van Asten et al., 2011; http://www.isar.rw, accessed on October 12th 2010. (**) Gaidashova et al., 2009 ; FAO, 2005b. "m*asl*": meters above sea-level.				

7.2.2. Data collection

A. Diagnostic survey in Butare and Kibungo (Rwanda)

The diagnostic survey in Butare and Kibungo was detailed in Gaidashova et al. (2009). Briefly, during this survey (March-April 2006), 20 smallholder farms were visited in both regions. Per farm two plots showing extremes in banana plant vigor were chosen. In each plot, five flowering banana-plants (Musa spp. AAA-EA, cv. *Intuntu*) at the stage of fully opened hands were selected.

For each of those plants, height, girth at 1 m, number of functional leaves, length and width of the third leave, and number of fingers per bunch were recorded. Bunch weights were estimated through the allometric relationship established by Gaidashova et al. (2007). The surface between banana-plants was evaluated by measuring and averaging the distances between one mat and four plants surrounding it. Per plot, a composite foliar sample was constituted by putting together the inner laminas of third leaves of the five selected flowering plants. Foliar samples were in agreement with the international reference method for banana (Martin-Prével, 1980, 1984). Foliar samples were oven-dried at 60°C for two days and then finely ground. Chemical analyses were performed at UCL-Michamps (Michamps, Belgium). Total N contents in the foliar samples were determined by the Kjedahl titration. To assess their total P-, K-, Ca- and Mg-contents, the foliar samples were dry ashed at 450°C for at least 12 hours. The ashes were then digested in hot concentrated nitric acid (Novozamsky et al., 1986). K-, Ca- and Mg-concentrations in the digest were determined by atomic absorption spectrophotometry (AAS); P-concentrations were determined by colorimetry. Foliar nutrient contents were expressed as elemental weight percentages.

A soil sample was taken at the base of each studied plant. The composite soil sample was obtained by thoroughly mixing the soil withdrawn between 0 and 0.25 m depth from three places at horizontal distances of 0.50-0.70 m from the plant. The soil samples were air-dried, softly ground and sieved to pass a 2 mm mesh. Soil chemical analyses were performed in the UCL-laboratories of Michamps or Louvain-la-Neuve (Belgium). pH was measured in a 1 : 5 soil : water-suspension after 1 hour of contact. Exchangeable K, Na, Ca, Mg were extracted using a 1M ammonium acetate solution at pH7. The cation contents in the extract were determined by AAS. The amount of ammonium retained by the soil, after washing it free of the excess of ammonium acetate by denatured ethanol, was considered an estimate of the cation exchange capacity (CEC) of the soil. The retained ammonium was released by leaching the soil with a 1M potassium chloride solution at pH3. Ammonium contents in the leachate were determined by distillation. CEC was determined in standard conditions at pH7, to allow comparison between soils. All data are expressed against dry soil weight (105°C). Total chemical analysis was performed by digesting finely ground powder (mineralized at 950°C for 72 h) in a mixture of lithium tetra- and metaborate at 950°C (Chao and Sanzolone, 1992). The cooled digestion beads were dissolved in hot (100°C) 2M nitric acid. Elemental (Al, Fe, Si, Ti, Ca, K, Mg, Mn and P) contents in 100 ml 2M HNO_3 were determined by inductively coupled plasma – atomic emission spectrometry (ICP-AES). Elemental contents were expressed as percentages of oxides. Organic carbon contents of finely ground powder were determined by the Walkley and Black (1934) procedure (correction factor: 1.32). Total carbon contents were determined on finely ground powder by dry combustion (“flash” combustion at 1800°C).

B. Monitoring campaign in Ntungamo (SW Uganda)

The monitoring campaign (March 2005-April 2007) in the Ntungamo area was detailed in Newton (2009). Briefly, ten smallholder farms in a same valley were selected on basis of (1) the relative wealth status of the household and (2) the position of the farm on the topographic slope. To represent an intra-farm range of plant performance and management, 15 banana-plants (Musa spp. AAA-EA, cv. *Enyeru*) were selected at varying distances from the homestead.

The surface between banana-plants was evaluated by measuring and averaging the distances between one selected mat and the four plants surrounding it. For each selected mat, the plant growth for one follower ratoon was monitored monthly from sucker emergence to harvest. Plants were harvested when farmers considered bunches mature. At harvest, growth-related components (height, girth at 1 m, number of functional leaves) were recorded. On the same occasion, biomasses of the above-ground parts of the plant were determined. Fresh weight of the bunch was measured using a balance (± 0.5 kg). So were the fresh weights of the peduncle, fingers, leaves and pseudostem. Representative subsamples of these organs were taken and their fresh weight measured. The subsamples were solar dried to constant weight, and moisture contents determined. In order to evaluate nutrient status of the plant, an additional subsample of the inner lamina of the third leave was taken in accordance with the international reference for banana (Martin-Prével, 1980, 1984). The third leave foliar samples were oven-dried at 60°C for 2 to 4 days, and then ground to pass a 2mm-mesh sieve. Chemical analysis of the samples was performed at the Kawanda Research Station (Kawanda, Uganda) by standard methods (Okalebo et al., 2002). The dried samples were digested by a mixture of sulfuric acid and selenic acid. N- and P-concentrations in the digest were determined by colorimetry; K-, Ca- and Mg-concentrations by AAS. Foliar nutrient contents were expressed as elemental weight percentages.

A composite sample was obtained as representative of the soil at the foot of each selected plant by mixing three to five cores of soil taken around the banana-plant and covering the 0-0.30 m depth. The soil samples were air-dried, softly ground and sieved to pass a 2 mm mesh. pH was measured in a 1 : 2 soil : water-suspension (Okalebo et al., 2002). Exchangeable K, Ca and Mg were evaluated by the Mehlich 3-procedure detailed in Okalebo et al. (2002). Organic carbon contents were determined by the Walkley and Black (1934) procedure (correction factor: 1.32). The above-mentioned soil data were obtained at the Kawanda Research Station (Kawanda, Uganda). Additional chemical data were obtained at UCL-Louvain-la-Neuve (Louvain-la-Neuve, Belgium): total carbon content and total elemental compositions were determined as for the Butare and Kibungo samples in section 7.2.2.A ("Diagnostic survey in Butare and Kibungo (Rwanda)").

C. Revisiting farms in Butare, Kibungo and Ntungamo - a second campaign completed by a field visit at Gitega (Burundi)

Subsequent to the first field campaigns (see sections 2.2.A and 2.2.B), 2 farms in Butare, 3 in Kibungo and 5 in Ntungamo were revisited (in January 2007 for the Rwandan sites, in September 2009 for Ntungamo). The soils of the revisited farms were considered representative of the soils of their respective regions. The revisiting of the farms was decided to obtain information on deeper parts of the soil. To do so, 1 to 3 pits (± 1.5*1.5*1.5 m^3) were excavated in the banana grove in each farm. The pit extended for 0.75 m to both sides of a banana-plant. The soil profiles at the foot of the banana-plants were described according to the FAO (2006) guidelines. Large undisturbed clods and bulk soil samples were collected for each horizon of each profile, except one. Indeed, because of gravelly nature of the soils in the farm 3 of Ntungamo, undisturbed clods proved impossible to retrieve. Augering from the floor of the pits allowed recovery of even deeper samples (max depth 3.00 m).

Conditioning of the samples and first analyses were performed at the laboratories of ISAR (Rubona, Rwanda) or of the Agricultural and Animal Production Research Institute of Numalonge (Uganda). Dry bulk densities of soil horizons were determined by the petrol method of Monnier et al. (1973). Soil moisture contents of the same subsamples were determined by the gravimetric method. The bulk soil samples were air-dried, softly ground and sieved to pass a 2 mm mesh.

Physical and chemical data on bulk samples were obtained at UCL-Louvain-la-Neuve (Louvain-la-Neuve, Belgium). For a selection of the fine earth (< 2000 µm) samples, sand (2000-63µm), silt (63-2µm) and clay (0-2µm) fractions were obtained through ultrasonic dispersion, sieving and prolonged dispersion with Na^+-resins (Rouiller et al., 1972), without preliminary destruction of organic matter. Grain size distribution was expressed as weight percentages. Samples were extracted with $CuCl_2$ 0.5M for 16h (Juo and Kamprath, 1979; Aitken, 1992). Na, K, Ca and Mg were determined in the extracts by AAS. The qualitative mineralogical compositions of the fine earth (< 2 mm) samples were obtained by X-Ray Diffractometry: albite, muscovite, K-feldspars, vermiculite, kaolinite. Occasional presence of calcite was suspected in soils with pH_{H2O} superior to 7. Calcite is indeed a major compound of wood ashes (Eteigni and Campbell, 1991; Ohno, 1992), dispersed on the soils with other kitchen residues. Abundances of albite, muscovite, K-feldspars, vermiculite, kaolinite and calcite were estimated by a normative calculation of the CIPW type (Cross et al., 1902) detailed in Chapter 6. In order not the overestimate the abundances of minerals containing Na, K, Ca and Mg in the calculation, only the fractions of Na, K, Ca and Mg effectively attributed to minerals were injected into the calculation. Mineral Na, K, Ca and Mg were calculated by subtracting $CuCl_2$ 1M extracted Na, K, Ca and Mg contents from, respectively, the total Na, K, Ca and Mg contents determined for fine earth samples (< 2 mm). pH, exchangeable base cations and cation exchange capacity, total chemical analysis, oxidizable organic carbon contents and total carbon contents of fine earth (< 2 mm) samples were determined as described in section 7.2.2.A. Data were expressed against dry soil weight (105°C). On the soil profiles of Ntungamo, primary banana root distributions were recorded by counting primary roots in 0.10 m x 0.10 m-squares over the entire soil profile.

The opportunity presented to gain data from Burundian sites by Gaidashova (2009). Four profiles were described in two farms near Gitega (Central Burundi, January 2007). The same physical and chemical analyses were performed on the undisturbed and bulk soil samples as for the Rwandan samples (section 7.2.2.A).

7.2.3. The *PROFILE* model

The model is a data-intensive method, in need of information on climate, inputs to the soil, uptake by vegetation, soil hydrology, soil solution and stream water chemistry, mineralogy and soil physics. Some data are general, applicable to the entire soil column; others need to be specified for each separate "layer" when the decision is made to cut the soil profile in different "layers" as is proposed by *PROFILE*.

When examining the data required by *PROFILE*, it appeared that few variables had been actually measured during this study. To bridge the gaps we used (1) values found in published reports on soils similar to those studied here, (2) estimates made through relationships with quantified properties. The sections here-under detail (1) the reports consulted when searching data and (2) the calculation of estimates.

The different agro-ecoregions of interest to this study were considered separately when using *PROFILE*. Within the regions of Gitega and Ntungamo, a further subdivision was made because of soil heterogeneity: Gitega farm 1 on pelitic rocks *vs.* Gitega farm 2 on granite, Ntungamo farms

2+4+5+7+8 on micaschists *vs.* Ntungamo farms 6+9+10 on quartzite. In *PROFILE* the soils of this study were cut in 2 or 3 “layers” in order to describe the top 0.60 m of the soil.

A. Climate

Average annual temperatures and precipitation were obtained with the *New_LocClim* tool by the FAO (2005b). The tool also provided minimum and maximum estimates for those parameters.

The annual averages of precipitation, minimum and maximum estimates hence obtained were the “precipitation ($m.year^{-1}$)” data entered in *PROFILE*. Minimum, mean and maximum estimates of rainfall are 0.972-1.17-1.378 $m.year^{-1}$ in Butare, 0.78-0.95-1.10 $m.year^{-1}$ in Kibungo, 0.929-1.176-1.329 $m.year^{-1}$ in Gitega, 0.871-1.100-1.1367 $m.year^{-1}$ in Ntungamo.

The annual averages for air temperature (19°C, same average for all the regions) were used in *PROFILE* as estimates of the soil “temperature (°C)”. Lower (15°C, 17°C) and higher temperatures (22°C, 24°C) were also considered in order to match up to the isothermic or isohyperthermic soil regimes reported for soils of the study areas (Van Wambeke, 1982; Neel, 1983; Opdecamp and Sottiaux, 1983; Matthieu, 1985; Rutunga et al., 1998; Verdoodt and Van Ranst, 2003).

B. Inputs to the soil and uptake by vegetation, percentage of uptake per soil horizon

Wet and dry deposition, canopy exchange

Under "wet and dry deposition" we understood removal of aerosols from the atmosphere by condensation processes (rainout), impaction with falling raindrops (washout), dry fallout and dry impaction of aerosol particles on foliage (throughfall). The averages, minimum and maximum values obtained by the two following procedures were used as estimates of "wet and deposition (keq.ha^{-1}.year^{-1})": (1) estimation through rainfall and composition of rainwater, (2) values actually measured or simply reported in other studies.

Data on rainfall were obtained by *New_LocClim* (FAO, 2005b). Data on rainwater composition were found in Galloway (1988, review for tropical countries), Bootsma et al. (1999, Lake Malawi), Braun et al. (2002, South Cameroon), Laclau et al. (2003, Congo-Brazzaville), Kulabako et al. (2007, Uganda), Schrumpf et al. (2007, Kenya). The compositions of rainwater (from Cameroon for instance) which by their Na and Cl contents indicated a marine origin were excluded from the estimation.

Data for wet and dry deposition in areas of Africa were found in Galloway (1988, review for tropical countries), Baijukya and De Steenhuysen-Piters (1998, Tanzania), Bootsma et al. (1999, Lake Malawi), Scheren et al. (2000, deposition on Lake Victoria), Braun et al. (2002, South Cameroon), Laclau et al. (2003, Congo-Brazzaville), Proctor (1987 *cited in* Chuyong et al., 2004, South Cameroon), Kulabako et al. (2007, Uganda) and Schrumpf et al. (2007, Kenya).

Net uptake, litter fall and net mineralization, canopy exchange

First attempts to use *PROFILE* on our soil data, proved that the iteration procedure was unable to converge when values for net mineralization were inferior to those of net uptake. This impossibility thus demanded consideration of a stable self-sufficient system where "net uptake (keq.ha^{-1}.year^{-1})" equals "litter fall (keq.ha^{-1}.year^{-1})" equals "net mineralization (keq.ha^{-1}.year^{-1})". Hence it was decided to consider only the nutrients concentrated in leaves, pseudostems and bunches when estimating the values to be entered in *PROFILE*. Field observation, discussion with farmers and literature survey, indeed confirmed that leaves and pseudostems are residues added to soils on a permanent basis. Considering a complete return of banana bunches to the soils was however a short-cut. In reality, part of the banana bunches were home-consumed, part was exported for sale. The temporarily storage of nutrients in banana roots and corms and the possible presence of intercrops were other factors not considered in this simplified scenario. The complete decomposition of leaves and pseudostems after 1 year seems a plausible approximation considering the high decomposition rates (0.7-0.9 year^{-1}) established by Yamaguchi and Araki (2004) or the rapid 50% decomposition times (t_{50} = 33-83 days for pseudostems; t_{50} = 60-169 days for leaves) observed by Wortmann et al. (1994b) or Lekasi et al. (2001) for the pseudostems and leaves of East African Highland Banana.

Data on (1) cycle duration, (2) plant density, (3) fresh weight biomass, (4) plant tissue moisture content and (5) plant tissue nutrient contents were needed to estimate total nutrient contents in leaves, pseudostems and bunches in terms of keq.ha^{-1}.year^{-1}.
Cycle durations of 1 year were considered as a matter of simplification. Hauser and van Asten (2010) report that cycle durations vary widely (between 1 and 3 years after planting) in function of cultivar, agroecological conditions, infestation by pests or diseases. Plant density, bunch weights and foliar nutrient contents were determined for Butare, Kibungo and

Ntungamo. Copus (2009) provided corresponding data for Gitega. Biomasses for pseudostems and leaves and associated plant tissue moisture contents were determined in Ntungamo. Average values were extrapolated to the other regions. Nutrient contents in pseudostem or bunches found in Martin-Prével (1962), Montagut and Martin-Prével (1965), Twyford and Walmsley (1973, 1974), Walmsley and Twyford (1976), Marchal and Mallessard (1979), Lekasi et al. (2001) were averaged. Data from literature hence supplemented measurements in order to calculate nutrient contents in leaves, pseudostems and bunches. The results of the calculations are given in Table 7.2. Data are expressed as the more usual $kg.ha^{-1}.year^{-1}$, instead of the $keq.ha^{-1}.year^{-1}$ demanded by *PROFILE*.

Table 7.2. Plant nutrients recycled through mulching of banana leaves, pseudostems and bunches.

Region / Amendments by organic matter	Butare	Kibungo	Gitega farm 1 farm 2	Ntungamo farms 2+4 +5+7+8	Ntungamo farms 6+9+10
N ($kg.ha^{-1}.year^{-1}$)	230	148	290	265	209
K ($kg.ha^{-1}.year^{-1}$)	1072	653	1326	1205	988
Ca ($kg.ha^{-1}.year^{-1}$)	161	93	193	166	138
Mg ($kg.ha^{-1}.year^{-1}$)	76	47	93	85	69
S ($kg.ha^{-1}.year^{-1}$)	21	14	27	25	20
N ($kg.ha^{-1}.year^{-1}$)	59	50	99	92	63
K ($kg.ha^{-1}.year^{-1}$)	167	143	281	260	179
Ca ($kg.ha^{-1}.year^{-1}$)	8	6	13	12	8
Mg ($kg.ha^{-1}.year^{-1}$)	10	9	17	16	11
S ($kg.ha^{-1}.year^{-1}$)	6	5	11	10	7

“Canopy exchange” was considered zero for all elements (Ca, Mg, K, N) since it was already accounted for by “wet and dry deposition” and “litter fall”.

Uptake per layer

"Cation and nitrogen uptake (% of total for profile)" per layer were assessed by considering root distribution patterns. For the soil profiles of Ntungamo, root distribution patterns were effectively recorded: 60-80% of the roots in the upper 0.30 m of the soil, 40-20% of the roots between 0.30 and 0.60 m. Observations overlap data published in Godefroy et al. (1992), Price (1995), Araya (2003), Kashaija et al. (2004), Sebuwufu et al. (2004), Lassoudière (2007) and Carr (2009). Data observed in Ntungamo were extrapolated to the other regions of this study.

C. Soil hydrology

"Soil water content ($m^3.m^{-3}$)" was actually measured on the undisturbed samples taken from the different horizons encountered in the soil profiles in Butare, Kibungo, Gitega and Ntungamo. The values effectively determined were punctual data, representing the moisture contents at one particular moment of the year: at the beginning of the short dry season for the data from Butare, Kibungo and Gitega, and during the long wet season for data from Ntungamo.

Besides the measured data, extreme values for "soil water contents" were also tested in *PROFILE*. Extreme values were established when hypothesizing that all the pores of the soil were saturated with water. Soil porosity was calculated by equation 1 (Bielders et al., 1990; Musy and Soutter, 1991):

$$\text{porosity} = 1 - \frac{\rho_b}{\rho_s} \qquad [\text{eq. }1]$$

where ρ_b is the dry bulk density ($g.cm^{-3}$),
ρ_s is the particle density ($g.cm^{-3}$), here assumed equal to 2.65 $g.cm^{-3}$

Considering the different profiles in one region and the different "layers" in the top 0.60 m of those profiles, the following values were observed or calculated. Minimum measured soil water contents and maximum soil water contents at saturation were 0.15 and 0.55 $m^3.m^{-3}$ in Butare, 0.21 and 0.65 $m^3.m^{-3}$ in Kibungo, 0.19 and 0.53 $m^3.m^{-3}$ in Gitega farm 1, 0.20 and 0.62 $m^3.m^{-3}$ in Gitega farm 2, 0.11 and 0.50 $m^3.m^{-3}$ in Ntungamo farms 2+7, 0.10 and 0.50 $m^3.m^{-3}$ in Ntungamo farms 6+9+10. *PROFILE* did not allow values superior to 0.50 $m^3.m^{-3}$. Values for all the "layers" were allowed to vary between the observed minimum and the calculated maximum (or 0.50 $m^3.m^{-3}$ when the extreme value was superior to 0.50 $m^3.m^{-3}$).

For each "layer" described in *PROFILE*, the "percentage of precipitation entering the layer" and the "percentage of precipitation leaving the layer" needed to be detailed. Estimates of percolation were deduced from practical considerations and literature data. *New_LocClim* (FAO, 2005b) provided monthly averages for precipitation and potential evapotranspiration. The percentage of precipitation entering the first soil layer was estimated by ([eq.2]):

$$\begin{aligned} &\%\text{ of precipitation entering layer 1} \\ &= 100\% - \%\text{ of precipitation intercepted by canopy, mulch, intercrop} \\ &\qquad\qquad - \%\text{ lost by runoff} \end{aligned} \qquad [\text{eq. }2]$$

Harris (1997, *cited in* Carr, 2009) estimates that 10% of rainfall is intercepted by a banana canopy (Musa spp., cv. *Robusta*; Windward Islands) and lost to the atmosphere by evaporation. Ninety percent of the rainfall reaches the soil by stemflow or throughfall. Ninety percent but also the lower values of 80 or 70% were entered in *PROFILE*. Values lower than 90% were intended to take into account unequally distributed mulch or intercrops. The permanent good cover in banana systems justified the choice to consider runoff as inexistent. The good cover was insured by a mature canopy of broad leaves, possible mulch and/or intercrops. The good canopy cover was indicated by the high Leaf Area Indexes (LAI). Relying on the allometric equation of Kumar et al. (2002), LAI was 5.26 ± 1.74 (N=30) for Butare and 7.33 ± 2.21 (N=38) for Kibungo. The allometric relationship established by Nyombi et al. (2009) when working with bananas in Ntungamo, allowed calculation of LAI for that region (11.89 ± 3.55).

Hypothesizing that there was no lateral flow, the percentage of precipitation leaving the first layer was equal to the percentage of precipitation entering the second layer. That percentage was calculated by making two assumptions: (1) because of the good cover of the soil, transpiration by plants was the major contributor to evapotranspiration, (2) the fraction of water lost in a layer was related to the banana root density in that layer. Calculation relied on equation 3.

$$\begin{aligned}
&\%\ \text{of water leaving layer 1} = \%\ \text{of water entering layer 2}\\
&= \frac{[\mathrm{P} - \mathrm{ETm1}]}{\mathrm{P}}\ \mathrm{x}\ 100\\
&= \frac{\left[\mathrm{P} - \left(\mathrm{ETm\ x(number\ of\ roots\ in\ layer\ 1/total\ number\ of\ roots)}\right)\right]}{\mathrm{P}}\,\mathrm{x}100
\end{aligned} \qquad [\mathrm{eq.}\ 3]$$

where P represents Precipitation (m, see data by *New_LocClim*)
ETm1 is the evapotranspiration in layer 1 (m)
ETm is the maximum rate of evapotranspiration from a banana crop (m) = ETo * Kc
ETo is the potential evapotranspiration (m, see data by *New_LocClim*)
Kc is the crop water use coefficient. Kc values vary in function of the age of the banana-plant: at flowering, Kc is 1.1 (Santana et al., 1993; FAO, 2002)
Number of roots are determined from vertical root profiles

For the “% of water leaving layer 2”, three options were considered:
(1) P < ETo : no percolation below layer 2,
(2) P > ETo : all the water entering layer 2 leaves this layer,
(3) P > ETo : part of the water entering layer 2 is used by the plant ([eq.4]):

$$\%\text{ of water leaving layer 2} = \frac{[\mathrm{P} - (\mathrm{ETm1} + \mathrm{ETm2})]}{\mathrm{P}} \text{ x } 100 = \frac{[\mathrm{P} - \mathrm{ETm}]}{\mathrm{P}} \text{ x } 100 \qquad [\text{eq. } 4]$$

where ETm1, ETm2 is the evapotranspiration in, respectively, layer 1 and 2 (m).

Percolation was supposed to vary over the months and the seasons. The percentages of water entering or leaving a layer were computed on a monthly basis, and the percentages extrapolated to one year. Calculations were performed for all the regions separately. When deciding on the percentages to enter in *PROFILE,* minimum and maximum values calculated for all the 4 regions were retained. Percentages of precipitation entering layer 1 used in *PROFILE* were 70, 80, 85, 90%. Percentages of precipitation leaving layer 1 and entering layer 2 were 5, 7.5, 10, 20%. Percentages of precipitation leaving layer 2 were 1, 5, 7.5, 10, 15, 20%.

D. Soil solution and stream water chemistry

Data published in Martins and Probst (1991, review on major African rivers), Spitzy and Leenheer (1991, review on tropical rivers), Viers et al. (2000, Cameroon), Campbell et al. (2003, Victoria Lake, Uganda), Johnson et al. (2006, Amazonia), Schwendenmann and Veldkamp (2006, review), Lalah and Wandinga (2006, Kenya), Bouillon et al. (2009, Kenya) and Koehler et al (2010, Panama) were adopted for DOC and pCO_2 in stream water (resp. 4 $mg.l^{-1}$ and 4 times ambient) and soil solution (resp. 10 $mg.l^{-1}$ and 5-20 times ambient).

E. Mineralogy and soil physics

Data on "particle size distribution (%)" and "dry soil (field) bulk density ($kg.m^{-3}$)" and "mineralogy" needed in *PROFILE*, were actually measured on soil samples from profiles described in Butare, Kibungo, Gitega and Ntungamo. Abundances of albite, muscovite, K-feldspar, calcite, vermiculite and kaolinite in the upper horizons of the soil profile are summarized in Table 7.3.

PROFILE recommends the use of the Brunauer-Emmett-Teller (BET) isotherm to evaluate total reactive surface area (Sverdrup and Warfinge, 1993). Since BET is not determined in a routine procedure, *PROFILE* provides an equation that calculates the total "surface area ($m^2.m^{-3}$)" from the "particle size distribution" ([eq.5]):

$$A = (P \times X_{coarse\ sand}) + (Q \times X_{fine\ sand}) + (R \times X_{silt}) + (S \times X_{clay}) \quad [eq. 5]$$

where A is the surface area in ($m^2.g^{-1}$); to express the surface area in ($m^2.m^{-3}$) as is required by *PROFILE*, the surface area A must be multiplied by the soil bulk density in ($g.m^{-3}$)

P, Q, R, S are coefficients (default values are 0, 0.3, 2.2 and 8, respectively)

x represents the weight percentages (divided by 100) of the coarse (> 2000 µm), sand (63-2000 µm), silt (2-63 µm) and clay (0-2 µm) fractions; the sum of all x's equals 1

The use of equation 5 has been heavily criticized by Hodson et al. (1998) and Hodson (2002) because of

- the unexplained changes to the equation by Sverdrup and coworkers, authors of the *PROFILE* model: changes to both the grain sizes and the coefficient S of equation 5. The grain sizes are > 250 µm, 60-250 µm, 2-60 µm, < 2 µm for the coarse, sand, silt, and clay fractions in Sverdrup and Warfinge (1993) or Sverdrup (1996). They are > 200 µm, 60-200 µm, 2-60 µm, < 2 µm in Sverdrup and Warfinge (1995) and become > 2000 µm, 63-2000 µm, 2-63 µm, < 2 µm in the version of *PROFILE* downloaded in 2009 for the present study. The default value for S is 0 in Sverdrup and Warfinge (1993) and in the version of *PROFILE* used here, but is 0.05 in Sverdrup (1996).

- the low correlation between predicted surface areas and surface areas measured by BET for Scottish podzol and gleysol soil samples (Hodson et al., 1998).

- the artificial limits the equation puts on the surface area of the soil (Hodson, 2002).

F. Two scenarios for estimating weathering rates with PROFILE

Taking into account the uncertainties on various estimates and considering the debate on calculation of surface area, ranges for the weathering rates were pursued rather than absolute values. *PROFILE* was used within two scenarios to cover all combinations of conditions (from the most realistic to the most favorable to weathering). The scenarios were applied to estimate weathering rates in the regions or subregions of Butare, Kibungo, Gitega farm 1, Gitega farm 2, Ntungamo farms 2+7, Ntungamo farms 9+10.

Scenario 1

All the profiles described were considered separately: 4 profiles in Butare, 3 in Kibungo, 2 in Gitega farm 1, 2 in Gitega farm 2, 1 in Ntungamo farm 2, 3 in Ntungamo farm 7, 3 in Ntungamo farm 9, 3 in Ntungamo farm 10. The data actually measured for the different horizons (height, water content and water content at saturation, bulk dry density, mineralogical composition) of each profile are entered in the model. Depending on the profile, two to three "layers" are considered in order to represent the (approximately) upper 60 cm. Each "layer" corresponds to one horizon effectively described and sample. When data for one horizon was lacking, data for the horizons directly superior and inferior were averaged.

Scenario 2

For each region or subregion, one profile actually described was selected as a representative of its region or subregion. Selection aimed for a profile with intermediate values for dry bulk density and texture, over the 0-0.30 m and 0.30-0.60 m soil depths.

The mineralogical composition attributed to the selected profile was one retaining the maximum values determined for the weatherable minerals (albite, K-feldspar, Al-vermiculite) within a region or subregion. In one way, this scenario remains realistic since the attributed mineral percentages were effectively determined. On the other hand, reality was bent by the consideration of the maximum observed mineral percentages for all minerals at the same time.

Data (water content, temperature, percolation, CO_2 pressure) which proved most sensitive to change in preliminary tests and in sensitivity studies (Jönsson et al., 1995; Hodson et al., 1996) were allowed to vary. The values entered for those inputs varied systematically between a minimum and a maximum value considered possible for the soils under study. The variation of this data was performed as a stepwise progression in which all data, but one, were held constant. The sole combination where 2 parameters varied together was high temperature (22 or 24°C) and high water contents.

Because adapting data in *PROFILE* and running the program was time-consuming, it was decided to perform this stepwise progression on 1 “medium” profile per region or subregion (6 in total), instead of performing it on each profile separately (altogether: 22).

Table 7.3 (continued on following pages). Mineralogical composition and dry bulk density for the upper horizons of the profiles described in Butare, Kibungo, Gitega and Ntungamo. "ND" stands for not determined. Profiles whose names are indicated by stars, are the profiles selected in scenario 2 when using *PROFILE.*

Region Farm Profile	Horizon	Depth (cm)	Dry bulk density ($kg.m^{-3}$)	Albite (%wt)	Musco-vite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Kaolinite (%wt)
Butare	Ap1	0-15	1180	0.00	3.7	0.5	0.03	0.0	12
Farm 1	Ap2	15-28	1440	ND	ND	ND	ND	ND	ND
Profile A	AB1	28-52	ND	0.00	3.4	0.5	0.10	0.0	12
*Butare	Ap	0-22	ND	0.00	3.7	0.0	0.0	0.4	15
*Farm 1	AB	22-45	1510	ND	ND	ND	ND	ND	ND
*Profile B	Bt1	45-93	1520	ND	ND	ND	ND	ND	ND
	BtG1	93-105	ND	0.00	3.8	0.0	0.06	0.5	17
Butare	Ap1	0-18	ND	0.32	2.8	0.2	0.00	0.0	15
Farm 67	Ap2	18-60	1560	ND	ND	ND	ND	ND	ND
Profile A	AB	60-88	1520	0.00	0.0	0.3	0.00	0.0	24
Butare	Ap	0-38	ND	0.27	0.0	0.4	0.00	0.6	19
Farm 67	Bt1	38-61	1490	ND	ND	ND	ND	ND	ND
Profile B	BtG1	61-92	1580	0.00	0.0	0.2	0.00	0.0	25
Kibungo	Ap1	0-22	930	0.00	0.0	0.1	0.00	1.0	53
Farm 32	AB	22-40	970	ND	ND	ND	ND	ND	ND
Profile B	B1	40-58	1130	ND	ND	ND	ND	ND	ND
	B2	58-103	1130	0.00	0.0	0.0	0.00	0.9	55

Table 7.3 (continued). Mineralogical composition and dry bulk density for the upper horizons of the profiles described in Butare, Kibungo, Gitega and Ntungamo. "ND" stands for not determined. Profiles whose names are indicated by stars, are the profiles selected in scenario 2 when using *PROFILE.*

Region Farm Profile	Horizon	Depth (cm)	Dry bulk density ($kg.m^{-3}$)	Albite (%wt)	Musco-vite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Kaolinite (%wt)
*Kibungo	Ap	0-28	990	0.00	0.0	0.0	0.00	0.9	47
*Farm 35	BA	28-41	1170	ND	ND	ND	ND	ND	ND
*Profile A	B1	41-76	1180	0.00	0.0	0.0	0.00	0.9	55
Kibungo	Ap	0-21	980	0.00	2.7	0.0	0.00	1.0	50
Farm 38	AB	21-45	1010	ND	ND	ND	ND	ND	ND
Profile B	BA	45-60	1130	0.00	0.0	0.1	0.00	1.0	49
Gitega	Ap1	0-27	1380	0.4	8.2	1.6	0.00	0.0	16
Farm 1	Ap2	27-54	1310	ND	ND	ND	ND	ND	ND
Profile A	AB	54-70	1370	0.0	5.5	0.6	0.00	0.0	21
*Gitega	Ap	0-25	1240	0.3	6.0	0.6	0.00	1.2	20
*Farm 1	B1	25-61	1360	ND	ND	ND	ND	ND	ND
*Profile B	2B2	61-88	ND	0.2	3.6	0.2	0.00	0.8	25
Gitega	Ap1	0-20	1010	0.3	4.0	0.0	0.18	1.2	19
Farm 2	Ap2	20-35	1150	ND	ND	ND	ND	ND	ND
Profile A	Ap3	35-62	1140	0.2	3.8	0.0	0.00	0.8	21

Table 7.3 (continued). Mineralogical composition and dry bulk density for the upper horizons of the profiles described in Butare, Kibungo, Gitega and Ntungamo. "ND" stands for not determined. Profiles whose names are indicated by stars, are the profiles selected in scenario 2 when using *PROFILE.*

Region Farm Profile	Horizon	Depth (cm)	Dry bulk density ($kg.m^{-3}$)	Albite (%wt)	Musco-vite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Kaolinite (%wt)
*Gitega	Ap1	0-22	1100	0.2	3.6	0.2	0.00	0.9	23
*Farm 2	Ap2	22-51	1180	ND	ND	ND	ND	ND	ND
*Profile B	AB	51-77	1020	0.1	3.3	0.0	0.00	0.9	26
Ntungamo	1	0-16	1320	1.3	10.1	1.0	0.00	0.6	17
Farm 2	2	16-35	1340	1.3	10.9	1.0	0.00	0.7	18
Mat 6	3	35-56	1410	1.3	11.6	1.1	0.00	0.6	18
	4	56-69	1450	1.3	11.4	1.1	0.00	0.6	19
*Ntungamo	1	0-20	1450	1.6	11.3	1.4	0.08	0.6	13
*Farm 7	2	20-45	1410	1.7	12.9	1.6	0.00	0.7	14
*Mat 4	3	45-115	1490	1.7	12.7	1.5	0.00	0.8	15
Ntungamo	1	0-13	1410	1.6	10.9	1.3	0.00	0.7	13
Farm 7	2	13-33	1390	1.6	10.8	1.3	0.00	0.7	12
Mat 7	3	33-75	1550	1.6	12.4	1.4	0.00	0.7	16
Ntungamo	1	0-14	1430	1.7	11.5	1.5	0.00	0.6	12
Farm 7	2	14-35	1420	1.7	11.3	1.4	0.00	0.6	13
Mat 15	3	35-53	ND	1.7	12.0	1.5	0.00	0.7	14
	4	53-100	1650	1.7	12.8	1.7	0.00	0.7	13

Table 7.3 (continued). Mineralogical composition and dry bulk density for the upper horizons of the profiles described in Butare, Kibungo, Gitega and Ntungamo. "ND" stands for not determined. Profiles whose names are indicated by stars, are the profiles selected in scenario 2 when using *PROFILE.*

Region Farm Profile	Horizon	Depth (cm)	Dry bulk density ($kg.m^{-3}$)	Albite (%wt)	Musco-vite (%wt)	K-feldspar (%wt)	Calcite (%wt)	Vermi-culite (%wt)	Kaolinite (%wt)
Ntungamo	1	0-19	1480	0.6	5.5	0.3	0.00	0.6	20
Farm 9	2	19-47	1420	0.7	7.0	0.4	0.00	0.7	25
Mat 6	3	47-90	1480	0.8	7.8	0.4	0.00	0.7	30
Ntungamo	1	0-34	1400	0.7	6.3	0.3	0.00	0.7	23
Farm 9	2	34-45	1350	0.7	6.8	0.4	0.00	0.7	24
Mat 8	3	45-80	1470	0.8	8.5	0.4	0.00	0.9	35
Ntungamo	1a	0-12	910	0.7	5.4	0.3	0.00	0.3	15
Farm 9	1b	12-44	1580	0.6	4.6	0.3	0.06	0.5	13
Mat 12	2	44-75	1530	0.7	6.4	0.4	0.05	0.6	19
Ntungamo	1	0-7	1590	0.8	5.4	0.4	0.10	0.4	13
Farm 10	2	7-48	1680	0.7	6.3	0.4	0.00	0.5	18
Mat 5	3	48-102	1450	0.8	6.6	0.4	0.00	0.7	21
Ntungamo	1	0-7	1620	0.7	5.8	0.4	0.00	0.5	17
Farm 10	2	7-46	1320	0.7	6.4	0.4	0.00	0.6	20
Mat 11	3A	46-63	1500	0.7	6.3	0.3	0.00	0.6	22
*Ntungamo	1	0-15	1540	0.7	5.3	0.3	0.00	0.5	16
*Farm 10	2	15-40	1380	0.7	5.8	0.4	0.00	0.6	18
*Mat 13	3	40-63	1420	0.8	6.3	0.4	0.00	0.6	19

7.3. Results and discussion

7.3.1. Minerals and organic matter as sources of nutrients

The abundances of the minerals effectively considered in *PROFILE* are detailed in Table 7.3. Albite abundances varied between 0.0-0.4%wt in Butare, Kibungo and Gitega, 0.7-0.8%wt in Ntungamo farms 9+10 and reached 1.7%wt in Ntungamo farms 2+7. Muscovite/sericite amounts were 0.0-3.8%wt in Butare, Kibungo and Gitega and 6-8%wt in Ntungamo farms 9+10. Muscovite abundances of 10-13%wt were calculated for the soils of Ntungamo 2+7, on micaschist. K-feldspar was estimated at 0.0-0.5%wt in Butare, Kibungo, Gitega, Ntungamo farms 9+10, but were higher in Ntungamo farms 2+7 (0.1-1.7%wt). In surface horizons amended with kitchen ashes calcite contents could reach 0.18%wt. Vermiculite was present in small amounts at all sites (0.4-1.2%wt). Kaolinite was the dominant mineral phase in Kibungo (49-53%wt) on pelitic rocks. In other sites kaolinite abundances reached 12-25%.

Weathering of albite released Na, but also some Ca and K considering the formula used by *PROFILE*. Muscovite released K and some Mg while weathering, and K-feldspar released K and some Na. Calcite released Ca. The release rates for the base cations (Na, K, Ca and Mg) estimated by *PROFILE* are summarized in Table 7.4 and are graphically presented in Figure 7.1. In the presented results,

- the weathering rates calculated for each "layer" separately are cumulated, to depict weathering on the entire soil profile entered in the model,

- all data relating to a same region or subregion are presented together: no discrimination is made between different profiles of a same region, or different combinations of input data.

The weathering rates calculated by *PROFILE*, were globally low but increased highly when calcite was supposed present. All scenarios and all regions considered, the release rates for Na, K and Mg varied respectively between 0.0-5.9 $kg.ha^{-1}.year^{-1}$, 1.6-32.5 $kg.ha^{-1}.year^{-1}$, 0.4-12.5 $kg.ha^{-1}.year^{-1}$. Ca release rates were near zero when no calcite was present ($pH_{H2O} < 7$). Ca release rates varied between 7.8-155 $kg.ha^{-1}.year^{-1}$ in the profiles of Butare, Gitega 2, Ntungamo farms 9+10, where calcite was supposed present ($pH_{H2O} > 7$). Cumulated rates (Na+K+Mg+Ca) range between 33-2326 $mol_c.ha^{-1}.year^{-1}$ for Butare, 83-524 $mol_c.ha^{-1}.year^{-1}$ for Kibungo, 223-1033 $mol_c.ha^{-1}.year^{-1}$ for Gitega farm 1, 141-1635 $mol_c.ha^{-1}.year^{-1}$ for Gitega farm 2, 250-1348 $mol_c.ha^{-1}.year^{-1}$ for Ntungamo farms 2+7 and 131-1469 $mol_c.ha^{-1}.year^{-1}$ Ntungamo farms 9+10. Differences in release rates between regions were explained by differences in weatherable mineral contents. Values similar or lower to these total release rates were observed by others using *PROFILE* on weathered tropical soil (Duan et al., 2002 (China); Laclau et al., 2005 (Congo)). For Luvisols, Cambisols, Chernozems, Andosols under less favorable climatic conditions (colder temperatures and less rainfall) but containing higher quantities of weatherable minerals, weathering rates (Na+K+Ca+Mg) increase to 2000-7000 $cmol_c.ha^{-1}.year^{-1}$, with even an exceptional value of 11000 $cmol_c.ha^{-1}.year^{-1}$ for some Cambisols (Duan et al., 2002 *and references therein*; Holmqvist et al., 2003). *PROFILE* calculated release rates of 40-1500 $cmol_c.ha^{-1}.year^{-1}$ for podzols in Scandinavia or Canada (Sverdrup and Warfinge, 1993; Kopstik et al., 1999; Ouimet and Duchesne, 2005; Koseva et al., 2010).

Table 7.4. Base cation release rates by mineral weathering, as calculated by *PROFILE*: ranges and most realistic estimate. Comparison of nutrient contents cumulated in banana leaves (L), pseudostems (PS) and/or bunches (B) to maximum release rates by weathering.

Region	Butare	Kibungo	Gitega farm 1	Gitega farm 2	Ntungamo farms 2+7	Ntungamo farms 9+10
Na ($kg.ha^{-1}.yr^{-1}$)						
range scenario 1+2	0.0-0.8	0.0-0.0	0.4-1.6	0.2-0.8	1.1-5.9	0.5-2.9
K ($kg.ha^{-1}.yr^{-1}$)						
range scenario 1+2	0.5-9.4	1.6-13.7	5.9-27.8	3.5-11.2	6.0-32.5	3.1-19.1
(nutrients in L+PS+B) / max	*33*	*13*	*14*	*34*	*10*	*14*
(nutrients in B) / max	*2*	*1*	*1*	*2*	*0.7*	*0.8*
Ca ($kg.ha^{-1}.yr^{-1}$)						
range scenario 1+2	0.0-155.4	0.0-0.0	0.2-0.6	0.1-107	0.4-2.2	0.2-77.6
(nutrients in L+PS+B) / max	*4*	*4650*	*1374*	*7*	*296*	*7*
(nutrients in B) / max	*0.2*	*320*	*90*	*0.5*	*21*	*0.4*
Mg ($kg.ha^{-1}.yr^{-1}$)						
range scenario 1+2	0.4-4.3	2.0-8.4	2.4-12.5	1.9-6.2	2.1-11.4	1.2-7.7
(nutrients in L+PS+B) / max	*71*	*22*	*30*	*60*	*30*	*36*
(nutrients in B) / max	*9*	*4*	*5*	*11*	*4*	*6*
Na+K+Ca+Mg ($kg.ha^{-1}.yr^{-1}$)						
range scenario 1+2	33-2326	83-524	223-1033	141-1635	250-1348	13-1469

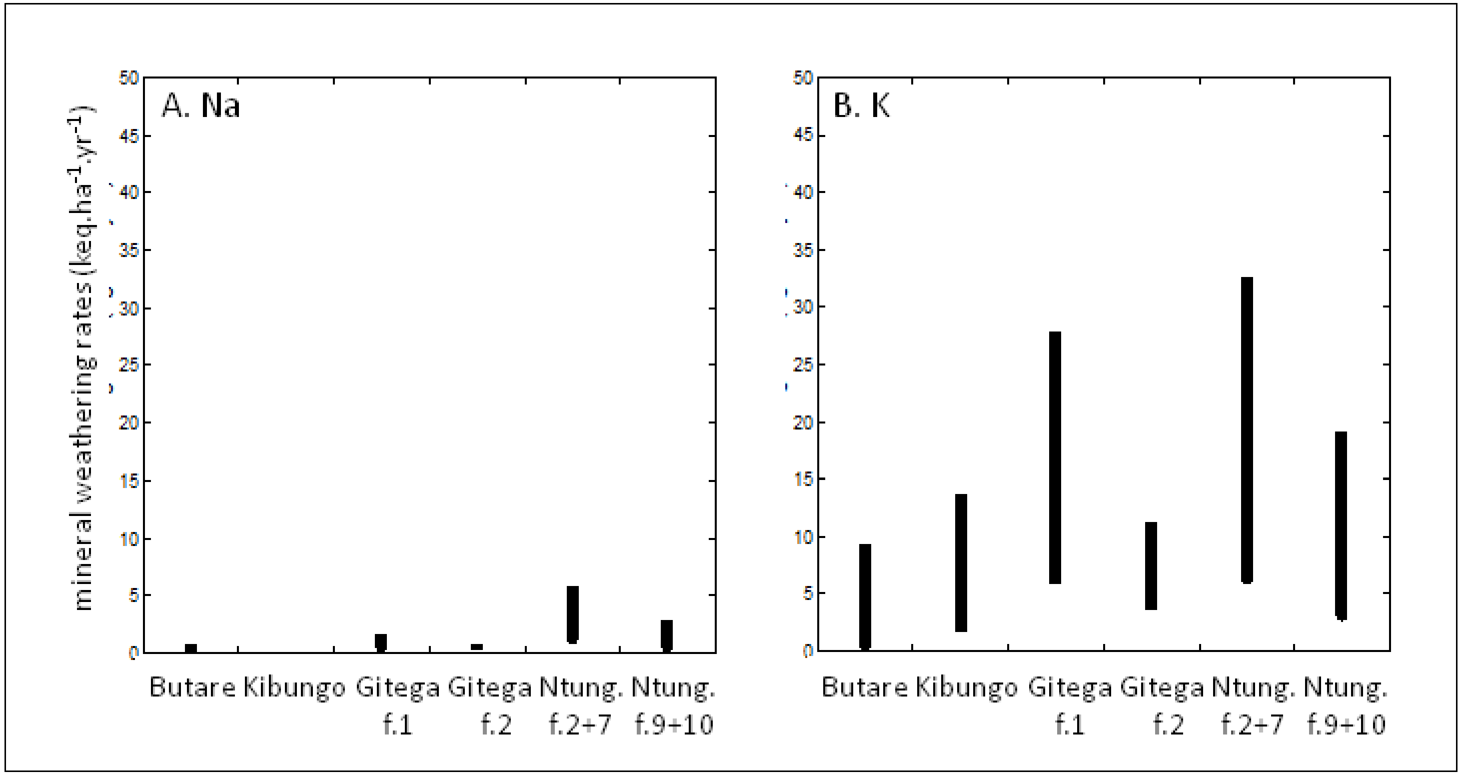

Figure 7.1 (continued on next page). Ranges of weathering rates calculated by *PROFILE*. "f" stands for farm. Note the difference in vertical scale for calcium (plot C).

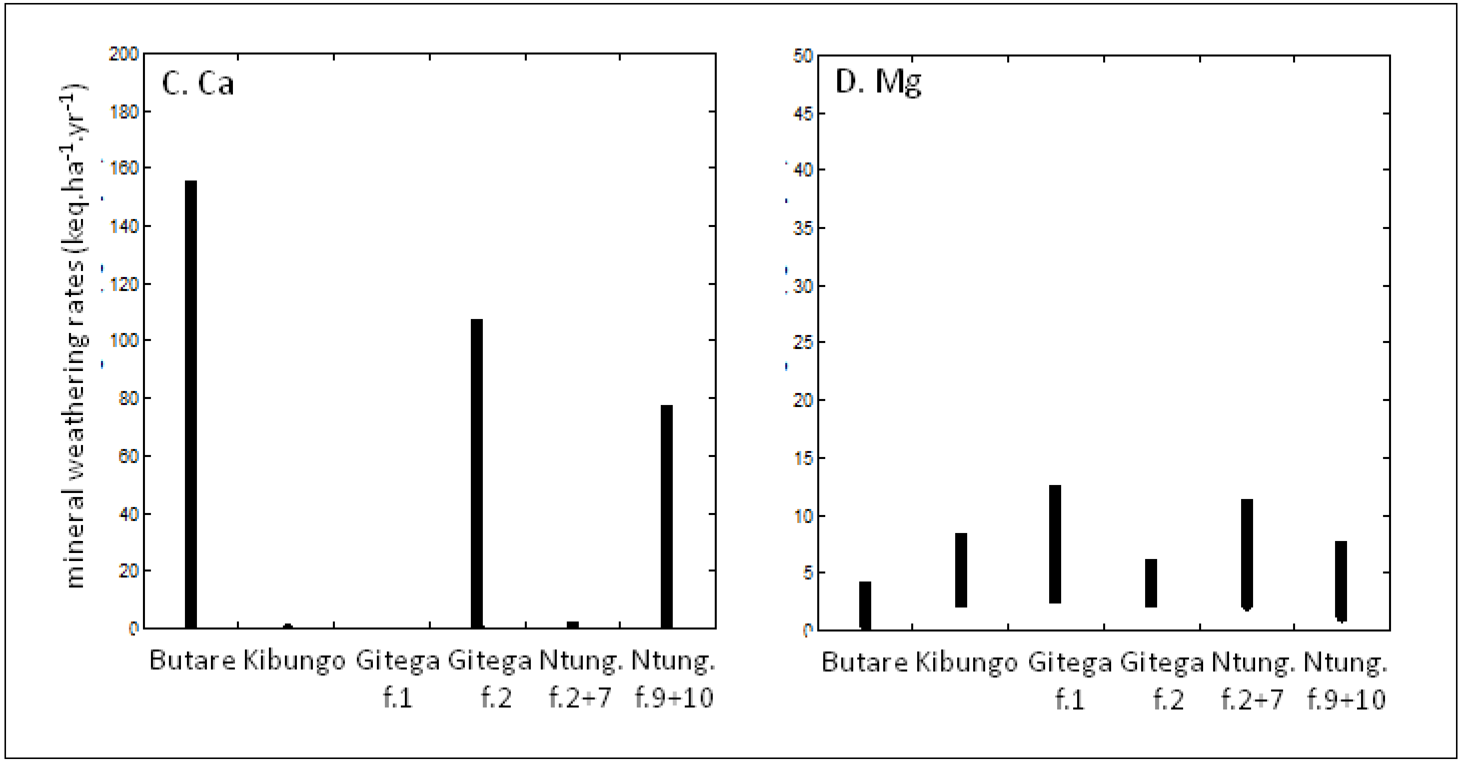

Figure 7.1 (continued). Ranges of weathering rates calculated by *PROFILE*. "f" stands for farm. Note the difference in vertical scale for calcium (plot C).

Complete mineralization of banana mulch (banana leaves, pseudostems and bunches according to the working hypothesis of this study) would release 653-1326 kg.ha^{-1}.year^{-1} of K, 47-93 kg.ha^{-1}.year^{-1} of Mg and 93-193 kg.ha^{-1}.year^{-1} of Ca (Table 7.2). Maximum release rates by weathering and complete mineralization of banana mulch thus differ by at least one order of magnitude (Table 7.4). Mineralization insures higher nutrient release rates than mineral weathering, except for Ca in the profiles where calcite was encountered. Nutrients accumulated in the produced bunches, equal all the K annually released by weathering in Kibungo, Gitega farm 1, Ntungamo farms 2+7 and Ntungamo 9+10 under the most favorable scenarios entered in *PROFILE*.

7.3.2. Minerals and organic matter as contributors to cation exchange capacity

The following section aimed to evaluate the contribution of organic and mineral soil constituents to soil cation exchange capacity (CEC).

In the present study, carbon contents were measured by both the Walkley and Black (1934) procedure and dry combustion. The dichromate oxidation method by Walkley and Black (1934) recovers the reactive organic carbon contained in microorganisms, plant or animal residues, but recovers only part of the elemental carbon and part of the carbon in "humus" (Nelson and Sommers, 1982; Skjemstad and Taylor, 1999; Kerven et al., 2000; Certini et al., 2002; Pansu and Gautheyrou, 2006). Inorganic carbon (carbonate and bicarbonate) does not play a role in the dichromate Walkley and Black procedure. By dry combustion the carbon in every organic or inorganic form is measured (Artiola, 1990; Matejovic, 1997; Pansu et Gautheyrou, 2006). Discarding all the samples having pH_{H2O} superior to 7 and possibly containing carbonates, the relationship between total carbon contents ($\%C_{tot}$) and Walkley and Black (1934) extracted organic carbon

($\%C_{orga,WB}$) was considered (Figure 7.2). All the regions or subregions and all profile depths were considered in the comparison. As shown in Table 7.5, total carbon contents ranged between 0.16 and 6.70 $\%C_{tot}$, and Walkley-Black organic carbon between 0.07 and 5.73 $\%C_{orga,WB}$. As expected, both $\%C_{tot}$ and $\%C_{orga.WB}$ were superior in surface horizons than at depth. The highest carbon contents were encountered in the clayey and iron-rich soils of Kibungo.

In the relationship relating $\%C_{tot}$ (Y-axis) to $\%C_{orga,WB}$ (X-axis), the slope was 1.09 ± 0.02 (1 standard error SE, N=253) and the intercept 0.06 ± 0.04 (1SE, N=253). The intercept was not significantly different from zero (P=0.08) but the slope was significantly different (P=0.00) from one. A slope significant different from one could indicate (1) that the correction factor (1.32, Walkley and Black, 1934) adopted in this study was not appropriate to correct for the incomplete reaction of organic carbon, or (2) that some material strongly correlated with organic carbon influenced the relationship. No indication allowed choosing one explanation over the other. Black carbon could be suggesting as one material possibly affecting the slope of the $\%C_{tot}$-$\%C_{orga,WB}$-relationship. Charcoal particles were observed in the field and in the coarse fraction of the soils of this study. Higher charcoal contents in soils with higher soil organic carbon were reported for anthropogenic soils in Amazonia (Glaser et al., 2001) or South Africa (Blackmore et al., 1990), but these mere tendencies do not imply strong correlations between the two of them.

Table 7.5 (continued on next page). Overview of the means and ranges of CEC, carbon and clay contents of the soil samples integrated in the evaluation of the contribution of organic matter and clay minerals to CEC. Soil samples with pH_{H2O} superior to 7 were discarded.

Region	Depth	Data for Figure 7.2		Data for equations 6, 7, 8	
		%Ctot Mean (min - max) N=number of samples	%Corga.WB Mean (min - max) N=number of samples	CEC ($cmol_c.kg^{-1}$) Mean (min - max) N=number of samples	%clay Mean (min -max) N=number of samples
Butare	0-0.25 m	1.71 (0.80-2.80) (N=30)	1.35 (0.55-2.03) (N=30)	10.69 (10.65-10.73) (N=2)	33 (30-36) (N=2)
	> 0.25 m	0.78 (0.58-0.99) (N=7)	0.74 (0.55-0.96) (N=7)	7.72 (3.66-9.43) (N=9)	48 (26-64) (N=9)
Kibungo	0-0.25 m	4.57 (3.37-5.32) (N=16)	3.53 (2.63-4.67) (N=16)	24.27 (20.17-29.24) (N=2)	84 (83-84) (N=2)
	> 0.25 m	1.17 (0.42-2.55) (N=8)	1.08 (0.32-2.43) (N=8)	10.79 (6.16-17.71) (N=8)	91 (85-95) (N=8)
Gitega farm 1	0-0.25 m	2.58 (1.97-3.19) (N=2)	2.58 (1.93-3.23) (N=2)	13.07 (10.97-15.17) (N=2)	40 (40-41) (N=2)
	> 0.25 m	0.78 (0.22-1.71) (N=5)	0.73 (0.22-1.68) (N=5)	7.16 (5.20-12.15) (N=7)	63 (43-74) (N=7)
Gitega farm 2	0-0.25 m	2.18 (N=1)	2.14 (N=1)	10.68 (N=1)	46 (N=1)
	> 0.25 m	1.05 (0.27-1.84) (N=6)	0.97 (0.24-1.79) (N=6)	5.19 (2.84-9.13) (N=7)	46 (41-50) (N=8)

Table 7.5 (continued). Overview of the means and ranges of CEC, carbon and clay contents of the soil samples integrated in the evaluation of the contribution of organic matter and clay minerals to CEC. Soil samples with pH_{H2O} superior to 7 were discarded.

Region	Depth	Data for Figure 7.2		Data for equations 6, 7, 8	
		%Ctot Mean (min - max) N=number of samples	%Corga.WB Mean (min - max) N=number of samples	CEC ($cmol_c.kg^{-1}$) Mean (min - max) N=number of samples	%clay Mean (min -max) N=number of samples
Ntungamo f.2+4+5+7+8	0-0.25 m	1.77 (0.76-2.80) (N=64)	1.63 (0.72-2.44) (N=64)	7.30 (6.18-8.36) (N=6)	25 (19-36) (N=6)
	> 0.25 m	0.33 (0.16-0.61) (N=19)	0.25 (0.07-0.52) (N=19)	4.56 (3.77-5.54) (N=10)	37 (32-44) (N=10)
Ntungamo f.6+9+10	0-0.25 m	1.53 (0.99-2.44) (N=46)	1.37 (1.00-2.04) (N=46)	8.65 (6.24-16.18) (N=11)	26 (17-38) (N=11)
	> 0.25 m	0.54 (0.24-1.79) (N=20)	0.44 (0.18-1.67) (N=20)	6.81 (5.67-10.00) (N=10)	41 (29-52) (N=10)
Ntungamo farms 1+3	0-0.25 m	4.52 (1.51-6.70) (N=27)	4.28 (1.76-5.73) (N=27)	ND	ND
	> 0.25 m	0.43 (N=1)	0.49 (N=1	ND	ND

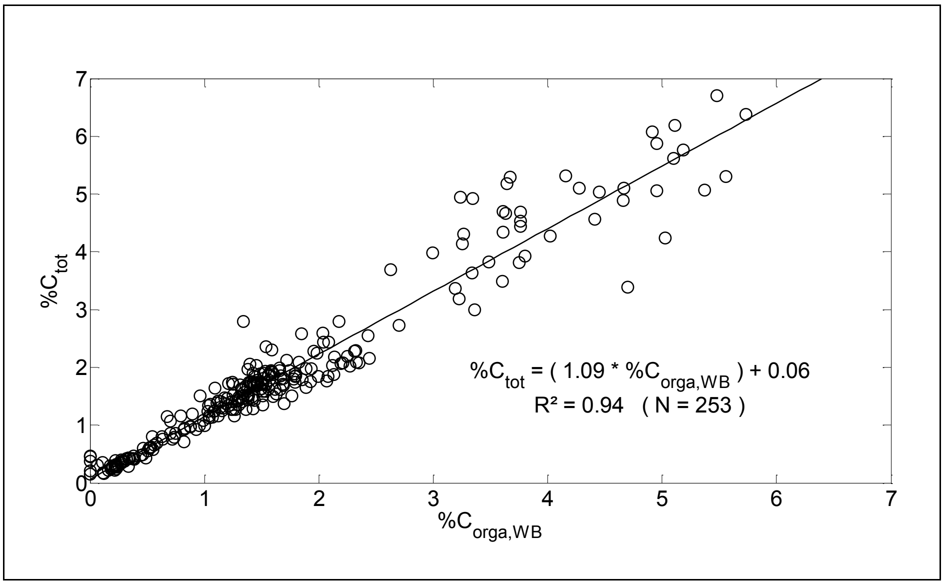

Figure 7.2. Relationship between total carbon and organic carbon contents. Soil samples with pH_{H2O} superior to 7 were discarded from the comparison.

In the samples retained for further analysis ($pH_{H2O} \leq 7$), CEC varied between 2.84 and 29.24 $cmol_c.kg^{-1}$. The highest CEC (24.71 $cmol_c.kg^{-1}$ on average (N=2)) were found for the surface horizons of Kibungo soils. These soils stood out by their high clay contents 83-95%, N=10). For the soils of all regions or subregions, CEC decreased with depth while clay percentages increased (Table 7.5).

For samples having pH_{H2O} equal or inferior to 7, soil cation exchange capacity (CEC_{soil}, $cmol_c.kg^{-1}$) was related to total carbon content ($\%C_{tot}$) by equation 6:

$$CEC_{soil} = (3.911 \text{ x } \%C_{tot}) + 3.858 \quad (R^2 = 0.81 ; N = 78) \quad [eq. 6]$$

The relationship improved considerably, when clay content (%clay, in fine earth) was taken into account ([eq.7]):

$$\mathrm{CEC_{soil}} = (3.093 \text{ x } \%\mathrm{C_{tot}}) + (0.063 \text{ x } \%\mathrm{clay}) + 0.984$$
$$(\mathrm{R}^2 = 0.81 \,;\mathrm{N} = 78) \quad [eq.7]$$

In the next part of the comparison, the unexplained factor (0.984) of equation 7 was redistributed over $\%C_{tot}$ and %clay by forcing the regression through the intercept ([eq.8]):

$$\mathrm{CEC_{soil}} = (4.060 \text{ x } \%\mathrm{C_{tot}}) + (0.142 \text{ x } \%\mathrm{clay})$$
$$(\mathrm{R}^2 = 0.90 \,;\mathrm{N} = 78) \quad [\mathrm{eq.}\,8]$$

Assuming that C represented 58% of the organic matter (Van Bemellen, 1891, *cited in* Nelson and Sommers, 1982), the coefficients 3.0983 and 4.060 for $\%C_{tot}$ in equations 7 and 8 suggested a CEC of 180-236 $cmol_c.kg^{-1}$ (per kg of organic matter). That figure is in the range of values published by others. Values of 100-300 $cmol_c.kg^{-1}$ (pH7) or 100-400 $cmol_c.kg^{-1}$ (soil pH 4.5-6.5) are reported for tropical soils (*references in* Oorts et al., 2000; Juo and Franzluebbers, 2003). More specifically, Oorts et al. (2003) observe CECs of 283 $cmol_c.kg^{-1}$ (pH 5.8) for soil organic matter of a Ferric Lixisol. Asadu et al. (1997) report a value of 163 $cmol_c.kg^{-1}$ for CEC of organic matter in the Highland Humid Zones of Africa and Foster et al. (1981) indicate a CEC of 214 $cmol_c.kg^{-1}$ for soil organic matter in Ugandan soils.

The CEC of the clay fraction suggested by equations 7 and 8 is 6.3-14.2 $cmol_c.kg^{-1}$ (kg of clay). This figure is in accordance with the clay mineralogy established in Chapter 6. In chapter 6, the clay fractions of 29 fine earth samples from the different regions are isolated and their mineralogical content quantified. The CEC of the clay fractions were estimated by using the determined clay abundances and adopting published values for the CECs (pH7) of the various clays (125, 25, 25, 10 $cmol_c.kg^{-1}$ for vermiculite, chlorite, illite and kaolinite respectively; Grim, 1968 *cited in* Calvert, 2003). The CECs hence calculated for the clay fractions varied between 6.9 and 13.5 $cmol_c.kg^{-1}$ (kg of clay) (N = 29).

Equation 8 was used to determine the relative contributions of $\%C_{tot}$ and %clay to the CEC of the soil. The contributions of carbon and minerals to the CEC of the soil were calculated by ([eq.9]):

$$\text{contribution of C to CEC}_{\text{soil}}(\%) = \frac{4.060 \text{ x } \%\text{C}_{\text{tot}}}{\text{CEC}_{\text{soil}}}$$

$$\text{contribution of clay to CEC } (\%) = 100 - \text{contribution of C to CEC}_{\text{soil}} \qquad [\text{eq. } 9]$$

The calculation of contributions of both carbon and minerals was performed for soil samples already considered when establishing the relationships ([eq.6, 7, 8]) and extrapolated to samples for which %clay was not available.

Table 7.6 summarizes the contribution of carbon to soil CEC, for each region or subregion individually. Soil samples having pH_{H2O} superior to 7 were discarded from the comparison. On average, carbon contributed between 60 and 98% of the soil CEC in surface samples. Contributions of clay particles hence ranged between 40 and 2%. Contribution of carbon to soil CEC decreased with depth (20-50% for samples lower than 1 m) while contribution of clay minerals accordingly increased (80-50%). These values corroborate published values for tropical soils. Klamt and Sombroek (1986) find that 25-95% of CEC (pH7) of weathered tropical soils are attributable to soil organic matter. They also indicate that contribution of organic matter to CEC decreases with depth, but remains significant in lower horizons (12-28%). Oorts et al. (2003) and Soares and Alleoni (2008), working at soil pH, indicate, respectively, that organic matter account for 87-96% or 50-95% of soil CEC. Similar values are also reported in Oades et al. (1989, *cited in* Soares and Alleoni, 2008) and Asadu et al. (1997, *and references therein*).

Table 7.6. Contribution of C to soil CEC for surface and deep samples of the regions and subregions of interest. Samples having pH_{H2O} superior to 7 were discarded from the comparison.

		Contribution of C to soil CEC (%)		
Region	Depth (N=nb of samples)	Mean	Minimum	Maximum
Butare	0-0.25 m (N=30)	60	42	82
	> 1 m (N=6)	35	24	43
Kibungo	0-0.25 m (N=16)	64	55	74
	> 1 m (N=5)	36	28	42
Gitega 1	0-0.27 m (N=2)	79	73	85
	0.82-1.05 m (N=4)	20	14	30
Gitega 2	0-0.30 m (N=1)	83		
	> 1 m (N=6)	50	21	85
Ntungamo farm 3	0-0.29 (N=1)	98	56	83
	0.29-0.60 (N=1)	54	14	34
Ntungamo farms 2+7	0-0.30 m (N=8)	71	51	71
	> 1 m (N=14)	25	16	30
Ntungamo farms 9+10	0-0.30 m (N=8)	66		
	> 1 m (N=11)	22		

7.4. Conclusions

The soils in Butare, Kibungo (Rwanda), Gitega (Central Burundi) and Ntungamo (South-West Uganda) are highly weathered. Quartz, kaolinite/nacrite, Fe-oxides, Al-oxides, Ti-oxides, muscovite, small quantities of vermiculite and occasional K-feldspars and albite constitute the soils. Calcite may be present in surface horizons because of amendments by kitchen ashes. Weathering of albite, muscovite/illite, K-feldspar, vermiculite as calculated by the data-intensive model *PROFILE* releases at most 5.9 $kg.ha^{-1}.year^{-1}$ of Na, 32.5 $kg.ha^{-1}.year^{-1}$ of K and 12.5 $kg.ha^{-1}.year^{-1}$ of Mg. Ca release rate may increase to 155.4 $kg.ha^{-1}.year^{-1}$ when calcite is supposed present in surface horizons, but are close to zero otherwise. Mineralization of recycled banana residues insures nutrient fluxes at least one order of magnitude higher than does mineral weathering. Besides as a nutrient source, organic matter is also an important contributor to the cation exchange capacity (CEC) of the soils. With a CEC of 180 $cmol_c.kg^{-1}$ (pH7) the organic matter of our tropical soils contributes for 60-98% to the CEC of surface horizons. Minerals account for the rest of the CEC; their contribution increases with depth (40-2% in surface samples; 50-80% of soil CEC in horizons >1 m). Although limited in their capacity to supply plant nutrients by weathering, minerals have thus their importance because of their capacity to retain and exchange cations.

Conclusions

8. Conclusions and outlook

8.1. General conclusions

As outlined in **Chapter 1**, the East African Highland banana (*Musa spp.* AAA-EA) is a crop of major importance in the African Great Lakes Region, because of the food and cash it provides to about 85 % of the population (FAOstat, estimates for 2010). Bananas are dominantly produced in small subsistence-oriented farms. Use of external inputs is low, and soil nutrient management is essentially limited to organic matter applications, often insufficient in quality and quantity. Chemical fertilizers are indeed rarely used, because of the high costs at purchase (low benefit/cost ratio), their low availability and the lack of knowledge on how to use them. Demographic growth exerts an increased pressure on the old and weathered soils dominating in the area. Intensification of cultivation has eliminated fallowing of land and losses of nutrients through harvest challenge the sustainability of the system if soil amendments do not increase. Low soil fertility is a major constraint explaining low banana yields. Drought or irregular rainfall, pests and diseases, and inadequate crop management practices are other constraints. Most of the studies addressing these constraints are geographically limited, conducted under controlled conditions and often focused on pests since those are often perceived as most important constraints by farmers. Studies that cover larger geographical areas and make the effort to rank constraints and quantify associated yield losses are rare. Although low soil fertility is recognized as being one of the problems, there is little understanding on the temporal and spatial variation of the different nutrient pools in the soil. Knowledge also lacks on the extent to which the limited reserves and maintenance of soil fertility relate to the mineralogical and organic components of the soil. By studying in-field data on soils, soil organic matter and mineralogy, banana plants, pests and diseases and management practices from various areas of the Great Lakes Region, this PhD-thesis contributes to fill in the knowledge and understanding gaps.

To get a general overview of the constraints faced by smallholder banana producers a Boundary Line Analysis (BLA) is performed in **Chapter 2**. The BLA takes into account soil, crop, management and pest data for the agro-ecoregions of Butare, Kibungo, Ruhengeri and Ntungamo. The BLA shows that the gap between actual production and attainable yield may attain 70-96%. Ranking the constraints, BLA highlights poor soil fertility as the major constraint on the poor Acrisols of Butare and Ntungamo. In the more fertile soils of Kibungo and Ruhengeri, soil fertility problems are the second most important constraints after suboptimal management practices. Pests explain part of the yield losses in the lower altitude regions of Kibungo and Ntungamo, but are not identified as major constraints. Complementary to BLA, the calculation of soil quality indices indicate that banana production potential does not only vary at regional scale, but also at inter-regional or intra-farm level. Since the BLA indentifies poor soil fertility as a major constraint over the entire region, the question of soil fertility and possible associated nutritional disorders needs to be investigated further. That effort is undertaken in Chapters 3 and 4.

Chapters 3 and 4 both rely on plant foliar analyses from Butare, Kibungo, Ruhengeri and Ntungamo to evaluate plant nutritional problems. While Chapter 3 is a more methodological analysis, Chapter 4 is an actual interpretation of the foliar data via the proposed procedures.

Indeed, **Chapter 3** compares four commonly used approaches to interpret tissue analyses for their ease of use and their final conclusions. The analysis brings to the conclusion that Critical Nutrient Values (CNV) and Sufficiency Ranges (SR) have the major disadvantage of being strongly dependent on the crops for which and the conditions under which they are established.

However, because of its ease of use in communication with farmers and extension officers, the method remains interesting and an effort is made to establish new CNV (for N, P, K, Ca, Mg) and SR (for major nutrients and cation ratios). When comparing the multi-elemental approaches DRIS (Diagnosis and Recommendation Integrated System) and CND (Compositional Nutrient Diagnosis), the study concludes that both methods provide useful and largely overlapping results. CND could nevertheless be recommended because of favorable indications in published reports and the ease of calculation. CNV, SR, DRIS- and CND-norms established in this study are derived from a wide range of agro-ecoregions and can therefore be used for other areas in the East African Highlands.

In **Chapter 4** we apply the CND approach that was recommended in Chapter 3 to actually map nutrient deficiencies and interactions in the Butare, Kibungo, Ruhengeri and Ntungamo areas. CND shows that K deficiencies are an overall problem in Rwanda, followed by Mg. In Ntungamo (SW Uganda), P and low and imbalanced K and Ca limit yields. Plant nutrient status do not only vary as a function of geology, but intra-regional and intra-farm differences are observed and attributed to potential management gradients. Improved understanding of nutrient deficiencies and disorders in various geographical areas will contribute to the development of site-specific recommendations.

Chapters 2 and 4 interpreted soil fertility constraints and nutritional disorders at the regional, intra-regional and intra-farm level by relying on soil chemical data. Regional differences in constraints are attributed to differences in soils and their parent materials. Differences at intra-farm level are tentatively explained by referring to published studies and the differential management they observe or deduce. In order to confirm of infirm the hypothesis of a management gradient in the areas of interest, a well-known tracer of human activities is called upon (**Chapter 5**). Indeed, since no quantified data are available for organic matter amendments, Chapter 5 tries to evaluate the impact of present and past soil management gradients by looking at soil phosphorus. Phosphorus is a tracer with a "memory" and thus reflects not only present-day management but also long-forgotten amendments. Phosphorus and its geochemical fractions have already proved their potential as tracers of human activities. Under the assumptions that (1) phosphorus losses are reduced and that places have (2) the same climate and (3) soil, that (4) they are grown with the same crop and (5) amended with organic matter of same nature, differences in total phosphorus contents or phosphorus fractions can be interpreted in terms of differences in the quantities of organic matter distributed over space and time. In Butare and part of the farms in Ntungamo, strong P gradients confirm the existence of soil management gradients within the farms. In Ruhengeri and Kibungo, the absence of P gradients seems to suggest the existence of more uniform soil management practices.

The phosphorus tool hence provided insights on the past and current organic matter management and on the human imprint on soil fertility. This raises the question whether the contribution of this man-made fertility is of importance to the global soil fertility, or whether it is only a minor change against the inherent soil fertility. To evaluate that inherent soil fertility, soil mineral reserves are needed. To provide quantified data on soil minerals, this PhD-thesis elaborates a normative calculation method to estimate the mineral abundances in highly weathered Acrisols and Nitisols of Butare, Kibungo, Gitega and Ntungamo (**Chapter 6**). Through a formalized sequence of calculations, the elemental oxides are attributed to quartz, kaolinite, hematite, Ti-oxides, gibbsite, muscovite/illite/sericite, vermiculite, K-feldspars, albite and possible calcite brought to the soil with kitchen ashes. Taking into account the (1) accuracy and (2) coherence of the results and (3) the ease of use and the (4) time saving, normative calculation proves superior to the more commonly used X-Ray Diffractometry. Our calculation confirm the commonly accepted but rarely verified statement that amounts of weatherable minerals are low in the weathered tropical soils of the African Highlands (< 2 %wt for feldspars,

< 1 %wt for vermiculite). Muscovite abundances are < 8 %wt, except in soils on micaschists (< 13 %wt)).

Chapter 7 relies on the mineralogical data calculated in Chapter 6 and the geochemical weathering model *PROFILE* to estimate Na, Ca, Mg and K releases through mineral weathering. Hypothesizing a self-sufficient system, nutrient release rates by mineral weathering as established by *PROFILE* are at least one order of magnitude lower than the nutrients released by complete organic matter decomposition. Although limited in their capacity to provide ample nutrient in the short and long term, soil minerals remain of importance because of the cation exchange capacity they offer. Minerals account for 2-40% of the CEC in surface soil samples. The complementary, major, part of the CEC was attributed to organic matter (98-60%). The analysis in Chapter 7 hence confirms and quantifies the key role of organic matter to maintain soil fertility in highly weathered Nitisols and Acrisols of Butare, Kibungo, Gitega and Ntungamo.

8.2. Outlook

1. Using two independent methods (Boundary Line Analysis (BLA) and Compositional Nutrient Diagnosis (CND)), this study highlights poor soil fertility as a major constraint to banana production and as a cause of nutritional disorders for various regions in Rwanda and in South-Western Uganda. While past research mainly focused on pest and diseases, our findings suggest that more attention should be given to soil fertility problems and adequate responses to address them. In old soils with low reserves of weatherable minerals, the sustainability of the systems cannot be insured without additional external nutrient inputs. Further intensification of the system to respond to the needs of a growing population, and further competition over organic matter as soil amendments, animal feed, fuel, or building materials, can only lead to

further depletion and soil mining. As organic matter does not suffice in quantity and quality, mineral fertilizers must be considered as complementary nutrient source. Site-specific recommendations taking into account the large regional variability in nutrient deficiencies could make fertilizers an economically viable solution.

2. This study brings the development of site-specific fertilizer recommendations one step closer by contributing directly and indirectly to the mapping of nutrient deficiencies at regional scale. (1) For the agro-ecroregions for which we had plant foliar data, specific nutrient deficiencies or nutritional disorders are already identified. (2) By providing researchers and farmers with critical nutrient values (CNV), sufficiency ranges (SV), DRIS- and CND-norms established over a wide range of agro-ecoregions, we provide tools to quickly help identifying nutrient deficiencies or disorders in other areas of the East African Highlands than those already effectively addressed. (3) The comparison and evaluation of CNV/SR, DRIS and CND-tools provides background information that allows further improvements on recommendations when studying new plant foliar data.

3. Our results emphasize the key-role of organic matter in maintaining soil fertility. In banana-based farms care should be taken, to preserve and use organic matter at best in order to avoid all possible losses. Organic matter could be combined to chemical fertilizers. The combination already proved beneficial in other parts of Africa (Bekunda, 1999 (Uganda); Ngailo et al., 2001 (Tanzania); Giller et al., 2006; Mafongoya et al., 2006; Zingore et al., 2007 (Zimbabwe); Vandeplas et al., 2010 (Kenya)) because of (1) the long-term build-up of soil organic matter, (2) the associated improvement of physical and physico-chemical properties of the soil and (3) possible insurance of synchrony of nutrient release and uptake.

4. The survey data used in this study provide very valuable information, but only represents a snapshot of the current cultivation, management and constraints. However, yields, crop management practices and crop production constraints will vary over time. These changes are likely to accelerate as crop production systems have to intensify to feed the rapidly growing population. Although P can be used to trace the cumulative effect of human activity, it would be good to better understand the rate at which soil nutrient stocks currently change. That would help us to predict the rate of soil fertility change and would allow timely intervention of improved management practices in order to prevent large production losses and degradation of this important natural resource base.

5. Throughout the study tools from various scientific disciplines (agronomy, geology, archeology) were used, criticized and adapted to our particular needs. We hope that the tools developed can be used and adapted by other researchers. Validation or rejection, adaptation or criticism, would only improve the use of the methods and would help better understand the results they are providing. As mentioned before in perspective 1, the use of CNV, SR, CND, DRIS and BLA could be encouraged to identify nutrient deficiencies and other production constraints. The use of the phosphorus tracer in other areas and over longer time periods, could help the science community to validate and better understand the tracer and its applications. Despite the estimations and hypotheses inherent to the computation, normative calculation of mineral abundances proved useful and time-saving in this study. This study hopes to make researchers aware of this easy and adaptable method to evaluate mineral reserves. Estimations through that kind of calculations are at least as accurate as more technically heavy and time-consuming technique of X-Ray Diffractometry.

Appendices

Appendix 1. Sequential fractionation procedure for soil phosphorous (*adapted from* Tiessen and Moir, 1993)

The sequential fractionation of phosphorus called upon in this study was a slightly modified version of the Tiessen and Moir (1993) procedure. The final step was adapted to respond to the material at disposal in the laboratory (UCL, Louvain-la-Neuve, Belgium): the H_2O_2/H_2SO_4-digestion recommended by Tiessen and Moir (1993) was replaced by a tri-acid digestion. Unground samples were preferred to ground material in an attempt to stay as close as possible to natural conditions. Duration of extraction steps were extended to 20 h (instead of 16 h in the original method).Half a gram of unground fine earth sample (< 2 mm) was placed in a pre-weighted centrifugation tube (100 ml).

Step 1. 30 ml of MilliQ-water and 2 strips of an anionic resin-membrane in HCO_3^--form (each 9 x 62mm, BDH no. 55164) were added. The centrifugation tube was placed on a reciprocal shaker. After 20 h of contact, the resin-strips were removed; soil particles adhering to the resin-strips were returned to the tube. The strips were then placed in a 50 ml-centrifugation tube containing 20 ml of HCl 0.5M. The tube was left open 1 h, to allow CO_2 to escape. After that, the tube was closed and desorption allowed to continue for 20 h, under agitation. The soil-water suspension was centrifuged (13000 rpm, 10 min, 5°C) and the supernatant filtrated through a polycarbonate Nuclepore filter (0.2 µm).

Step 2. Any soil lost during filtration at the end of step 1 was washed back into the tube with $NaHCO_3$ 0.5M (pH 8.5). In total 30 ml of $NaHCO_3$ were added. After 20 h of contact, under continuous agitation, the suspension was centrifuged (13000 rpm, 10 min, 5°C) and the supernatant filtrated (Nuclepore, 0.2 µm).

Steps 3 and 4. Any soil particles on the filter were washed back into the tube by NaOH 0.1M. The same procedure – adding 30 ml of solution, 20 h of contact on a reciprocal shaker, centrifugation (13000 rpm, 10 min, 5°C), filtration (Nuclepore, 0.2 µm) – was done for NaOH 0.1M, then for HCl 1M. Losses of soil particles were avoided by washing them back into the tube (after the NaOH-step) or by decanting suspension as gently as possible (for HCl 1M). All steps mentioned above were performed in a thermostatized room (20±1°C).

Step 5. The next step involved contact of soil residue with heated concentrated HCl. 10 ml of concentrated HCl were added to the soil residue. The tube was placed in a water bath at 80°C for 20 min (10 min to come to temperature, 10 min of contact), under regular stirring. When the tube was taken out of the bath, 5 more ml of concentrated HCl were added. The tube was allowed to cool at room temperature for 1 h; the contents of the tube were regularly stirred. After centrifugation (10 min, 13000 rpm, 5°C), the concentrated HCl-solution was filtrated trough a Whatmann cellulose filter (no 2) and recovered in a 50 ml-volumetric flask. Soil residue was washed with 10 ml of MilliQ-water, the suspension centrifuged, supernatant filtered and added to the 50 ml-flask. After recovering the water of wash (washing-step repeated twice), the 50 ml-flask was made to volume with MilliQ-water.

Step 6. Soil residue was oven-dried at 105°C for at least 24 h. Using an agate mortar and pestle, the dried soil was finely ground by hand. Losses were minimized but could not be entirely avoided. The ground material was submitted to digestion in a mixture of concentrated HF/HNO_3 (at 130°C) at first, and $HClO_4$ (at 160°C) afterwards. When the perchloric acid was completely evaporated, the residue was solubilized in concentrated hot HCl/HNO_3. The solution was filtrated (Whatmann cellulose filter, grade 2) and recovered in a 50 ml-volumetric flask, made to volume with MilliQ-water.

In all the solutions (HCl 0.5 M after resin desorption, $NaHCO_3$ 0.5M pH8.5, NaOH 0.1M, HCl 1M, concentrated HCl, HCl/HNO_3), concentrations of P were determined by inductively coupled plasma – atomic emission spectrometry (ICP-AES). P concentrations in one solution were corrected for the "pollution" induced by the previous extractant. Indeed, when a fresh solution was added, a minor fraction of the previous reagent still remained in contact with the soil. The volume of the solution remaining in the tube was evaluated by weight. Knowing the volume of solution remaining and the P concentrations therein, correction for P concentrations in the subsequent solution was possible.

On the $NaHCO_3$- and NaOH-extracts, a supplementary step was performed to discard organic matter. 10 ml of the extracts were acidified to pH 1.5, with H_2SO_4 0.9 M. The acidified solutions were allowed to stand for 30 min at 4°C, before being centrifuged for 10 min (13000 rpm, 5°C). Precipitated organic matter accumulated on the bottom of the centrifugation-tube. The supernatant was decanted through a Whatmann cellulose filter and recovered in a 50 ml-volumetric flask. A diluted H_2SO_4-solution (0.01M) was used to rinse the tube, and was added to the volumetric flask. The flask was made to volume with this diluted H_2SO_4-solution. Phosphorus in the supernatant acidified solutions was supposed to be in inorganic forms. Inorganic phosphorus contents were determined by ICP-AES. Organic phosphorus in $NaHCO_3$- or NaOH-solutions was determined indirectly by subtracting inorganic phosphorus from total P contents determined in non-acidified solutions.

Appendix 2. Regional differences in soils as captured by Principal Component Analysis

The regional variability of soil chemical characteristics is mentioned in Chapters 2 and 4 as a support to interpret plant nutrition data. The variability can also be summarized by Principal Component Analysis (PCA). The results by this statistical tool are presented in this second Appendix.

A2.1. Soil chemical data and selection of variables

The following data were initially considered for surface and deep soil samples gathered over the four field campaigns (described in Chapter 5): pH in water, total carbon and nitrogen contents, exchangeable K, Mg, Ca and sum of exchangeable K, Ca and Mg, total chemical analyses (Fe, Si, Al, Ti, Fe, Ca, K, Mg, Mn, Na, P) and total reserve in bases (TRB, Herbillon, 1986). Laboratory analyses are described in Chapter 2 for instance. In order to avoid redundancies, the correlation coefficients between data were considered. When different variables were closely associated, only one was selected as representative of that group and retained for further analysis. The data finally selected were: pH in water (pH_{H2O}), total carbon contents ($\%C_{tot}$), total iron, silicon, phosphorus and potassium contents ($\%Fe_2O_3$, $\%SiO_2$, $\%P_2O_5$, $\%K_2O$).

Data from deep horizons (> 100 cm) and surface samples (0-25/30 cm) are considered separately in order to isolate influence of sole geology from potential influence of soil management by farmers.

A2.2. Results and discussion

The j out of (h+1) original principal components showing eigenvalues equal or superior to 0.7 (Parent et al., 1994), are varimax rotated in order to maximize the loadings of each variable on only one principal component and hence simplify the global structure (Sharma, 1996). When interpreting the Principal Components in the rotated structure, only the variables having loadings superior to the selection criterion of Ovalles and Collins (1988, eq. [1]) are considered influential in the formation of the Principal Components:

$$\text{selection criterion } = \frac{0.5}{\sqrt{\text{eigenvalue of the PC}}} \qquad [eq.1]$$

The results are graphically presented in Figure A and Table A.

Deep soil samples

In the original Principal Component Analysis (PCA) performed on 6 variables (pH_{H2O}, $\%C_{tot}$, $\%Fe_2O_3$, $\%SiO_2$, $\%P_2O_5$, $\%K_2O$) for 57 deep soil samples from Butare, Kibungo, Gitega farm 1, Gitega farm 2, Ntungamo farms 2+7 and 9+10, the three first Principal Components have eigenvalues equal or superior to 0.7. They explain respectively 47, 29 and 13 % of the total variance. The PCA-structure after varimax rotation of the three first principal components, is detailed in Table A. The selection criterion of Ovalles and Collins (1988, eq. [1], Table A) is used to determine which variables are influential in the formation of the Principal Components (PC). $\%Fe_2O_3$ and $\%P_2O_5$ contribute negatively to PC1 while $\%SiO_2$ contributes positively. pH_{H2O} and $\%K_2O$ have respectively high positive and negative loadings on PC2. $\%C_{tot}$ has high positive loadings on PC3. The biplot of Figure A.A represents simultaneously the loadings of the two first PCs and the related Principal Component scores. The iron rich soils of Kibungo and Gitega farm 1 plot are closely related to total phosphorus contents, because of fixation of phosphorus on iron oxides. Butare, and to a lesser extent Kibungo and Gitega 1, are positively related to pH recalling the higher pH_{H2O} values found in those regions compared to the soils in Ntungamo. The soils of Butare have high quartz contents, which explain the relation with $\%SiO_2$. Soils on micaschists (Ntungamo farms 2+7) are related to higher total K contents. Wide scatter is observed for the soils of farms 9+10.

Surface soil samples

In the original Principal Component Analysis (PCA) performed on 6 variables (pH_{H2O}, $\%C_{tot}$, $\%Fe_2O_3$, $\%SiO_2$, $\%P_2O_5$, $\%K_2O$) for 218 surface soil samples from Butare, Kibungo, Ruhengeri and the three subgroups in Ntungamo (farms 1+3, 2+4+5+7+8 and 6+9+10), three first Principal Components have eigenvalues equal or superior to 0.7. They explain respectively 58, 24 and 11 % of the total variance. The PCA-structure after varimax rotation of the three first principal components, is detailed in Table A. $\%Fe_2O_3$ and $\%C_{tot}$ contribute positively to PC1 while $\%SiO_2$ contributes negatively. $\%K_2O$ and $\%P_2O_5$ have high loadings on PC2 and pH_{H2O} on PC3 (Figure A.B). The young Andosols of Ruhengeri are correlated to high amounts of K and P, and are, in this, opposed to the weathered old soils of Butare, Kibungo, Ntungamo 2+4+5+7+8 and 6+9+10. Soils of Ntungamo farms 1+3 are shallow soils on micaschists showing a higher chemical fertility than other soils of Ntungamo. Farms 1+3 are on steep slopes, so their soils probably know some rejuvenation through erosion. High iron contents of the Kibungo soils are closely correlated to high carbon contents, because of stabilization of carbon by organo-mineral interactions.

Table A. Eigenvectors and eigenvalues describing the three first Principal Components (PC) after orthogonal axis rotation (varimax rotation).

	Deep samples (Figure A.A)			Surface samples (Figure A.B)		
	PC1	PC2	PC3	PC1	PC2	PC3
pH_{H2O}	-0.01	**0.84**	-0.20	0.00	-0.02	**-0.99**
$\%C_{tot}$	-0.04	-0.04	**0.87**	**0.54**	-0.14	0.10
$\%Fe_2O_3$	**-0.63**	-0.06	-0.22	**0.59**	0.14	-0.05
$\%SiO_2$	**0.57**	0.03	-0.14	**-0.57**	0.03	0.04
$\%P_2O_5$	**-0.52**	0.09	0.05	0.14	**-0.63**	-0.03
$\%K_2O$	0.01	**-0.53**	-0.36	-0.13	**-0.75**	0.02
Eigenvalues	2.80	1.76	0.76	3.51	1.41	0.66
Selection criterion [eq. 1]	0.30	0.38	0.57	0.27	0.42	0.61
Percentage of variance explained	52.61	33.04	14.36	0.63	0.25	0.12

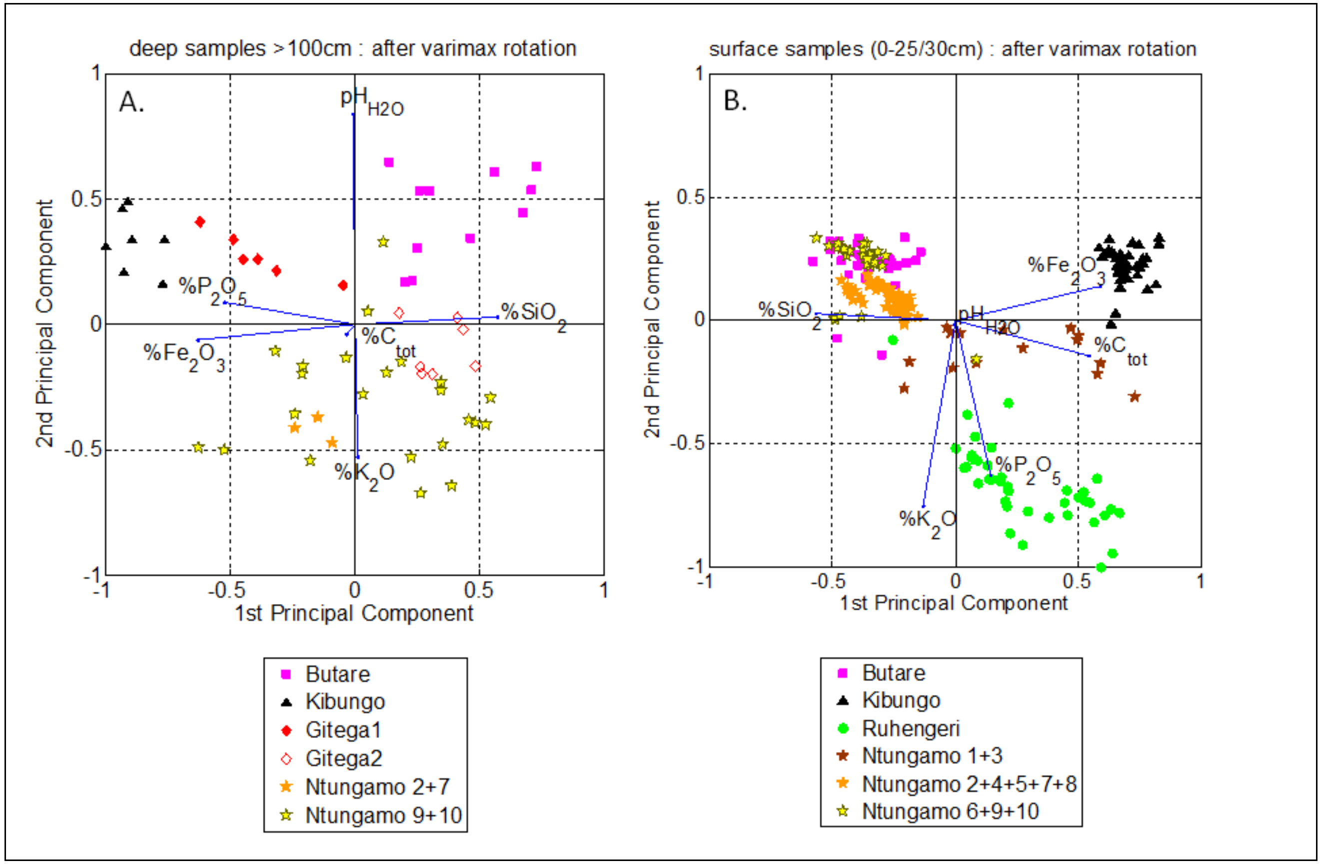

Figure A. Principal Component Analysis on (A) deep and (B) surface soil samples.

References

References

Abekoe M.K. and Sahrawat K.L. (2003). Long-term cropping effect on phosphorus fractions in an Ultisol of the humid forest zone in West Africa. Communications in Soil Science and Plant Analysis, 34, 427-437.

Abele S. and Pillay M. (2007). Bacterial wilt and drought stresses in banana production and their impact on economic welfare in Uganda: implications for banana research in East African Highlands. Journal of Crop Improvement, 19, 173-191.

Adepetu J.A. and Corey R.B. (1976). Organic phosphorus as a predictor of plant available phosphorus in soils of Southern Nigeria. Soil Science, 122, 159-164.

Aitchison J. (1983). Principal component analysis of compositional data. Biometrika, 70, 57-65.

Aitken R.L. (1992). Relationship between extractable Al, selected soil properties, pH buffer capacity and lime requirement in some acidic Queensland soils. Australian Journal of Soil Research, 30, 119-130.

Alexandratos N. (2005). Countries with rapid population growth and resource constraints: issues of food, agriculture and development. Population and Development Review, 31, 237-258.

Alves M.E. and Omotoso O. (2009). Improving Rietveld-based clay mineralogic quantification of Oxisols using SIROQUANT. Soil Science Society of America Journal, 73, 2191-2197.

Amonette J.E. (2002). Methods for determination of mineralogy and environmental availability). In: Soil Mineralogy with Environmental Applications (J.B. Dixon and D.G. Schulze (eds.)), Soil Science Society of America, Book Series nb 7, 153-198.

Andrews S.S. and Carroll C.R. (2001). Designing a soil quality assessment tool for sustainable agroecosystem management. Ecological Applications, 11, 1573-1585.

Andrews S.S., Karlen D.L. and Mitchel, J.P. (2002). A comparison of soil quality indexing methods for vegetable production systems in Northern California. Agriculture, Ecosystems and Environment, 90, 25-45 S.

Andrews S.S., Karlen D.L. and Cambardella C.A. (2004). The management assessment framework: a quantitative soil quality evaluation method. Soil Science Society of America Journal, 68, 1945-1962.

Andrist-Rangel Y., Simonsson M., Andersson S., Oborn I. and Hillier S. (2006). Mineralogical budgeting of potassium in soil: a basis for understanding standard measures of reserve potassium. Journal of Plant Nutrition and Soil Science, 169, 605-615.

Andrist-Rangel Y., Hillier S., Oborn I., Lilly A., Towers W., Edwards A.C. and Paterson E. (2010). Assessing potassium reserves in northern temperate grassland soils: a perspective based on quantitative mineralogical analysis and aqua-regia extractable potassium. Geoderma, 158, 303-314.

Angeles, D.E., Sumner, M.E. and Lahav, E. (1993). Preliminary DRIS norms for banana. Journal of Plant Nutrition, 16, 1059-1070.

Aniku J., Kataama D., Nkedi-Kizza P. and Ssessanga S. (2001). PCDO and soil fertility management: Uganda results and experience. In: Soil and nutrient management in Sub-Saharan Africa in support of the soil fertility initiative. Proceedings of the expert consultation, 6-9 December *1999*, Lusaka, Zambia (R.N. Roy and H. Nabhan (eds.)). FAO Publications, Rome. 65-75.

Ansoms A., Verdoodt A. and van Ranst, E. (2008). The inverse relationship between farm size and productivity in rural Rwanda. Discussion Paper 2008.09, Institute of Development Policy and Management, 36pp.

Antun P., Gérards J. and Petricec V. (1971). Carte Géologique du Rwanda. Feuille Ruhengeri Nord (S2/29 NW et NE) [Geological map Rwanda, north Ruhengeri] Champs Volcanique des Birunga, 1/100.000.

Appenroth K.J. and Gabrys H. (2003). Ion antagonism between calcium and magnesium in phytochrome-mediated degradation of storage starch in Spirodela polyrhiza. Plant Science, 165, 1261-1265.

Appenroth K.J., Gabrys H. and Scheuerlein R.W. (1999). Ion antagonsim in phytochrome-mediated calcium-dependent germination of turions of Spirodela polyrhiza (L.) Schleiden. Planta, 208, 583-587.

Araya M. (2003). Stratification and spatial distribution of the banana (Musa AAA, Cavendish subgroup, cvs 'Valery' and 'Grande Naine') root system. In: Banana root system: towards a better understanding for its productive management (D.W. Turner and F.E. Rosales (eds.)), Proceedings of an international symposium held in San José, Costa Rica, 3-5 November 2003, 83-103.

Arshad M.A. and Martin S. (2002). Identifying critical limits for soil quality indicators in agro-ecosystems. Agriculture, Ecosystems and Environment, 88, 153-160.

Artiola J.F. (1990). Determination of Carbon, Nitrogen and Sulfur in soils, sediments and wastes: a comparative study. International Journal of Environmental Analytical Chemistry, 41, 159-171.

Asadu C.L.A., Diels J. and Vanlauwe B. (1997). A comparison of the contributions of clay, silt, and organic matter to the effective CEC of soils of subsaharan Africa. Soil Science, 162, 785-794.

Badgujar C.D., Dusane S.M. and Deshmukh S.S. (2003). Influence of weeding regime on the performance of "Basrai" (AAA). InfoMusa, 12, 12-13.

Baijukya F.P. and de Steenhuijsen Piters B. (1998). Nutrient balances and their consequences in the banana-based land use systems of Bukoba district, northwest Tanzania. Agriculture, Ecosystems and Environment, 71, 174-158.

Baldock, J.O.and Schulte, E.E. (1996). Plant analysis with standardized scores combines DRIS and sufficiency range approaches for corn. Agronomy Journal, 88, 448-456.

Bananuka J.A., Rubaihayo P.R. and Zake J.Y.K. (2000). Effect of organic mulches on growth, yield components and yield of East African Highland banana. Acta Horticulturae, 540, 293-297.

Barekye A., Kashaija I.N., Tushemereirwe W.K. and Adipala E. (2000). Comparison of damage levels caused by Radopholus similis and Helicotylenchus multicunctus on bananas in Uganda. Annals of Applied Biology, 137, 273-278.

Barré P., Montagnier C., Chenu C., Abbadie L. and Velde B. (2008). Clay minerals as a soil potassium reservoir: observation and quantification through X-ray diffraction. Plant and Soil, 302, 213-220.

Barrios E., Delve R.J., Bekunda M., Mowo J., Agunda J., Ramisch J., Trejo M.T. and Thomas R.J. (2006). Indicators of soil quality: a South-South development of a methodological guide for linking local and technical knowledge. Geoderma, 135, 248-259.

Barrow N.J. (1983). On the reversibility of phosphate sorption by soils. Journal of Soil Science, 34, 751-758.

Bates, T.E. (1971). Factors influencing critical nutrient concentrations in plants and their evaluation: a review. Soil Science, 112, 116-130.

Bationo A., Hartemink A., Lungu O., Naimi M., Okoth P., Smaling E. and Thiombiano L. (2006). African soils: their productivity and profitability of fertilizer use. Background paper for the Africa Fertilizer Summit, Abuja (Nigeria), 9-13 June 2006, 1-24.

Baudet D., Hanon M., Lemonne E., Theunissen K., Buyagu S., Dehandschutter J., Ngizimana W., Nsengiyumva P., Rusanganwa J.B. and Tahon A. (1988). Lithostratigraphie du domaine sédimentaire de la chaîne kibarienne du Rwanda. Annales de la Société Géologique de Belgique, 112, 225-246.

Bayite-Kasule (2009). Inorganic fertilizer in Uganda - knowledge gaps, profitability, subsidy and implications of a national policy. Uganda strategy support program (USSP), brief no 8, 1-6.

Beauchemin S., Hesterberg D., Chou J., Beauchemin M., Simard R.R. and Sayers D.E. (2003). Speciation of phosphorus in phosphorus-enriched agricultural soils using X-Ray Absorption Near-Edge Structure Spectroscopy and chemical fractionation. Journal of Environmental Quality, 32, 1809-1819.

Beaufils, E.R. and Sumner, M.E. (1977). Effect of time of sampling on the diagnosis of the N, P, K, Ca and Mg requirements of sugercane by the DRIS approach. Proceedings of the South African Sugar Technologists' Association, 51, 62-67.

Bekunda M. A. (1999). Farmer responses to soil fertility decline in banana-based cropping systems of Uganda. Managing Africa's Soils: Working Paper No. 4. IIED, London, UK. 26pp.

Bekunda M.A. and Woomer P.L. (1996). Organic resource management in banana-based cropping systems of the Lake Victoria Basin, Uganda. Agriculture, Ecosystems and Environment, 59, 171-180.

Bekunda M. and Manzi G. (2003). Use of the partial nutrient budget as an indicator of nutrient depletion in the Highlands of southwestern Uganda. Nutrient Cycling in Agroecosystems, 67, 187-195.

Bekunda M.A., Wortmann C.S., Bwamiki D.P. and Okwakol M. (2003). Potentials and challenges of soil fertility management in the banana-based cropping systems of Eastern Africa. In: Soil fertility management in Africa: a regional perspective (M.P. Gichuri, A.Bationo, M.A. Bekunda, H.C. Goma, P.L. Mafongoya, D.N. Mugendi, H.K. Murwuira, S.M. Nandwa, P. Nyathi and M.J. Swift (eds.)). Academy Science Publishers (ASP), Centro Internacional de Agricultura Tropical (CIAT), Tropical Soil Biology and Fertility (TSBF). Nairobi, Kenya. 123-147.

Bekunda M., Ebanyat P., Nkonya E., Mugendi D. and Msaky J.J. (2004). Soil fertility status, management and research in East Africa. Eastern Africa Journal of Rural Development 20, 94-112.

Beverly, R.B., Stark, J.C., Ojala, J.C. and Embleton, T.W. (1984). Nutrient diagnosis of "Valencia" oranges by DRIS. Journal of the American Society of Horticultural Science, 109, 649-654.

Bielders C.L., De Backer L.W. and Delvaux B. (1990). Particle density of volcanic soils as measured with a gas pycnometer. Soil Science Society of America Journal, 54, 822-826.

Bish D.L. (1994). Quantitative X-Ray Diffraction analysis of soils. In: Quantitative methods in soil mineralogy (J.E. Amonette and L.W. Zelazny (eds.)), Soil Science Society of America Miscellaneous Publication. 267-295.

Bish D.L. and Reynolds R.C.Jr. (1989). Sample preparation for X-Ray Diffraction. In: Modern powder diffraction (Bish D.L. and Post J.E. (eds.)), Reviews in Mineralogy vol. 20, Mineralogical Society of America, 73-100.

Bidner-Barhava, N. and Ravikovitch, S. (1958). The influence of various soils on the mineral composition of banana leaves. Ktavim, 8, 255-272.

Biruma M., Pillay M., Tripathi L., Blomme G., Abele S., Mwangi M., Bandyopadhyay R., Muchunguzi P., Kassim S., Nyine M., Turyagyenda L. and Eden-Green, S. (2007). Banana Xanthomonas wilt: a review of the disease, management strategies and future research directions. African Journal of Biotechnology, 6, 953-962.

Black, C.A. (1993). Soil fertility evaluation and control). Lewis Publishers edit., Boca Rota, USA, 1st edition, 746pp.

Blackmore A.C., Mentis M.T. and Scholes R.J. (1990). The origin and extent of nutrient-enriched patches within a nutrient-poor savanna in South Africa. Journal of Biogeography, 17, 463-470.

Blakemore L.C., Searle P.L. and Daly B.K. (1981). Extractable iron, aluminium and silicon). In: Methods for Chemical Analysis of Soils. New Zealand Soil Bureau, Scientific Report 10A, 2nd edition, 71-76.

Blanco-Macias F., Lara-Herrera A., Valdez-Cepeda R.D., Cortes-Banuelos J.O., Luna-Flores M. and Salas-Luevano M.A. (2006). Interacciones nutrimentales y normas de la tecnica de nutrimento compuesto en nopal (Opuntia ficus-indica L. Miller). Revista Chapingo Serie Horticultura, 12, 165-175.

Blanco-Macias F., Magallanes-Quintanar R., Valdez-Cepeda R.D., Vazquez-Alvarado R., Olivares-Saenz E., Gutierrez-Ornelas E. and Vidales-Contreras J.A. (2009). Comparison between CND norms and boundary-line approach nutrient standards (Opuntia ficus-indica L. Case). Revista Chapingo Serie Horticultura, 15, 217-223.

Blanco-Macias F., Magallanes-Quintanar R., Valdez-Cepeda R.D., Vazquez-Alvarado R., Olivares-Saenz E., Gutierrez-Ornelas E., Vidales-Contreras J.A. and Murillo-Amador B. (2010). Nutritional reference values for Opuntia ficus-indica determined by means of the boundary-line approach. Journal of Plant Nutrition and Soil Science, 000, 1-8.

Bolan N.S., Barrow N.J. and Posner A.M. (1985). Describing the effect of time on sorption of phosphate by iron and aluminium hydroxides. Journal of Soil Science, 36, 187-197.

Bootsma H.A., Mwita J., Mwichande B., Hecky R.E., Kihedu J. and Mwambungu J. (1999). The atmospheric deposition of nutrients on Lake Malawi/Nyasa (H.A. Bootsma and R.E. Hecky (eds.)) Water Quality Report. Lake Malawi/Nyasa Biodiversity Conservation Project, p.85–111.

Borges A.L., De Oliveira E Silva S., Correa Caldas R. and Da Silva Ledo C.A. (2006). Leaf nutrients contents in banana genotypes. Revista Brasileira de Fruticultura Jaboticabal, 28, 314-318.

Bougnom B., Mair J., Etoa F.X. and Insam H. (2009). Compost with wood ash addition: a risk or a chance for ameliorating acid tropical soils? Geoderma, 153, 402-407.

Bouillon S., Abril G., Borges V.A., Dehairs F., Govers G., Hughes H.J., Merckx R., Meysman F.J.R., Nyunja J., Osburn C. and Middelburg J.J. (2009). Distribution, origin and cycling of carbon in the Tana River (Kenya): a dry season basin-scale survey from headwaters to the delta. Biogeosciences, 6, 2475-2493.

Bouwmeester H., van Asten P. and Ouma E. (2009). Mapping key variables of banana based cropping systems in the Great Lakes Region. CIALCA technical report 11, 51pp.

Bowman R.A. and Cole C.V. (1978). An exploratory method for fractionation of organic phosphorus from grassland soils. Soil Science, 125, 95-101.

Braun J.J., Dupre B., Viers J., Ngoupayou J.R.N., Bedimo J.P.B., Sigha-Nkamdjou L., Freydier R., Robain H., Nyeck B., Bodin J., Oliva P., Boeglin J.L., Stemmler S. and Berthelin J. (2002). Biogeohydrodynamic in the forested humid tropical environment: the case study of the Nsimi small experimental watershed (South Cameroon). Bulletin de la Société Géologique de France, 173, 347-357.

Brejda J.J., Moorman T.B., Karlen D.L. and Dao T.H. (2000). Identification of regional soil quality factors and indicators: I. Central and Southern Plains. Soil Science Society of America Journal, 64, 2115-2124.

Bridge J., Fogain R. and Speijer P. (1997). The root lesion nematodes of banana Pratylenchus coffeae (Zimmermann) Filip. and Schu. Stek, 1941, and Pratylenchus goodeyi Sher and Allen, 1953"). Musa Pest Fact Sheet no 2, http://bananas.bioversityinternational.org/files/files/pdf/publications/pest2.pdf (accessed August 8th, 2010).

Briggs L. and Twomlow S.J. (2002). Organic material flows within a smallholder highland farming system of South West Uganda. Agriculture, Ecosystems and Environment, 89, 191-212.

Brindley G.W. and Brown G. (1980). Crystal structures of clay minerals and their X-Ray identification, Mineralogical Society (Great Britain), Monograph nb 5, 2nd edition, 495pp.

Burri C. (1964). Petrochemical calculations based on equivalents: methods of Paul Niggli. Israel Program for Scientific Translation, Jerusalem. 304pp.

Byers, A. (1990). Preliminary results of the RRAM project soil loss and erosion control trials, Rwanda, 1987-1988. Research needs and applications to reduce erosion and sedimentation in tropical steeplands (Proceedings of the Fiji Symposium, June 1990), IAHS-AISH Publications, 192, 94-102.

Calvert R. (2003). Le sol : propriétés et fonctions, tome 1 : structure, phénomènes aux interfaces. Référence Scientifique. France Agricole edt., 455pp.

Campbell A.S. and Schwertman U. (1984). Iron oxide mineralogy of placic horizons. Journal of Soil Science, 35, 569-582.

Campbell L.M., Hecky R.E., Muggide R., Dixon D.G. and Ramlal P.S. (2003). Variation and distribution of total mercury in water, sediment and soil from northern Lake Victoria, East Africa. Biogeochemistry, 65, 195-211.

Carr M.K.V. (2009). The water relations and irrigation requirements of banana (Musa spp.). Exploratory Agriculture, 45, 333-371.

Casanova D., Goudriaan J., Bouma J. and Epema G.F. (1999). Yield gap analysis in relation to soil properties in direct-seeded flooded rice. Geoderma, 19, 191-216.

Cavanagh W.G., Hirst S. and Litton C.D. (1988). Soil phosphate, site boundaries, and change point analysis. Journal of Field Archaeology, 15, 67-83.

Certini G., Corti G. and Fernandez Sanluro M.J. (2002). Comparison of two soil organic matter extractants and determination of the "Walkley-Black" correction factors for organic fractions from a volcanic soil. Communications in Soil Science and Plant Analysis, 33, 685-693.

Chardon W.J. (2000). Phosphorus extraction with iron oxide-impregnated filter paper (Pi test). In : Methods of phosphorus analysis for soils, sediments, residuals and water. G.M. Pierzynski (edt.), Southern Cooperative Series Bulletin nb 396, 27-30.

Chamayou H. and Legros J.-P. (1989). Les bases physiques, chimiques et minéralogiques de la science du sol, Agence de coopération culturelle et technique, conseil international de la lange française, Presses Universitaires de France, 593pp.

Chao T.T. and Sanzolone R.F. (1992). Decomposition techniques. Journal of Geochemical Exploration, 44, 65-106.

Chikanda A. (2009). Environmental degradation in Sub-Saharan Africa. In : Environment and health in Sub-Saharan Africa : Managing an emerging crisis (I.N. Luginaah et E.K. Yanful (eds.)), Springer Science+Business Media, 79-94.

Churchman G.J., Whitton J.S., Claridge G.G.C. and Theng B.K.G. (1984). Intercalation method using formamide for differentiating halloysite from kaolinite. Clays and Clay Minerals, 19, 161-175.

Chuyong G.B., Newbery D.M. and Songwe N.C. (2004). Rainfall input, throughfall and stemflow of nutrients in a Central African rain forest dominated by Ectomycorrhizal trees. Biogeochemistry, 67, 73-91.

Claessens W. and Theunissen K. (1988). Gitega S4/29NE [geological map], 1/100.000, carte géologique du Burundi, Tervuren (Belgium), edited by the Département de géologie et Minéralogie du Musée de l'Afrique Centrale et le Ministère des travaux publics, de l'énergie et des mines de la République du Burundi.

Clay D., Reardon T. and Kangasniemi J. (1998). Sustainable intensification in the Highland Tropics: Rwandan farmers' investment in land conservation and soil fertility. Economic Development and Cultural Change, 46, 351-377.

Clay D.C., Reardon T., Kelly V. and Mpyisi E. (2001). Promoting Input Use and Conservation Investments among Farm Households in Rwanda. International Development Collaborative Working Papers RW-FSRP-RR-06, Department of Agricultural Economics, Michigan State University.

Comerford N.B. (2005). Soil factors affecting nutrient bioavailability. In: Nutrient acquisition by plants- an ecological perspective (H. BassiriRad (edt.)), Ecological Studies, Springer-Verlag, 1-14.

Condron L.M., Turner B.L. and Cade-Menun B.J. (2005). Chemistry and dynamics of soil organic phosphorus. In: Phosphorus - agriculture and environment. (J.T. Sims and A.N. Sharpley (eds.)), American Society of Agronomy, Agronomy Series nb 46, 87-122.

Copus A. (2009). Etude du statut nutritionnel de systèmes bananiers-caféiers au Burundi. MSc-thesis, Université catholique de Louvain, 112pp.

Craswell E.T. and Lefroy R.D.B. (2001). The role and function of organic matter in tropical soils. Nutrient Cycling in Agroecosystems, 61, 7-8.

Cross A.F. and Schlesinger W.H. (1995). A literature review and evaluation of the Hedley fractionation: Applications to the biogeochemical cycle of soil phosphorous in natural ecosystems. Geoderma, 64, 197-214.

Cross A.F. and Schlesinger W. H. (2001). Biological and geochemical controls on phosphorus fractions in semiarid soils. Biogeochemistry 52, 155-172.

Cross W., Iddings J.P., Pirsson L.W. and Washington H.S. (1902). A quantitative chemico-mineralogical classification and nomenclature of igneous rocks. Journal of Geology, 10, 555-690.

Crowley E.L. and Carter S.E. (2000). Agrarian change and the changing relationships between toil and soil in Maragoli, Western Kenya (1900-1994). Human Ecology, 28, 383-414.

Dahal G., Ortiz R., Tenkouano A., Hughes J.A., Thottappilly G., Vuylsteke D. and Lockhart B.E.L. (2000). Relationship between natural occurrence of banana streak badnavirus and symptom expression, relative concentration of viral antigen, and yield characteristics of some micropropagated Musa spp. Plant Pathology, 49, 68-79.

Daniells J.W., Geering A.D.W., Bryde N.J. and Thomas J.E. (2001). The effect of Banana streak virus on the growth and yield of dessert bananas in tropical Australia. Annals of Applied Biology, 139, 51-60.

Darke A.K. and Walbridge M.R. (1994). Estimating non-crystalline and crystalline aluminum and iron by selective dissolution in a riparian forest soil. Communications in Soil Science and Plant Analysis, 25, 2089-2101.

Davies G. (1995). Banana and plantain in the East African highlands. In: Bananas and plantains (S. Gowen (edt.)), Chapman and Hall, London, 493-503.

Davis B.L. (1987). Quantitative determination of mineral content of geological samples by X-Ray Diffraction: discussion. American Mineralogist, 72, 438-440.

Deer W.A., Howie R.A. and Zussman J. (1992). An introduction to the rock-forming minerals). Longman, 2nd edition, Essex, UK, 696pp.

de Jager A., Kariuku I., Matiri F.M., Odendo M. and Wanyama J.M. (1998). Monitoring nutrient flows and economic performance in African framing systems (NUTMON) : IV. Linking nutrient balances and economic performance in three districts in Kenya. Agriculture, Ecosystems and Environment, 71, 81-92.

Demeyer A., Voundi Nkana J.C.V. and Verloo M.G. (2001). Characteristics of wood ash and influence on soil properties and nutrient uptake: an overview). Bioresource Technology, 77, 287-295.

Dixon J.B. and Schulze D.G. (eds.) (2002). Soil mineralogy with environmental applications, Soil Science Society of America book series nb 7, 866pp.

Dixon J.B., Weed S.B., Kittrick J.A., Milford M.H., White J.L. (eds.) (1977). Minerals in Soil Environments, Soil Science Society of America, Madison, WI, 603pp.

Doran J.W. and Parkin T.B. (1994). Defining and assessing soil quality. In: Defining soil quality for a sustainable environment. Soil Science Society of America Special Publication no 35, 3-22.

Dow, A.I. and Roberts, S. (1982). Proposal: critical nutrient ranges for crop diagnosis. Agronomy Journal, 74, 401-403.

Dowiya N.B., Rweyemamu C.L. and Maerere A.P. (2009). Banana (Musa spp. Colla) cropping systems, production constraints and cultivar preferences in eastern Democratic Republic of Congo. Journal of Animal and Plant Sciences, 4, 341-356.

Drabek O., Boruvka L., Mladkova L. and Kocarek M. (2003). Possible method of aluminum speciation in forest soils. Journal of Inorganic Biology, 97, 8-15.

Duan L., Hao J., Xie S., Zhou Z. and Ye X. (2002). Determining weathering rates of soils in China. Geoderma, 110, 205-225.

Dumas J. and Martin–Prével P. (1958). Contrôle de nutrition des bananeraies en Guinée (Premiers résultats). Fruits, 13, 375-386.

Eden-Green S. (2004). How can the advance of banana Xanthomonas wilt be halted? InfoMusa, 13, 38-41.

Eidt R.C. (1973). A rapid chemical field test for archaeological site surveying. American Antiquity, 38, 206-210.

Eidt R.C. (1977). Detection and examination of Anthrosols by phosphate analysis - Field and laboratory tests for phosphate, well known in soil science, find new applications in archeology. Science, 197, 1327-1333.

Eledu C.A., Karamura E.B. and Tushemereirwe W.K. (2004). Agroecological distribution of banana systems in the Great Lakes region. African Crop Science Journal, 12, 33-42.

Eswaran H. and Sys C. (1970). An evaluation of the free iron in tropical basaltic soils. Pédologie, 20, 62-85.

Escano C.R., Jones C.A. and Uehara G. (1981a). Nutrient diagnosis in corn grown on Hystric Dystrandepts: I. Optimum tissue nutrient concentrations. Soil Science Society of America Journal, 45, 1135-1139.

Escano C.R., Jones C.A. and Uehara G. (1981b). Nutrient diagnosis in corn grown on Hystric Dystrandepts: II. Comparison of two systems of tissue diagnosis. Soil Science Society of America Journal, 45, 1140-1144.

Esilaba A.O., Nyende P., Nalukenge G., Byalebeka J.B., Delve R.J. and Ssali H. (2005). Resource flows and nutrient balances for crop and animal production in smallholder farming systems in eastern Uganda. Agriculture, Ecosystems and Environment, 109, 192-201.

Eteigni L. and Campbell A.G. (1991). Physical and chemical characteristics of wood ash. Bioresource Technology, 37, 173-178.

Fageria V.D. (2001). Nutrient interactions in crop plants. Journal of plant nutrition, 24, 1269-1290.

Fairhead J. and Leach M. (2009). Amazonian Dark Earths in Africa? In: Amazonian Dark Earths - Wim Sombroek's Vision (W.I. Woods, W.G. Teixeira, J. Lehmann, C. Steiner, A. WinklerPrins and L. Rebellato (eds.)), Springer, 265-278.

Fanning D.S. and Keramidas V.Z. (1977). Micas. In: Minerals in Soil Environments (J.B. Dixon and D.G. Weed (eds.)), Soil Science Society of America, USA, 195-258.

FAO (2001). Lecture notes on the major soils of the world. (P. Driessen and J. Deckers (eds.)), World soil resources reports vol.94, Rome, 334pp.

FAO (2002). Crop water management: banana. Land and Water development division, http://www.fao.org/WAICENT/faoINFO/AGRICULT/agl/aglw/cropwater/banana.stm, accessed 9th July 2011.

FAO (2005a). Irrigation in Africa in figures. FAO water reports nb 29, Aquastat Survey, FAO land and water development division editions, Rome, 635pp.

FAO (2005b). New LocClim 1.10 - Local Climate estimator. Accessed on 15th of July 2011, tool downloaded from : http://www.fao.org/nr/climpag/data_5_en.asp.

FAO (2006). Guidelines for soil description, 4th edition, Rome, 109pp.

FAOstat (online). Statistics: FAOstat. http://faostat.fao.org/ (accessed July 1st, 2010).

Fermont A.M., van Asten P.J.A., Tittonell P., van Wijk M.T. and Giller K.E. (2009). Closing the cassava yield gap: an analysis from smallholder farmers in East Africa. Field Crops Research, 112, 24-36.

Fedo C.M., Nesbitt H.W. and Young G.M. (1995). Unraveling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleoweathering conditions and provenance. Geology, 23, 921-924.

Fernandez-Alonso M., Lavreau J. and Klerkx J. (1986). Geochemistry and geochronology of the Kibaran granites in Burundi, Central Africa: implications for the Kibaran orogeny. Chemical Geology, 57, 217-234.

Fitzpatrick R.W. and Schwertmann U. (1982). Al-substituted goethite : an indicator of pedogenic and other weathering environments in South Africa. Geoderma, 27, 335-347.

Foster H.L. (1981). The basic factors which determine inherent soil fertility in Uganda. Journal of Soil Science, 32, 149-160.

Foth H.D. (1990). Fundamentals of soil science. 8th edition, Wiley and Sons, 360pp.

Frost R.L., Horvath E., Mako E. and Kristof J. (2004). Modification of low and high defect kaolinite surfaces - implications for kaolinite mineral processing. Journal of Colloid and Interface Science, 270, 337-346.

Gahoonia T.S. and Nielsen N.E. (1992). The effects of root-induced pH changes on the depletion of inorganic and organic phosphorus in the rhizosphere. Plant and Soil, 143, 185-191.

Gaidashova S. (2009). Effect of plant parasitic nematodes and arbuscular mycorrizal fungi on banana (Musa spp.) in the East African Highland cropping systems. PhD-Dissertation, Université catholique de Louvain, Louvain-la-Neuve, Belgium, 270pp.

Gaidashova S.V., Germeau G., van Asten P.J.A. and Delvaux B. (2007). Identification of constraints to banana production in three ecoregions of Rwanda). In: Sustainable productivity for improved food security and livelihoods (R.W. Njeru, D.M. Kogabo, T. Ndabamenye, D. Kayiranga, P. Ragama, P.Y.K. Sallah, D. Nkerabahizi, A. Ndayiragije, L. Ndiramiye, G. Night, S.O.S. Akinyemi, N. Kanuya, M.C. Bagabe, J. Mugabe (eds.)). Proceedings of ISAR National Conference, 26-27 March 2007, ISAR, Kigali, Rwanda, pp. 97-105.

Gaidashova S.V., van Asten P.J.A., De Waele D. and Delvaux B. (2009). Relationship between soil properties, crop management, plant growth and vigor, nematode occurrence and root damage in East African Highland banana-cropping systems: a case-study in Rwanda. Nematology, 11, 883-894.

Gaidashova S.V., van Asten P.J.A., Delvaux B. and De Waele D. (2010). The influence of the topographic position within highlands of Western Rwanda on the interactions between banana (Musa spp. AAA-EA), parasitic nematodes and soil factors. Scientia Horticulturae, 125, 316-322.

Galloway J.N. (1988). Effects of acid deposition on tropical aquatic ecosystems). In: acidification in tropical countries (H. Rodhe and R. Herrerra (eds)), SCOPE, John Wiley and Sons, 141-166.

Garcia-Hernandez J., Valdez-Cepeda R.D., Murillo-Amador B., Nieto-Garibay A., Beltran-Morales L.F., Magallanes-Quintanar R. and Troyo-Dieguez E. (2004). Compositional nutrient diagnosis and main nutrient interactions in yellow pepper grown on desert calcareous soils. Journal of Plant Nutrition and Soil Science, 167, 509-515.

Garcia-Hernandez J., Valdez-Cepeda R.D., Avila-Serrano N.Y., Murillo-Amador B., Nieto-Garibay A., Magallanes-Quintanar R., Larrrinaga-Mayoral J. and Troyo-Dieguez E. (2005). Preliminary compositional nutrient diagnosis norms on cowpea (Vigna unguiculata (L.) Walp.) grown on desert calcareous soil. Plant and Soil, 271, 297-307.

Garcia-Hernandez J.L., Valdez-Cepeda R.D., Murillo-Amador B., Beltran-Morales F.A., Ruiz-Espinoza F.H., Orona-Castillo I., Flores-Hernandez A. and Troyo-Dieguez E. (2006). Preliminary compositional nutrient diagnosis norms in Aloe Vera L. grown on calcareous soil in arid environment. Environmental and Experimental Botany, 58, 244-252.

Garcia-Hernandez J.L., Orona-Castillo I., Gonzalez-Cervantes G., Valdez-Cepeda R.D., Murillo-Amador B., Troyo-Dieguez E., Fortis-Hernandez M. and Segura-Castruita M.A. (2009). Interacciones nutrimentales y normas de diagnostico de nutrimento compuesto en Nogal Pecanero (Carya illinoensis). Revista Chapingo Serie Horticultura, 15, 141-147.

Garcia-Rodeja E., Novoa J. C., Pontevedra X., Martinez-Cortizas A., and Buurman P. (2004). Aluminum fractionation of European volcanic soils by selective dissolution techniques: Volcanic Soil Resources: Occurrence, Development and Properties. Catena 56[1-3], 155-183.

Garrels R.M. (1984). Montmorillonite/illite stability diagrams. Clays and Clay Minerals, 32, 161-166.

Geological Survey of Uganda. (1961). Mbarara [geological map], 1:250.000, Entebbe, Geological Survey Department.

Gérards J. and Ledent D. (1970). Grands traits de la géologie du Rwanda, différents types de roches granitiques et premières données sur les âges des roches. Annales de la Société Géologique de Belgique, 93, 477-189.

Gérards J., Lepersonne J.J. and Petricec V. (1967). Kibungo S3/30NE [geological map], 1/100.000, carte géologique du Rwanda, Tervuren (Belgium), edited by the Département de Géologie et Minéralogie du Musée royal d'Afrique Centrale et le Ministère de l'Industrie et de l'Artisanat du Rwanda.

Gerke J. and Hermann R. (1992). Adsorption of orthophosphate to humic-Fe-complexes and to amorphous Fe-oxide. Zeitschrift fur Planzenährung und Bodenkunde, 155, 233-236.

German L.A. (2004). A geographical method for Anthrosol characterization in Amazonia: contributions to method and human ecological theory). In: Amazonian Dark Earths - explorations in space and time (B. Glaser and W.I. Woods (eds.)). Springer, Berlin, 29-52.

Giller K.E., Cadish G., Ehaliotis C., Adams E., Sakala W. and Mafongoya P. (1997). Building soil nitrogen capital in Africa. In: Resplenishing soil fertility in Africa (R.J. Buresh, P.A. Sanchez, F. Calhoun (eds.)), Soil Science Society of America Special Publication nb. 51, Madison, 151-192.

Giller K.E., Rowe E.C., de Ridder N. and van Keulen H. (2006). Resource use dynamics and interactions in the tropics: scaling up in space and time. Agricultural Systems, 88, 8-27.

Glaser B. and Woods W.I. (eds) (2004). Amazonian Dark Earths: explorations in space and time, Springer-Verlag, Berlin, 216pp.

Glaser B., Haumaier L., Guggenberger G. and Zech W. (2001). The "Terra Preta" phenomenon : a model for sustainable agriculture in the humid tropics. Naturwissenschaften, 88, 37-41.

Glaser B., Guggenberger G. and Zech W. (2004). Identifying the Pre-Columbian anthropogenic input on present soil properties of Amazonian Dark Earths (Terra Preta). In: Amazonian Dark Earths: explorations in space and time (Glaser B. and Woods W.I.(eds.)), Springer, 145-158.

Godefroy J., Perrier X., Rutunga V. and Sebahutu A. (1991). Relations entre les caractéristiques physico-chimiques des sols de la région de Kibungo au Rwanda et le potentiel de production des bananiers. Application à la gestion de la fertilité des sols. Fruits, 46, 625-631.

Godefroy J., Lassoudiere A., Rutunga V. and Sebahutu A. (1992). Caractéristiques des parties aériennes et du système racinaire des bananiers triploïdes AAA sous-groupe bananes ą bière de l'Afrique de l'Est cultivées au Rwanda. Fruits, 47, 277-280.

Gold C.S. and Messiaen S. (2000). The banana weevil Cosmopolites sordidus. Musa Pest Fact Sheet no 4: http://bananas.bioversity international.org/files/files/pdf/publications/pest4.pdf (accessed August 8th, 2010).

Gold C.S., Speijer P.R., Rukazambuga N.D. and Karamura E.B. (1994). Assessment of banana weevils in East African Highland banana systems and strategies for control). In: banana nematodes and weevil borers in Asia and the Pacific (R.V. Valmayor, R.G. Davide, J.M. Stanton, N.L. Trerrow, V.N. (Roa eds.), INIBAP, Los Banos, Philippines, 170-190.

Gold C.S., Karamura E.B., Kiggundu A., Bagamba F. and Abera A.M.K. (1999). Monograph on geographic shifts in highland cooking banana (Musa, group AAA-EA) production in Uganda. African Crop Science Journal, 7, 223-298.

Gold C.S., Okech S.H., Nankinga C.M., Tushemereirwe W.K. and Ragama P.E. (2005). The biology and pest status of the banana weevil in the East Africa Great Lakes Region: A review of research at IITA and NARO). In: Farmer-participatory testing of integrated pest management options for sustainable banana production in Eastern Africa (G. Blomme, C. Gold and E. Karamura (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). The International Network for the Improvement of Banana and Plantain, Montpellier, France, 129-140.

Guo F., Yost R.S., Hue N.V., Evensen C.I. and Silva J.A. (2000). Changes in phosphorus fractions in soils under intensive plant growth). Soil Science Society of America Journal, 64, 1681-1689.

Habarurema E. and Steiner K.G. (1997). Soil suitability classification by farmers in southern Rwanda. Geoderma, 75, 75-87.

Haileslassie A., Pries J.A., Veldkamp E. and Lesschen J.P. (2007). Nutrient flows and balances at the field and farm scale: exploring effects of land-use strategies and access to resources. Agricultural Systems, 94, 459-470.

Harper G., Hart D., Moult S. and Hull R. (2002). Detection of Banana Streak Virus in field samples of bananas from Uganda. Annals of Applied Biology, 141, 247-257.

Harper G., Hart D., Moult S. and Hull R. (2004). Banana streak virus is very diverse in Uganda. Virus Research, 100, 51-56.

Harris W.G. (2002). Phosphate minerals. In: Soil Mineralogy with Environmental Applications (J.B. Dixon and D.G. Schulze (eds.)), 637-665.

Haynes R.J. and Mokolobate M.S. (2001). Amelioration of Al toxicity and P deficiency in acid soils by addition of organic residues: a critical review of the phenomenon and the mechanisms involved. Nutrient Cycling in Agroecosystems, 59, 47-63.

Hauser S. and van Asten P. (2010). Methodological considerations on banana (Musa spp.) yield determinations. Proceedings UC on banana and plantain in Africa (T. Dubois et al. (eds.)), Acta Horticulturae ISHS, 879, 433-444.

Havlin J.L., Beaton J.D., Tisdale S.I. and Nelson W.L. (2004). Soil fertility and fertilizers, Pearson Education, Patparganj Delhi, India, 6th edition, 515pp.

Haynes R.J. and Mokolobate M.S. (2001). Amelioration of Al toxicity and P deficiency in acid soils by addition of organic residues: a critical review of the phenomenon and the mechanisms involved). Nutrient Cycling in Agroecosystems, 59, 47-63.

Hedley M.J., Stewart J.W.B. and Chaunan B.S. (1982). Changes in inorganic and organic soil phosphorous fractions induced by cultivation practices and by laboratory incubations). Soil Science Society of America Journal, 46, 970-976.

Herbillon A.J. (1986). Chemical estimation of weatherable minerals present in the diagnostic horizons of low activity clay soils. In: Proceedings of the 8th international soil classification workshop: classification, characterization and utilization of oxisoils, Part I (F.H. Beinroth, M.N. Camargo, H. Eswaran (eds.)). EMBRAPA, Rio de Janeiro., 39-48.

Hodson M.E. (2002). Comments on "calculations of weathering rate and soil solution chemistry for forest soils in the Norwegian-Russian border area with the PROFILE model" byG. Koptsik, S. Tevedal, D. Aamlid and K. Venn. Applied Geochemistry, 17, 117-121.

Hodson M.E. and Langan S.J. (1999). Considerations of uncertainty in setting critical loads of acidity of soils: the role of weathering rate determination. Environmental Pollution, 106, 73-81.

Hodson M.E., Langan S.J. and Wilson M.J. (1996). A sensitivity analysis of the PROFILE model in relation to the calculation of soil weathering rates. Applied Geochemistry, 11, 835-844.

Hodson M.E., Langan S.J. and Wilson M.J. (1997). A critical evaluation of the use of the PROFILE model in calculating mineral weathering rates. Water, Air and Soil Pollution, 98, 79-104.

Hodson M.E., Langan S.J. and Meriau S. (1998). Determination of mineral surface area in relation to the calculation of weathering rates. Geoderma, 83.

Hoffmann R.B., Tavares De Oliveira F.H., Pereira De Souza A., Raj Gheyi H. and Fidelis De Souza R.Jr. (2010). Accumulation of dry matter and macronutrient in cultivars of irrigated banana tree. Revista Brasileira de Fruticultura, 32, 268-275.

Holliday V.T. and Gartner W.G. (2007). Methods of soil P analysis in archaeology. Journal ofArchaeological Science, 34, 301-333.

Holmqvist J., Ogaard A.F., Oborn I., Edwards A.C., Mattsson L. and Sverdrup H. (2003). Application of the PROFILE model to estimate potassium release from mineral weathering in Northern European agricultural soils. European Journal of Agronomy, 20, 149-163.

Hsu P.H. (1989). Aluminum hydroxides and oxyhydroxides. In: Minerals in soil environments (J.B. Dixon and S.B. Weed (eds.)), Soil Science Society of America, Madison, Wisconsin, USA. 331-378.

Huang P.M., Wang M.K., Kämpf N. and Schulze D.G. (2002). Aluminium hydroxides. In: Soil mineralogy with environmental applications (J.B. Dixon and D.G. Schulze (eds.)), Soil Science Society of America Book Series, Madison, Wisconsin, USA, 261-289.

Hussain I., Olson K.R., Wander M.M. and Karlen D.L. (1999). Adaptation of soil quality indices and application to three tillage systems in southern Illinois. Soil and Tillage Research, 50, 237-249.

Hutson S.R., Magnoni A., Beach T., Terry R.E., Dahlin B.H. and Schabel M.J. (2009). Phosphate fractionation and spatial patterning in ancient ruins: a case study from Yucatan. Catena, 78, 260-269.

Imbrie J. and Poldervaart A. (1959). Mineral compositions calculated from chemical analyses of sedimentary rocks. Journal of Sedimentary Petrology, 29, 588-595.

Institut des Sciences agronomiques du Rwanda (ISAR) (online). Official website of the Rwanda Agricultural Research Institute, accessed 12th October 2010, < http://www.isar.rw >

IUSS Working Group WRB (2006). World reference base for soil resources 2006 - a framework for international classification, correlation and communication. World soil resources reports nb 103, 2n edition, FAO, Rome, 145pp.

Iyamuremye F., Dick R.P. and Baham J. (1996). Organic amendments and phosphorus dynamics: II. Distribution of soil phosphorus fractions. Soil Science, 161, 436-443.

Jeanroy E., Guillet B. and Ortiz R. (1984). Applications pédogénétiques de l'étude des formes du fer par les réactifs d'extraction: cas des sols brunifiés et podzolisés sur roches cristallines. Sciences du Sol, 3, 199-211.

Johnson M.S., Lehmann J., Guimaraes Couto E., Novaes Filho J.P. and Riha S.J. (2006). DOC and DIC in flowpaths of Amazonian headwater catchments with hydrologically contrasting soils. Biogeo-chemistry, 81, 45-57.

Jönsson C., Warfinge P. and Sverdrup H. (1995). Uncertainty in predicting weathering rate and environmental stress factors with the PROFILE model. Water, Air and Soil Pollution, 81, 1-23.

Joussein E., Petit S., Churchman G.J., Theng B.K.G., Righi D. and Delvaux B. (2005). Halloysite clay minerals - a review. Clay Minerals, 40, 383-426.

Joussein E., Petit S. and Delvaux B. (2007). Behavior of halloysite clay under formamide treatment. Applied Clay Science, 35, 17-24.

Juo A.S.R. and Kamprath E.J. (1979). Copper chloride as extractant for estimating the potentially reactive aluminum pool in acid soils. Soil Science Society of America Journal, 43, 35-38.

Juo A.S.R. and Franzluebbers K. (2003). Soil fertility. In : Properties and management for sustainable agriculture. Oxford University Press Inc, 88-107.

Kagoda, F., Rubaihayo, P.R. and Tenywa, M.M. (2005). The potential of cultural and chemical control practices for enhancing productivity of banana ratoons. African Crop Science Journal, 13, 71-81.

Kaiser K. and Guggenberger G. (2000). The role of DOM sorption to mineral surfaces in preservation of organic matter in soils. Organic Geochemistry, 31, 711-725.

Kaiser K. and Guggenberger G. (2003). Mineral surfaces and soil organic matter. European Journal of Soil Science, 54, 219-236.

Kaiser K. and Guggenberger G. (2007). Sorptive stabilization of organic matter by microporous goethite: sorption into small pores vs. surface complexation. European Journal of Soil Science, 58, 45-59.

Kalembasa S.J. and Jenkinson D.S. (1973). A comparative study of titrimetric and gravimetric methods for the determination of organic carbon in soil. Journal of the science of food and agriculture, 24, 1085-1090.

Kalyebara M.R., Ragama P.E., Kagezi G.H., Kubiriba J., Bagamba F., Nankinga K.C. and Tushemereirwe W. (2006). Economic importance of the banana bacterial wilt in Uganda. African Crop Science Journal, 14, 93-103.

Kangasniemi J. (1998). People and Bananas on Steep Slopes: Agricultural Intensification and Food Security under Demographic Pressure and Environmental Degradation in Rwanda. PhD-Dissertation, Michigan State University, USA, 244pp.

Karamura E., Frison E., Karamura D.A. and Sharrock S. (1999). Banana production systems in eastern and southern Africa. In: Bananas and Food security (C. Picq, E. Fouré and E. Frison E. (eds.)). Proceedings of the International Symposium, Douala, Cameroon, 10-14 November 1998, INIBAP, Montpellier, pp.401-412).

Karlen D.L. and Stott D.E. (1994). A framework for evaluating physical and chemical indicators of soil quality. In: Defining soil quality for a sustainable environment. Soil Science Society of America Special Publication no 35, 38-52.

Karlen D.L., Mausbach M.J., Doran J.W., Cline R.G., Harris R.F. and Schuman G.E. (1997). Soil quality: a concept, definition and framework for evaluation (a guest editorial). Soil Science Society of America Journal, 61, 4-10.

Karlen D.L., Ditzler C.A. and Andrews S.S. (2003). Soil quality: why and how? Geoderma, 114, 145-156.

Karlen D.L., Andrews S.S., Wienhold B.J. and Zobeck T.M. (2008). Soil quality assessment: past, present and future. Electronic Journal of Integrative Biosciences, 6, 3-14.

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

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, 7-12.

Kelling K.A., Combs S.M. and Peters J.B. (2000). Using plant analysis as a diagnostic tool. New Horizons in Soil Science No 6-2000. Department of Soil Science, University of Wisconsin-Madison.

Kelly V., Mpyisi E., Shingiro E. and Nyarwaya J.-B. (2001). Agricultural Intensification in Rwanda: An Elusive Goal. Fertilizer Use and Conservation Investments. International Development Collaborative Policy Briefs RW-FSRP-PB-01, Department of Agricultural Economics, Michigan State University.

Kelsey C.H. (1965). Calculation of the C.I.P.W. norm. Mineralogical Magazine, 34, 276-282.

Kerven G.L., Menzies N.W. and Geyer M.D. (2000). Soil carbon determination by high temperature combustion: a comparison with dichromate oxidation procedures and the influence of charcoal and carbonate carbon on the measured value. Communications in Soil Science and Plant Analysis, 31, 1935-1939.

Khiari L., Parent L.-E. and Tremblay N. (2001a). Selecting the high-yield subpopulation for diagnosing nutrient imbalance in crops. Agronomy Journal, 93, 802-808.

Khiari L., Parent L.-E. and Tremblay N. (2001b). The phosphorus compositional nutrient diagnosis range for potato. Agronomy Journal, 93, 815-819.

Khiari L., Parent L.-E. and Tremblay N. (2001c). Critical compositional nutrient indexes for sweet corn at early growth stage. Agronomy Journal, 93, 809-814.

Kiely P.V. and Jackson M.L. (1964). Selective dissolution of micas from potassium feldspars by sodium pyrosulfate fusion of soils and sediments. The American Mineralogist, 49, 1648-1659.

Kim S. and Park H.D. (2003). The relationship between physical and chemical weathering indices of granite around Seoul, Korea. Bulletin of engineering geology and the environment, 62, 207-212.

Kirkby R.A. and Ngendahayo D. (eds.) (1985). Production et recherche sur la banane en Afrique de l'Est et en Afrique Centrale). Manuscript Report of the regional workshop held in Bujumbura (ref MR114f), Burundi, 14-17 December. International Development Research Center, Ottawa, Canada). 154pp.

Klamt E. and Sombroek W.G. (1986). Contribution of organic matter to exchange properties of Oxisols. 8th International Soil Classification Workshop on classification, Characterization and Utilization of Oxisols, Brazil, 12-23 May, n° 86/5.

Klein C. and Hurlbut C.S.Jr. (1999). Manual of mineralogy. John Wiley and Sons Inc., 21st edition, 681pp.

Koehler B., Zehe E., Corre M.D. and Veldkamp, E. (2010). An inverse analysis reveals limitations of the soil-pCO2 profile method to calculate CO2 production and efflux for well-structured soils. Biogeosciences, 7, 2311-2325.

Koljonen T. and Carlson L. (1975). Behaviour of the major elements and minerals in sediments of four humic lakes in south-western Finland. Fennia, 137, 5-47.

Koptsik G., Teveldal S., Aamlid D. and Venn K. (1999). Calculations of weathering rate and soil solution chemistry for forest soils in the Norwegian-Russian border area with the PROFILE model. Applied Geochemistry, 14, 173-185.

Koseva I.S., Watmough S.A. and Aherne J. (2010). Estimating base cation weathering rates in Canadian forest soils using a simple texture-based model. Biogeochemistry, 101, 183-196.

Kulabako N.R., Nalubega M. and Thunvik R. (2007). Study of the impact of land use and hydrogeological settings on the shallow groundwater quality in a peri-urban area of Kampala, Uganda. Science of the Total Environment, 381, 180-199.

Kumar N., Krishnamoorthy V., Nalina L. and Soorianathasundharam K. (2002). A new factor for estimating total leaf area in banana. InfoMusa, 11, 42-43.

Kyomugisha E. (2008). Land tenure and agricultural productivity in Uganda. Uganda strategy support program (USSP), brief no 5, 1-3.

Laclau J.-P., Ranger J., Bouillet J.-P., de Dieu Nzila J. and Deleporte Ph. (2003). Nutrient cycling in a clonal stand of Eucalyptus and an adjacent savanna ecosystem in Congo. 1-Chemical composition of rainfall, throughfall and stemflow solutions. Forest Ecology and Management, 176, 105-119.

Laclau J.-P., Ranger J., Deleporte Ph., Nouvellon Y., Saint-André L., Marlet S. and Bouillet J.-P. (2005). Nutrient cycling in a clonal stand of Eucalyptus and an adjacent savanna ecosystem in Congo. 3 - Input/output budgets and consequences for the sustainability of the plantations. Forest Ecology and Management, 210, 375-391.

Lacoeuilhe J. and Martin-Prével P. (1971a). Carences en K, Ca, Mg chez le bananier: analyse foliaire. Fruits, 26, 243-253.

Lacoeuilhe J. and Martin-Prével P. (1971b). Carences en N, P, S chez le bananier: analyse foliaire. Fruits, 26, 161-167.

Lahav, E. (1995). Banana nutrition. In: Bananas and Plantains (Gowen S. (edt.)), Chapman and Hall, 258-316.

Lahav E. and Turner D.W. (1983). Banana nutrition. IPI-Bulletin no 7, International Potash Institute.

Lajtha K. and Schlesinger W.H. (1988). The biogeochemistry of phosphorus cycling and phosphorus availability along a desert soil chronosequence. Ecology, 69, 24-39.

Lalah J.O. and Wandiga S.O. (2006). Extinction coefficients and dissolved organic carbon content in freshwater in Kenya. Bulletin of Environmental Contamination and Toxicology, 77, 533-542.

Landon J.R. (1991). Soil suitability guidelines for major tropical crops. In: Booker tropical soil manual- a handbook for soil survey and agricultural land evaluation in the tropics and subtropics (J.R. Landon (edt.)), Longman Scientific and Technical, 269-293.

Lark R.M. (1997). An empirical method for describing the joint effects of environmental and other variables on crop yields. Annals of Applied Biology, 131, 141-159.

Lassoudière A. (1989). Enquête-diagnostic sur la culture bananière: préfecture de Kibungo - rapport final. Université Nationale du Rwanda, ISAR, IRFA-CIRAD, 452pp).

Lassoudière A. (2007). Besoins en eau du bananier. In: Le bananier et sa culture, Quae editions, Paris, 83-93.

Leece D.R. (1976). Diagnosis of nutritional disorders of fruit trees by leaf and soil analyses and biochemical indices. The Journal of the Australian Institute of Agricultural Science, 42, 3-19.

Lehmann J., Kern D.C., Glaser B. and Woods W.I. (eds.) (2003). Amazonian Dark Earths - origin, properties, management. Kluwer Academic Publishers, Dordrecht, The Netherlands, 503pp.

Lehmann J., Vabose Campos C., Vasconselos de Macedo J.L. and German L. (2004). Sequential P fractionation of relict anthropogenic Dark Earths of Amazonia. In: Amazonian Dark Earths - explorations in space and time (B. Glaser and W.I. Woods (eds)). Springer, Berlin, 113-124.

Lekasi J.K., Woomer P.L., Tenywa J.S. and Bekunda M.A. (2001). Effect of mulching cabbage with banana residues on cabbage yield, soil nutrient and moisture supply, soil biota and weed biomass. African Crop Science Journal, 9, 499-506.

Levy E.T. and Schlesinger W.H. (1999). A comparison of fractionation methods for forms of phosphorus in soils. Biogeochemistry, 47, 25-38.

Liebig M.A., Varvel G. and Doran J. (2001). A simple performance-based index for assessing multiple agroecosystem functions. Agronomy Journal, 93, 313-318.

Lillios K.T. (1992). Phosphate fractionation of soils at Agroal, Portugal. American Antiquity, 57, 495-506.

Lippi R.D. (1988). Paleotopography and phosphate analysis of a buried jungle site in Ecuador. Journal of Field Archaeology, 15, 85-97.

Mafongoya P.L., Batiano A., Kihara J. and Waswa B.S. (2006). Appropriate technologies to resplenish soil fertility in southern Africa. Nutrient Cycling in Agroecosystems, 76, 137-151.

Magallanes-Quintanar R., Valdez-Cepeda R.D., Olivares-Saenz E., Perez-Veyna O., Garcia-Hernandez J. and Lopez-Martinez L. (2006). Compositional Nutrient Diagnosis in maize grown in a calcareous soil. Journal of Plant Nutrition, 29, 2019-2033.

Mairura F.S., Mugendi D.N., Mwanje J.I., Ramisch J.J., Mbugua P.K. and Chianu J.N. (2007). Integrating scientific and farmers' evaluation of soil quality indicators in Central Kenya. Geoderma, 139, 134-143.

Marchal J. and Martin-Prével P. (1971). Les oligo-éléments Cu, Fe, Mn, Zn dans le bananier - niveaux foliaires et bilans. Fruits, 26, 483-499.

Marchal J. and Mallessard R. (1979). Comparaison des immobilisations minérales de quatre cultivars à fruits pour cuisson et de deux "Cavendish". Fruits, 34, 373-392.

Mareschal L., Nzila J.D.D., Turpault M.P., Thongo M'Bou A., Mazoumbou J.C., Bouillet J.P., Ranger J. and Laclau J.P. (2011). Mineralogical and physico-chemical properties of Ferralic Arenosols derived from unconsolidated Plio-Pleistocenic deposits in the coastal plains of Congo. Geoderma, 162, 159-170.

Martin-Prével P. (1962). Les éléments minéraux dans le bananier et dans son régime. Fruits, 17, 123-128.

Martin-Prével P. (1980). La nutrition minérale du bananier dans le monde - Première partie. Fruits, 35, 503-518.

Martin-Prével P. (1984). Bananier. In: L'analyse végétale dans le contrôle de l'alimentation des plantes tempérées et tropicales (P. Martin-Prével, J. Gagnard, P. Gautier P. (eds.)), Technique et Documentation Lavoisier, Paris, France. 715-751. 715-751.

Martin-Prével P. and Montagut G. (1966). Essais sol-plante sur bananiers - Les interactions dans la nutrition minérale du bananier. Fruits, 21, 19-36.

Martin-Prével, P., Gagnard J. and Gautier P. (1984). Bases de l'interprétation des résultats analytiques. In: L'analyse végétale dans le contrôle de l'alimentation des plantes tempérées et tropicales (P. Martin-Prével, Gagnard J., Gautier P. (eds.)), Technique et Documentation Lavoisier, Paris, France. 179-191.

Martins O. and Probst J.-L. (1991). Biogeochemistry of major African rivers: carbon and mineral transport. In: SCOPE 42 - Biogeochemistry of major world rivers (E.T. Degens, S. Kempe, L.E. Richey (eds.)), Wiley and Sons, 127-156.

Matejovic I. (1997). Determination of carbon and nitrogen samples of various soils by the dry combustion). Communications in Soil Science and Plant Analysis, 28, 1499-1511.

Mathieu C.C. (1985). Dixième forum international sur la "Soil Taxonomy" et les transferts d'agrotechnologie, 1-12 avril 1985, Rwanda - Burundi: profils pédologiques au Burundi. Département de sciences du Sol, Faculté des Sciences agronomiques, Université du Burundi. 93pp.

Mayer L.M.and Xing B. (2001). Organic-matter surface area relationship in acid soils. Soil Science Society of America Journal, 65, 250-258.

Mayer L.M., Schick L.L., Hardy K.R., Wagal R. and McCarthy J. (2004). Organic matter in small mesopores in sediments and soils. Geochimica et Cosmochimica Acta, 68, 3863-3872.

McIntyre B.D., Speijer P.R., Riha S.J. and Kizito F. (2000). Effect of mulching on biomass, and soil water in banana inoculated with nematodes. Agronomy Journal, 92, 1081-1085.

McIntyre B.D., Bouldin D.R., Urey G.H. and Kizito F. (2001). Modeling cropping strategies to improve human nutrition in Uganda. Agricultural Systems, 67, 105-120.

McIntyre B.D., Gold C.S., Ssali H. and Riha S.J. (2003). Effect of mulch location on banana weevil, soil and plant nutrients, soil water and biomass in banana fields. Biology and Fertility of Soils, 39, 74-79.

Mehra O.P. and Jackson M.L. (1960). Iron oxide removal from soils and clays by dithionite-citrate system buffered with sodium carbonate. Clays and Clay Minerals, 7, 317-327.

Memon N., Zia-Ul-Hassan N. and Oad F.C. (2001). Banana nutrition management through plant analysis. Pakistan Journal of Applied Sciences, 1, 563-574.

Memon N., Memon K.S. and Zia-Ul-Hassan N. (2005). Plant analysis as a diagnostic tool for evaluating nutritional requirements of bananas. International Journal of Agriculture and Biology, 7, 824-831.

Menon R.G., Hammond L.L. and Sissingh H.A. (1988). Determination of plant-available phosphorus by the iron hydroxide-impregnated filter paper (Pi) soil test. Soil Science Society of America Journal, 52, 110-115.

Mendelovici E., Yariv S. and Villalba R. (1979). Aluminum-bearing goethite in Venezuelan laterites. Clays and Clay Minerals, 27, 368-372.

Mengel K. and Kirkby E.A. (2001). In: Principles of Plant Nutrition. Kluwer Academic Publishers, Dordrecht, The Netherlands, 5th edition, 851pp.

Menon R.G., Hammond L.L. and Sissingh H.A. (1988). Determination of plant-available phosphorus by the iron hydroxide-impregnated filter paper (Pi) soil test. Soil Science Society of America Journal, 52, 110-115.

Messing, J.H.L. (1974). Long term changes in potassium, magnesium and calcium content of banana plants and soils in the Windward Islands. Tropical Agriculture (Trinidad), 51, 154-160.

Metzner C. and Grimmeisen W. (1990). MONA: a user-friendly computer-program for calculating the modal mineralogy of rocks from chemical analyses. European Journal of Mineralogy, 2, 735-738.

Middleton, G.V. (2000). Data Analysis in the Earth Sciences using Matlab. Prentice Hall, New Jersey, USA. 260pp.

Milne A.E., Wheeler H.C. and Lark R.M. (2006). On testing biological data for the presence of a boundary. Annals of Applied Biology, 149, 213-222.

Mizota C. and Chapelle J. (1988). Characterization of some Andepts and Andic soils in Rwanda, Central Africa. Geoderma, 41, 193-209.

Monnier G., Stengel P. and Fies J.-C. (1973). Une méthode de mesure de la densité apparente de petits agglomérats terreux. Application a l'analyse des systèmes de porosité du sol. Annales Agronomiques, 24, 533-545.

Montagut G. and Martin-Prével P. (1965). Essais sol-plante sur bananiers - Besoins en engrais des bananeraies antillaises. Fruits, 20, 265-273.

Mowo J.G., Jannsen B.H., Oenema O., German L.A., Mrema J.P. and Shemdoe R.S. (2006). Soil fertility evaluation and management by smallholder farmer communities in Northern Tanzania. Agriculture, Ecosystems and Environment, 116, 47-59.

Mtabanengwe F. and Mapfumo P. (2005). Organic matter management as an underlying cause for soil fertility gradients on smallholder farms in Zimbabwe. Nutrient Cycling in Agroecosystems, 73, 227-243.

Muggler C.C., Buurman P., and van Doesburg J. D. J. (2007). Weathering trends and parent material characteristics of polygenetic oxisols from Minas Gerais, Brazil: I. Mineralogy. Geoderma, 138[1-2], 39-48.

Mugwe J., Mucheru-Muna M., Mugendi D., Kung'u J., Batiano A. and Mairura F. (2009). Adoption potential of selected organic resources for improving soil fertility in central Highlands of Kenya. Agroforestry Systems, 76, 467-485.

Mukasa H.H., Ocan D., Rubaihayo P.R. and Blomme G. (2005). The influence of nematodes, weevils and management level on high mat, plant growth traits and yields in southwestern Uganda. In: Farmer-participatory testing of integrated pest management options for sustainable banana production in Eastern Africa (G. Blomme, C.Gold and E. 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. The International Network for the Improvement of Banana and Plantain, Montpellier, France, 65-85.

Mukashema A. (2007). Mapping and modeling landscape-based soil fertility change in relation to human induction. MSc-Dissertation, International Institute for Geo-Information science and Earth Observation (ITC), Enschede, The Netherlands, 75pp.

Murekezi C. (2005). Effects of banana streak virus and crop management on the growth and yield of East African Highland Bananas (Musa spp., AAA-EA), PhD Dissertation, Reading, UK.

Musy A. and Soutter M. (1991). Physique du sol. Presses polytechniques et universitaires romandes, Lausanne, 1st edition, 335pp.

Mwijage N.A., de Ridder N., Baijukya F., Pacini C. and Giller E.K. (2009). Exploring the variability among smallholder farms in the banana-based farming systems in Bukoba district, Northwest Tanzania. frican Journal of Agricultural Research, 4, 1410-1426.

Myers R.G., Sharpley A.N., Thien S.J. and Pierzynski, G.M. (2005). Ion-sink phosphorus extraction methods applied on 24 soils from the continental USA. Soil Science Society of America Journal, 69, 511-521.

Namazzi J. (2008). Use of inorganic fertilizers in Uganda. Uganda strategy support program (USSP), brief no 4, 1-3.

Nandwa S.M. and Bekunda M.A. (1998). Research on nutrient flows and balances in East and Southern Africa: state-of-art. Agriculture, Ecosystems and Environment, 71, 5-18.

National Institute of Statistics of Rwanda (2010). National agricultural survey 2008, report of national data analysis. 265pp.

Ndindabahizi I. and Gwabije R. (1981). Evaluation des systèmes d'exploitation agricole pour une régionalisation des techniques de conservation et d'amélioration de fertilité des sols au Rwanda. Ministry of Agriculture and Animal Resources, Kigali, Rwanda. Project PNUD / FAO Rwa 89/003, 147pp.

Needham T.D., Burger J.A. and Oderwald R.G. (1990). Relationship between Diagnosis and Recommendation Integrated System (DRIS) optima and foliar nutrient critical levels. Soil Science of America Journal, 54, 883-886.

Neel H. (1983). An overview of the physiography and the soils of Rwanda. In: Proceedings of the Fourth International Soil Classification Workshop - part 2: field trip and background soil data. (F.H. Beinroth, H. Neel, H. Eswaran (eds.)), ABOS-AGCD, Brussels, 1-22.

Negassa W. and Leinweber P. (2009). How does the Hedley sequential phosphorus fractionation reflect impacts of land use and management on soil phosphorus: a review. Journal of Plant Nutrition and Soil Science, 172, 305-325.

Nelson D.W. and Sommers L.E. (1982). Total carbon, organic carbon and organic matter. In: Methods of soil analysis: 2. Chemical and microbiological properties (A.L. Page, R.H. Miller, D.R. Keeney (eds.)). Agronomy Monograph n° 9., 539-579.

Nesbitt H.W. and Young G.M. (1982). Early Proterozoic climates and plate motions inferred from major element chemistry of lutites. Nature, 299, 715-717.

Newton A.I. (2009). Biophysical and crop management gradients driving within farm variability of Highland banana yield in Butare Valley (SW Uganda). MSc-thesis, Makerere University, Uganda. 158pp.

Ngailo J.A., Wickama J.M., Nyaki A.S. and Kaswamila A.L. (2001). Nutrient flow analysis for selected farming systems in Northern Tanzania: the case of Mbulu, Moshi Area and Lushoto Districts. In: Soil and nutrient management in Sub-Saharan Africa in support of the soil fertility initiative. Proceedings of the expert consultation, 6-9 December 1999, Lusaka, Zambia (R.N. Roy and H. Nabhan (eds.)). FAO Publications, Rome. 49-64.

Nibasumba A. (2008). Garniture cationique des sols et des racines dans des systèmes de culture bananière du Burundi et du Rwanda. MSc-thesis, UCL, Belgium.

Nicholls G.D. (1962). A scheme for recalculating the chemical analyses of argillaceous rocks for comparative purposes). The American Mineralogist, 47, 34-46.

Niggli P. (1936). Uber Molekularnormen zur Gesteinsberechnung. Schweizerische Mineralogische und Petrografische Mitteilungen, 16, 335-339.

Nizeyimana E. (1997). A toposequence of soils derived from volcanic materials in Rwanda: morphological, chemical and physical properties. Soil Science, 162, 350-359.

Nkonya E., Pender J., Kaizzi C., Edward K. and Mugarura S. (2005). Policy options for increasing crop productivity and reducing soil nutrient depletion and poverty in Uganda. International Food Policy Research Institute, EPT Discussion Paper 134, 107pp.

Northcliff. S. (2002). Standardization of soil quality attributes. Agriculture, Ecosystems and Environment, 88, 161-168.

Novozamsky V.J.G., van Eck R., van der Lee J.J., Houba V.J.G. and Temminghoff E. (1986). Determination of total sulphur and extractable sulphate in plant materials by inductively coupled plasma atomic emission spectrometry. Communications in Soil Science and Plant Analysis, 17, 1147-1157.

Nyaki A. (2001a). Soil fertility initiative: the Tanzania experience). In: Soil and nutrient management in Sub-Saharan Africa in support of the soil fertility initiative). Proceedings of the expert consultation, 6-9 December 1999, Lusaka, Zambia. (R.N. Roy and H. Nabhan (eds.)). FAO Publications, Rome, 203-210.

Nyaki A. (2001b). Proven and cost-effective soil fertility restoration and maintenance technologies in Tanzania. In: Soil and nutrient management in Sub-Saharan Africa in support of the soil fertility initiative). Proceedings of the expert consultation, 6-9 December 1999, Lusaka, Zambia. (R.N. Roy and H. Nabhan (eds.)). FAO Publications, Rome. 237-254.

Nyobe J.B. (1991). Application of normative calculations in quantitative comparative mineralogical studies of bauxite. Ore Geology Reviews, 6, 45-50.

Nyombi K., Esser K.B. and Zake J.Y.K. (2006). Efforts by small-scale farmers to maintain soil fertility and their impacts on soil properties, Luwero District, Uganda. Journal of Sustainable Agriculture, 27, 5-23.

Nyombi K., van Asten P.J.A., Leffelaar P.A., Corbeels M., Kaizzi C.K. and Giller, K.E. (2009). Allometric growth relationships of East Africa Highland Bananas (Musa AAA-EAHB) cv. Kisansa and Mbwazirume. Annals of Applied Biology, 155, 403-418.

Nyombi K., van Asten P.J.A., Corbeels M., Taulya G. and Giller K.E. (2010). Mineral fertilizer response and nutrient use efficiencies of East African highland banana (Musa spp., AAA-EAHB, cv Kisansa). Field Crops Research, 117, 38-50.

Nzila J.D., Turpault M.P., Laclau J.P. and Ranger J. (2004). Mineralogy and weathering of soils under Eucalypt plantations in Pointe-Noire Region, the Congo). In: Site management and productivity in tropical plantation forest: proceedings of workshops in Congo (July 2001) and China (February 2003), E.K.S. Nambiar, J. Ranger, Tiarks A., T. Tome eds., CIFOR. 205-207.

Oates K.M. and Kamprath E.J. (1983). Soil acidity and liming: I. Effect of the extracting solution cation and pH on the removal of aluminum from acid soils. Soil Science Society of America Journal, 47, 686-689.

Odeke M., Rubaihayo P.R. and Osiru D.S.O. (1999). Effect of spacing, stage and method of desuckering on bunch size and yield of banana cultivar Kibuzi (AAA-EA). African Crop Science Journal, 7, 349-353.

Oduol P.A. and Aluma J.R.W. (1990). The banana (Musa spp.) - coffee Robusta: traditional agroforestry of Uganda. Agroforestry Systems, 11, 213-226.

O'Halloran I.P. (1993). Total and organic phosphorus. In: Soil sampling and methods of analysis (M.R. Carter (edt.)). 213-229.

Ohno T. (1992). Neutralization of soil acidity and release of phosphorus and potassium by wood ash. Journal of Environmental Quality, 21, 433-438.

Okalebo J.R., Gatna K.W. and Woomer P.L. (2002). Laboratory methods for soil and plant analysis: a working manual. Tropical Soil Biology and Fertility Program, Nairobi, Kenya, 2nd edition.

Okalebo J.R., Othieno C.O., Woomer P.L., Karanaja N.K., Semoka J.R.M., Bekunda M.A., Mugendi D.N., Muasya R.M., Batiano A. and Mukhwana E.J. (2006). Available technologies to resplenish soil fertility in East Africa. Nutrient Cycling in Agroecosystems, 76, 153-170.

Okech S.H.O., Gold C.S., Speijer P., Ssali H. and Karamura E. (2000). Relationships between soil fertility, banana weevil and nematodes in the East African highland cooking banana in Ntungamo, Southwestern Uganda. Acta Horticulturae, 540, 505-514.

Okech S.H., van Asten P.J.A., Gold C.S. and Ssali H. (2004). Effects of potassium deficiency, drought and weevils on banana yield and economic performance in Mbarara, Uganda. Uganda Journal of agricultural Sciences, 9, 511-519.

Okech S.H.P., Gaidashova S., Gold C.S., Nyagahungu I. and Mushumhu J.T. (2005). The influence of socio-economic and marketing factors on banana production in Rwanda: results from a Participatory Rural Appraisal. International Journal of Sustainable Development and World Ecology, 12, 149-160.

Okumu M.O., van Asten P.J.A., Kahangi E., Okech S.H., Jefwa J. and Vanlauwe B. (2011). Production gradients in smallholder banana (sc. Giant Cavendish) farms in Central Kenya. Scientia Horticulturae, 127(4), 475-481.

Okusami T.A., Rust R.H. and Alao A.O. (1997). Red soils of different origins from southwest Nigeria: characteristics, classification and managements considerations. Canadian Journal of Soil Science, 77, 295-307.

Olsen S.R. and Sommers L.E. (1982). Phosphorus. In: Methods of soil analysis: 2. Chemical and microbiological properties (A.L. Page, R.H. Miller, D.R. Keeney (eds.)). Agronomy Monograph nb 9., 403-430.

Oorts K., Vanlauwe B., Cofie O.O., Sanginga N. and Merckx R. (2000). Charge characteristics of soil organic matter fractions in a Ferric Lixisol under some multipurpose trees. Agroforestry Systems, 48, 169-188.

Oorts K., Vanlauwe B. and Merckx R. (2003). Cation exchange capacities of soil organic matter fractions in a Feeric Lixisol with different organic matter inputs. Agriculture, Ecosystems and Environment, 100, 161-171.

Opdecamp L. and Sottiaux G. (1983). The Oxisols in Burundi. In: Fouth International Soil Classification Workshop, Rwanda 2-12 June 1981: Part I. Papers (F.H. Beinroth, H. Neel and H. Eswaran (eds.)). 34-47.

Ottner F., Gier S., Kuderna M. and Schwaighofer B. (2000). Results of an inter-laboratory comparison of methods for quantitative clay analysis. Applied Clay science, 17, 223-243.

Ouimet R. and Duchesne L. (2005). Base cation mineral weathering and total release rates from soils in three calibrated forest watersheds on the Canadian Boreal Shield). Canadian Journal of soil Science, 85, 245-206.

Ouma G. (2009). Intercropping and its application to banana production in East Africa: a review. Journal of Plant Breeding and Crop Science, 1, 13-15.

Ovalles F.A. and Collins M.E. (1988). Variability of Northwest Florida soils by principal component analysis. Soil Science Society of America Journal, 52, 1430-1435.

Page A.L., Miller R.H. and Keeney D.R. (eds.) (1982). Methods of soil analysis, part 2: chemical and microbiological properties. Agronomy series nb 9, American Society of Agronomy, Madison, WI, USA, 1159pp.

Palm C.A., Myers R.J.K. and Nandwa S.N. (1997). Combined use of organic and inorganic nutrient sources for soil fertility maintenance and resplenishment. In: Replenishing soil fertility in Africa (R.J. Buresh, P.A Sanche and F. Calhoon (eds.)). Soil Science Society of America Special Publication No. 51, Madison, Wisconsin, USA, 193-217.

Palm C.A., Gilller K.E., Mafongoya P.L. and Swift M.J. (2001). Management of organic matter in the tropics: translating theory into practice. Nutrient Cycling in Agroecosystems, 61, 63-75.

Paniagua A., Mazzarino M.J., Kass D., Szott L. and Fernandez C. (1995). Soil phosphorus fractions under five tropical agro-ecosystems on a volcanic soil. Australian Journal of Soil Research, 33, 311-320.

Pansu M. and Gautheyrou J. (2006). Handbook of soil analysis: mineralogical, organic and inorganic methods. Springer, 993pp.

Parent L.E. and Dafir M. (1992). A theoretical concept of compositional nutrient diagnosis. Journal of the American Society for Horticultural Science, 117, 239-242.

Parent L.E., Cambouris A.N. and Muhawenimana A. (1994). Multivariate diagnosis of nutrient imbalance in potato crops. Soil Science Society of America Journal, 58, 1432-1438.

Parfitt R.L. (1978). Anion adsorption by soils and soil materials. Advances in agronomy, 30, 1-50.

Parfitt R.L. (1989). Phosphate reactions with natural allophane, ferrihydrite and goethite. Journal of Soil Science, 40, 359-369.

Parnell J.J., Terry R.E. and Nelson Z. (2002). Soil chemical analysis applied as an interpretive tool for ancient human activities in Piedras Negras, Guatemala. Journal of Archaeological Science, 29, 379-404.

Pender J., Ssewanyana S., Edward K. and Nkonya E. (2004). Linkages between poverty and land management in rural Uganda: evidence from the Uganda National Household Survey, 1999/2000. International Food Policy Research Institute, EPTD Discussion Paper 122, 112pp.

Pierzynski G.M., McDowell R. and Sims J.T. (2005). Chemistry, cycling, and potential movement of inorganic phosphorus in soils. In: Phosphorus : Agriculture and the environment. J.T. Sims and A.N. Sharpley (eds.), ASA, CSSA and SSSA, Madison, WI, 53-86.

Pillay M., Ogundiwin E., Nwakanma D.C., Ude G. and Tenkouano A. (2001). Analysis of genetic diversity and relationships in East African banana germplasm. Theoretical and Applied Genetics, 102, 965-970.

Place F., Pender J. and Ehui S. (2006). Key issues for the sustainable development of smallholder agriculture in the East African Highlands. In: Strategies for sustainable land management in the East African Highlands (J. Pender, F. Place, S. Ehui (eds)). International Food Policy Research Institute, Washington D.C., 30pp.

Porebska G. and Mulder J. (1996). The chemistry of aluminum in strongly acidified sandy soil in Poland. European Journal of Soil Science, 47, 81-87.

Posch M. and Kurz D. (2007). A2M - a program to compute all possible mineral modes from geochemical analyses. Computers and Geosciences, 33, 563-572.

Potter R.L., Jordan C.F., Guedes R.M., Batmanian G.J. and Han X.G. (1991). Assessment of a phosphorus fractionation method for soils: problems for further investigation. Agriculture, Ecosystems and Environment, 34, 453-463.

Price J.R. and Velbel M.A. (2003). Chemical weathering indices applied to weathering profiles developed on heterogeneous felsic metamorphic parent rocks. Chemical Geology, 202, 397-416.

Price N.S. (1995). Banana morphology - Part I: roots and rhizomes. In: Bananas and Plantains (S. Gowen (edt.)), Chapman and Hall, London, 179-189.

Prudencio C.Y. (1993). Ring management of soils and crops in the West-African semi-arid tropics: the case of the Mossi farming system in Burkina Faso. Agriculture, Ecosystems and Environment, 47, 237-264.

Quansah C., Drechsel P., Yirenkyi B.B. and Asante-Mensah S. (2001). Farmers' perceptions and management of soil organic matter - a case study from West Africa. Nutrient Cycling in Agroeco-systems, 61, 205-213.

Quesnel P.-O., Côté B., Fyles J.W. and Munson A.D. (2006). Optimum nutrient concentrations and CND scores of mature white spruce determined using a boundary-line approach and spatial variation of tree growth and nutrition. Journal of Plant Nutrition, 29, 1999-2018.

Raemakers R.H.E. 2001. Eastern Africa. In : Crop production in tropical Africa (R.H. Raemakers (edt.)), Directorate General for International Co-operation, Belgium, 1390-1435.

Raghupati H.B., Reddy B.M.C. and Srinivas K. (2002). Multivariate diagnosis of nutrient imbalance in banana. Communications in soil science and plant analysis, 33, 2131-2143.

Raghupati H.B., Reddy Y.T.N., Kurian Reju M. and Bhargava B.S. (2004). Diagnosis of nutrient imbalance in mango by DRIS and PCA approaches. Journal of Plant Nutrition, 27, 1131-1148.

Rezai S.A., Gilkes R.J. and Andrews S.S. (2006). A minimum set for assessing soil quality in rangelands. Geoderma, 136, 229-234.

Rietveld H.M. (1967). Line profiles of neutron powder-diffraction peaks for structure refinement. Acta Crystallographica, 22, 151-152.

Rietveld H.M. (1969). A profile refinement method for nuclear and magnetic structures. Journal of Applied Crystallography, 2, 65-71.

Robinson J.C. (1995). Systems of cultivation and management. In: Bananas and plantains (S. Gowen (edt.)), Chapman and Hall, London, 15-65.

Robson A.D. and Pitman M.G. (1983). Interactions between nutrients in higher plants. In: Inorganic plant nutrition (A. Läuchli A. and R.L. Bielseki (eds.)), Springer-Verlag, 147-180.

Roose E. and Ndayizigiye F. (1994). L'agroforesterie, la fertilisation minérale et la GCES au Rwanda. In: Introduction à la gestion conservatoire de l'eau, de la biomasse et de la fertilité des sols (GCES) (E. Roose (edt.)). Bulletin pédologique de la FAO no 70, http://www.fao.org/docrep/t1765f/t1765f00.htm, accessed February 2, 2010.

Roose E. and Ndayizigiye F. (1997). Agroforestry, water and soil fertility management to fight erosion in tropical mountains of Rwanda. Soil Technology, 11, 109-119.

Roose E. and Barthès B. (2001). Organic matter management for soil conservation and productivity restoration in Africa: a contribution from Francophone research. Nutrient Cycling in Agroecosystems, 61, 159-170.

Rosen O.M. and Abbyasov A.A. (2003). The quantitative mineral composition of sedimentary rocks: calculation from chemical analyses and assessment of adequacy (MINLITH computer program). Lithology and Mineral Resources, 38, 252-264.

Rosen O.M., Abbyasov A.A. and Tipper J.C. (2004). MINLITH - an experience-based algorithm for estimating the likely mineralogical compositions of sedimentary rocks from bulk chemical analyses. Computers and Geosciences, 30, 647-661.

Rouiller J., Butrin G. and Souchier B. (1972). La dispersion des sols dans l'analyse granulométrique, méthode utilisant les résines échangeuses d'ions. Bulletin ENSAIA Nancy, 14, 193-205.

Rowe E.C., van Wijk M.T., de Ridder N. and Giller K.E. (2006). Nutrient allocation strategies across a simplified heterogeneous African smallholder farm. Agriculture, Ecosystems and Environment, 116, 60-71.

Ruan C.-D. and Ward C.R. (2002). Quantitative X-ray powder diffraction analysis of clay minerals in Australian coals using Rietveld methods. Applied Clay Science, 21, 227-240.

Rubaek G.H. and Sibbesen E. (1993). Resin extraction of labile soil organic phosphorus. Journal of Soil Science, 44, 467-478.

Rubaihayo P.R., Makumbi D. and Mukasa S.B.B. (1994). Preliminary evaluation of banana and plantain cultivars for resistance to Black Sigatoka in Central Uganda. In: African crop science conference proceedings (E. Adipala, M.A. Bekunda, J.S. Tenywa, M.W. Ogenga-Latigo, J.O. Mugah (eds.)), African Crop Science Conference, held at Kampala 14-18 June 1993, 237-239.

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 the banana weevil, Cosmopolites sordidus Germar. Crop Protection, 17, 581-589.

Rutunga V., Steiner K.G., Karanja N.K., Gachehe C.K.K. and Nzabonihankuye G. (1998). Continuous fertilization on non-humiferous acid Oxisols in Rwanda "Plateau Central": soil chemical changes and plant production. Biotechnology, Agronomy, Society and Environment, 2, 135-142.

Sahwney B.L. and Stilwell D.E. (1994). Dissolution and elemental analysis of minerals, soils and environmental samples. In: Quantitative methods in soil mineralogy (J.E. Amonette and L.W. Zelazny (eds.)), Soil Science Society of America Miscellaneous Publication. 49-82.

Salminen R., Gregorauskiene V. and Tarvainen T. (2008). The normative mineralogy of 10 soil profiles in Fennoscandia and north-western Russia. Applied Geochemistry, 23, 3651-3665.

Sanchez P.A. (1976). Phosphorus, silicon and sulfur. In: Properties and management of soils in the tropics, John Wiley and sons - Interscience, 254-294.

Sanchez P.A., Shepherd K.D., Soule M.J., Place F.M., Buresh R.J., Izac A.-M.N., Mokwunye A.U., Kwesiga F.R., Ndiritu C.G. and Woomer P.L. (1997). Soil fertility replenishment in Africa: an investment in natural resource capital. In: Replenishing soil fertility in Africa (R.J. Buresh, P.A. Sanchez, F. Calhoon (eds.)), Soil Science Society of America Special Publication nb 51, Madison, Wisconsin, USA, 1-46.

Santana J.L., Suarez C.L. and Fereres E. (1993). Evapotranspiration and crop coefficients in banana. Acta Horticulturae, 335, 341-348.

Sarah J.L., Pinochet J. and Stanton J. (1996). The burrowing nematode of bananas, Radopholus Similis Cobb 1913. Musa Pest Fact Sheet no 1, http://bananas.bioversityinternational.org/files/files/pdf/ publications/pest1.pdf (accessed, September 22 2010).

Sattell R.R. and Morris R.A. (1992). Phosphorus fractions and availability in Sri Lankan Alfisols. Soil Science Society of America Journal, 56, 1510-1515.

Savoy H.J.Jr. and Robinson D.L. (1990). Norm range size effects in calculating Diagnosis and Recommendation Integrated System Indices. Agronomy Journal, 82, 592-596.

Scheren P.A.G.M., Zanting H.A. and Lemmens A.M.C. (2000). Estimation of water pollution sources in Lake Victoria, East Africa: application and elaboration of rapid assessment methodology. Journal of Environmental Management, 58, 235-248.

Schlichting E. (1983). Explanatory notes on graphs of depth functions of features in some soils of Rwanda). In: Fourth International Soil Classification Workshop, Rwanda 2-12 June 1981: Part II. Field trip and background soil data (F.H. Beinroth, H. Neel, H. Eswaran (eds.)), 34-46.

Schlüter T. (2008). Geological atlas of Africa: with notes on stratigraphy, tectonics, economic geology, geohazards, geosites and geoscientific education of each country. Springer-Verlag, Berlin, 2nd edition, 272pp.

Schnug E., Heym J. and Achwan F. (1996). Establishing critical values for soil and plant analysis by means of the Boundary Line Development System (BOLIDES). Communications in Soil Science and Plant Analysis, 27, 2739-2748.

Schoenau J.J. and Bettany J.R. (1987). Organic matter leaching as a component of carbon, nitrogen, phosphorus and sulfur cycles in a forest, grassland and gleyed soil. Soil Science Society of America Journal, 51, 646-651.

Schrumpf M., Axmacher J.C., Zech W., Lehmann J. and Lyaruu H.V.C. (2007). Long-term effects of rainforest disturbance on the nutrient composition of throughfall, organic layer percolate and soil solution at Mt Kilimanjaro. Science of the Total Environment, 376, 241-254.

Schweigman C. (2008). Food security problems in sub-Saharan Africa: Operations Research as a tool of analysis. International Transactions in Operational Research, 15, 173-193.

Schwendenmann L. and Veldkamp E. (2006). Long-term CO2 production from deeply weathered soils of a tropical rain forest: evidence for a potential positive feedback to climate warming. Global Change Biology, 12, 1878-1893.

Schwertmann U. (1966). Inhibitory effect of soil organic matter on the crystallization of amorphous ferric hydroxyde. Nature, 5062, 645-646.

Schwertmann U. (1993). Relations between iron oxides, soil color, and soil formation. In: Soil color. Soil Science Society of America, special Publication nb 31. 51-70.

Schwertmann U. and Kämpf N. (1985). Properties of goethite and hematite in kaolinitic soils of Southern and Central Brazil. Soil Science, 139, 344-350.

Schwertmann U. and Taylor R.M. (1989). Iron oxides. In: Minerals in soil environments (J.B. Dixon and S.B. Weed (eds.)), Soil Science Society of America, Madison, Wisconsin, USA, 379-438.

Schwertmann U., Fitzpatrick R.W., Taylor R.M. and Lewis D.G. (1979). The influence of aluminum on iron oxides : II. Preparation and properties of Al-substituted hematites. Clays and Clay Minerals, 27, 105-112.

Schwertmann U., Schulze D.G. and Murad E. (1982). Identification of ferrihydrite in soils by dissolution kinetics, differential X-ray diffraction and Mössbauer spectroscopy. Soil Science Society of America Journal, 46, 869-875.

Sebuwufu G., Rubaihayo P.R. and Blomme G. (2004). Variability in the root system of East African Banana genotypes. African Crop Science Journal, 12, 85-93.

Selles F., Kochhann R.A., Denardin J.E., Zentner R.P. and Faganello A. (1997). Distribution of phosphorus fractions in a Brazilian oxisol under different tillage systems. Soil and Tillage Research, 44, 23-34.

Sharma S. (1996). Applied multivariate techniques, John Wiley and Sons, USA, 493pp.

Sharpley A.N. (1995). Soil phosphorus dynamics: agronomic and environmental impacts. Ecological Engineering, 5, 261-279.

Sharpley A.N. and Smith J. (1985). Fractionation of inorganic and organic phosphorus in virgin and cultivated soils. Soil Science Society of America Journal, 49, 127-130.

Sharpley A.N., Tiessen H. and Cole C.V. (1987). Soil phosphorus forms extracted by soil tests as a function of pedogenesis. Soil Science Society of America Journal, 51, 362-365.

Shatar T.M. and McBratney A.B. (1999). Empirical modeling of relationships between sorghum yield and soil properties. Precision Agriculture, 1, 249-276.

Shatar T.M. and McBratney A.B. (2004). Boundary-line analysis in field-scale yield response to soil properties. Journal of agricultural science, 142, 553-560.

Six J., Conant R.T., Paul E.A. and Paustian K. (2002). Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant and Soil, 241, 155-176.

Skjemstad J.O. and Taylor, J.A. (1999). Does the Walkley-Black method determine soil charcoal? Communications in Soil Science and Plant Analysis, 30, 2299-2310.

Smaling E.M.A. and Fresco L.O. (1993). A decision-support model for monitoring nutrient balances under agricultural land use (NUTMON). Geoderma, 60, 235-256.

Smaling E.M.A., Fresco L.O. and de Jager A. (1996). Classifying, monitoring and improving soil nutrient stocks and flows in African agriculture. Ambio, 25, 492-496.

Smaling E.M.A., Stoorvogel J.J. and de Jager A. (2002). Decision making on integrated nutrient management through the eyes of the scientist, the land-user and the policy maker. In: Integrated plant nutrient management in Sub-Saharan Africa (B. Vanlauwe, J. Diels, N. Sanginga and R. Merck (eds.)), CAB International, 265-283.

Smeck N.E. (1973). Phosphorus: an indicator of pedogenetic weathering processes. Soil Science, 115, 199-206.

Smeck N.E. (1985). Phosphorus dynamics in soils and landscapes. Geoderma, 36, 185-199.

Smith Z.R. and Wells C.S. (2006). Central Limit Theorem and sample size. Paper presented at the annual meeting of the Northeastern Educational research Association, Kerhonson, New York, October 18-20, 22pp.

Smithson P.C., McIntyre B.D., Gold C.S., Ssali H. and Kashaija I.N. (2001). Nitrogen and potassium fertilizer vs. nematode and weevil effects on yield and foliar status of banana in Uganda. Nutrient Cycling in Agroecosystems, 59, 239-250.

Smithson P.C., McIntyre B.D.G.C.S., Ssali H., Night G. and Okech S. (2004). Potassium and magnesium fertilizers on banana in Uganda: yields, weevil damage, foliar nutrient status and DRIS analysis. Nutrient Cycling in Agroecosystems, 69, 43-49.

Soares M.R. and Alleoni L.R.F. (2008). Contribution of soil organic carbon to the ion exchange capacity of tropical soils. Journal of Sustainable Agriculture, 32, 439-462.

Solomon D. and Lehmann J. (2000). Loss of phosphorus from soil in semi-arid northern Tanzania as a result of cropping: evidence from sequential extraction and ^{31}P-NMR spectroscopy. European Journal of Soil Science, 51, 699-708.

Solomon D., Lehmann J., Tekalign M., Fritzsche F. and Zech W. (2002). Phosphorus forms and dynamics as influenced by land use changes in the sub-humid Ethiopian highlands. Geoderma, 105, 21-48.

Soltanpour P. N., Malakowti M. J., and Ronaghi A. (1995). Comparison of Diagnosis and Recom-mendation Integrated System and nutrient sufficiency range for corn. Soil Science Society of America Journal 59, 133-139.

Sombroek W.G. (1966). Amazon soils: a reconnaissance of the soils of the Brazilian Amazon region. Centre for Agricultural Publications and Documentation, Wageningen, 275pp.

Speijer P.R. and Gold C.S. (1996). Musa root health assessment: a technique for the evaluation of Musa germplasm for nematode resistance. In: new frontiers in resistance breeding for nematode, Fusarium and Sigatoka (E.A. Frison, J.-P. Horry, D. Waele D. (eds.)), Proceedings of the workshop held 2-5 October 1995 in Kuala Lumpur, Malaysia, 62-76.

Speijer P.R. and De Waele D. (1997). Screening of Musa germplasm for resistance and tolerance to nematodes. INIBAP technical guidelines, no 1, 48pp.

Speijer P.R. and Fogain R. (1999). Musa and Ensete nematode pest status in selected African countries). In: Mobilizing IPM for sustainable banana production in Africa (E.A. Frison, C.S.Gold, E.B. Karamura and R.A. Sikora (eds.)). Proceedings of a workshop on banana IPM, Nelspruit, 23-28 November 1998, INIBAP, Montpellier, 99-108.

Speijer P.R. and Kajumba C. (2000). Yield loss from plant parasitic nematodes in East African Highland Banana (Musa spp. AAA). ISHS Acta Horticulturae, 540, 453-459.

Speijer P.R., Kashaija I.N. and Karamura E.B. (1994). Banana weevil and nematode distribution pattern in highland banana systems in Uganda: preliminary results from a diagnostic survey. African Crop Science Conference Proceedings, 1, 285-289 (abstract).

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

Speijer P.R., Kajumba C. and Ssango F. (1999). East African highland banana production as influenced by nematodes and crop management in Uganda. International journal of pest management, 45, 41-49.

Spitzy A. and Leenheer J. (1991). Dissolved Organic Carbon in rivers. In: SCOPE 42 - Biogeochemistry of major world rivers (E.T. Degens, S. Kempe, J.E. Richey (eds.)), Wiley and Sons, 213-232.

Srodon J., Drits V.A., McCarty D.K., Hsieh J.C.C. and Eberl D.D. (2001). Quantitative X-Ray Diffraction analysis of clay-bearing rocks from random preparations. Clays and Clay Minerals, 49, 514-528.

Ssali H. (2001). Soil fertility initiative: the Uganda experience. In: Soil and nutrient management in Sub-Saharan Africa in support of the soil fertility initiative. Proceedings of the expert consultation, 6-9 December 1999, Lusaka, Zambia (R.N. Roy and H. Nabhan (eds.)). FAO Publications, Rome. 193-199.

Ssali H., McIntyre, B.D., Gold, C.S., Kashaija, I.N. and Kizito, F. (2003). Effects of mulch and mineral fertilizer on crop, weevil and soil quality parameters in highland banana. Nutrient Cycling in Agroecosystems, 65, 141-150.

Sseguya H., Semana A.R. and Bekunda M.A. (1999). Soil fertility management in the banana-based agriculture of central Uganda: farmers' constraints and opinions. African Crop Science Journal, 7, 559-567.

Steiner K.G. (1998). Using farmers' knowledge of soils in making research results more relevant to field practice: experiences from Rwanda. Agriculture, Ecosystems and Environment, 69, 191-200.

Stevenson F.J. (1982). Humus chemistry - Genesis, composition, reaction. John Wiley and sons, 443pp.

Sumner M.E. (1979). Interpretation of foliar analyses for diagnostic purposes. Agronomy Journal, 7, 343-348.

Sumner M.E. (1981). Diagnosing the sulfur requirements of corn and wheat using foliar analysis. Soil Science Society of America Journal, 45, 87-90.

Sverdrup H. (1996). Geochemistry, the key to understanding environmental chemistry. The Science of the Total Environment, 183, 67-87.

Sverdrup H. and Warfinge P. (1988). Weathering of primary silicate minerals in the natural soil environment in relation to a chemical weathering model. Water, Air and Soil Pollution , 38, 387-408.

Sverdrup H. and Warfinge P. (1993). Calculating field weathering rates using a mechanistic geochemical model PROFILE. Applied Geochemistry, 8, 273-283.

Sverdrup H. and Warfinge P. (1995). Critical loads of acidity for Swedish forest ecosystems. Ecology Bulletin, 44, 75-89.

Swennen R. and Vuylsteke D. (2001). Fruit crops: Banana. In: Crop production in tropical Africa (R.H. Raemakers (edt.)), Directorate General for International Co-operation, Belgium, 530-552.

Syers J.K., Williams J.D.H., Campbell A.S. and Walker T.W. (1967). The significance of apatite inclusions in soil phosphorus studies. Soil Science Society of America Proceedings, 31, 752-756.

Syers J.K., Smillie G.W. and Williams J.D.H. (1972). Calcium fluoride formation during extraction of calcareous soils with fluoride: I. Implications to inorganic P fractionation schemes. Soil Science Society of America Proceedings, 36.

Sys C., Van Ranst E., Debaveye J. and Beernaert F. (1993). Land evaluation Part III Crop requirements: banana. Agricultural Publications nb. 7, General Administration for Development Cooperation, Brussels, Belgium, 20-24.

Tahon A., Nsengiyumva P., Dehandschutter J., Buyagu S. and Mattheusens M. (1991). Nyabisindu S3/29NE [geological map], 1/100.000, carte géologique du Rwanda, Tervuren (Belgium), edited by the département de Géologie et Minéralogie du Musée royal d'Afrique Centrale et le Ministère de l'Industrie et de l'Artisanat du Rwanda.

Talwana H.A.L., Speijer P.R., Gold C.S., Swennen R.L. and De Waele D. (2003). A comparison of the effects of the nematodes Radopholus similis and Pratylenchus goodeyi on growth, root health and yield of an East African highland cooking banana (Musa AAA-group). International Journal of Pest Management, 49, 199-204.

Tardy Y. (1993). Pétrologie des latérites et des sols tropicaux. Masson edit., Paris, France, 459pp.

Tarrah J., Meiwes K.J. and Meesenburg H. (2000). Normative calculation of minerals in North German loess soils using the modified CIPW norm. Journal of Plant Nutrition and Soil Science, 163, 307-312.

Tarvainen T., Aatos S. and Raisanen M.-L. (1996). A method for determining the normative mineralogy of tills. Applied Geochemistry, 11, 117-120.

Taylor G., Eggleton R.A., Foster L.D., Tilley D.B., Le Gleuher M. and Morgan, C.M. (2008). Nature of the Weipa Bauxite deposit northern Australia. Australian Journal of Earth Sciences, 55, S45-S70.

Taylor J.C. (1991). Computer programs for standardless quantitative XRD analysis of minerals using the full powder diffraction profile. Powder Diffraction, 6, 2-9.

Taylor J.C. and Hinczak I. (2001). Rietveld made easy: a practical guide to understanding the method and successful phase quantifications. Sietronics, Belconnen, ACT, Australia. 201 pp.

Teixeira L.A.J., Zambrosi F.C.B. and Neto J.E.B. (2007). Nutritional diagnosis in banana in the state of Sao Paulo (Brazil): DRIS norms and critical levels. Revista Brasileira de Fruticultura Jaboticabal, 29, 613-620.

Tenywa M.M., Isabirye M.I., Lal R., Lufafa A. and Achan P. (1999). Cultural practices and production constraints in smallholder banana-based cropping systems of Uganda's Lake Victoria Basin. African Crop Science Journal, 7, 613-623.

Theng B.K.G., Churchman G.J., Whitton J.S. and Claridge G.G.C. (1984). Comparison of intercalation methods for differentiating halloysite from kaolinite. Clays and Clay Minerals, 3, 249-258.

Tiessen H. (2005). Phosphorus dynamics in tropical soils. In: Phosphorus - agriculture and environment (J.T. Sims and A.N. Sharpley (eds.)), American Society of Agronomy, Agronomy Series nb 46, 253-262.

Tiessen H. and Moir J.O. (1993). Characterization of available P by sequential extraction. In: Soil sampling and methods of analysis (M.R. Carter (edt.)), 75-86.

Tiessen H., Stewart J.X.B. and Moir O.J. (1983). Changes in organic and inorganic phosphorous composition of two grassland soils and their particle size fractions during 60-90 years of cultivation. Journal of Soil Science, 34, 815-823.

Tiessen, H., Stewart, J.X.B. and Cole, C.V. (1984). Pathways of phosphorus transformations in soils of differing pedogenesis. Soil Science Society of America Journal, 48, 853-858.

Tiessen H., Cuevas E. and Chacon P. (1994). The role of soil organic matter in sustaining soil fertility. Nature, 371, 783-785.

Tinzaara W., Barekye A., Gold C.S., Nankinga C., Kagezi G.H., Ragama P., Tushemereirwe W. and Blomme G. (2005). Effect of natural practices, biorationals and neem on the banana weevil, Cosmopolites sordidus (Germar), and nematodes in Masaka District, Uganda. In: Farmer-participatory testing of integrated pest management options for sustainable banana production in Eastern Africa (G. Blomme, C.Gold, E. Karamura (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. The International Network for the Improvement of Banana and Plantain, Montpellier, France, 53-64.

Tittonell P., Vanlauwe B., Leffelaar P.A., Rowe E.C. and Giller K.E. (2005a). Exploring diversity in soil fertility management of smallholder farms in western Kenya. I. Heterogeneity at region and farm scale. Agriculture, Ecosystems and Environment, 110, 149-165.

Tittonell P., Vanlauwe B., Leffelaar P.A., Rowe E.C. and Giller K.E. (2005b). Exploring diversity in soil fertility management of smallholder farms in western Kenya. II. Within-farm variability in resource allocation nutrient flows and soil fertility status. Agriculture, Ecosystems and Environment, 110, 166-184.

Tittonell P., Vanlauwe B., de Ridder N. and Giller K.E. (2007). Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: soil fertility gradients or management intensity gradients? Agricultural Systems, 94, 376-390.

Tittonell P., Muriuki A., Shepherd K.D., Mugendi D., Kaizzi K.C., Okeyo J., Verchot L., Coe R. and Vanlauwe B. (2010). The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa - a typology of smallholder farms. Agricultural Systems, 103, 83-97.

Tugume A.K., Lubega G.W. and Rubaihayo P.R. (2002). Genetic diversity of East African Highland bananas using AFLP. InfoMusa, 11, 28-32.

Tuhela L., Carlson L. and Tuovinen O.H. (1992). Ferrihydrite in water wells and bacterial enrichment cultures. Water Research, 26, 1159-1162.

Tunesi S., Poggi V. and Gessa C. (1999). Phosphate adsorption and precipitation in calcareous soils: the role of calcium ions in solution and carbonate minerals. Nutrient Cycling in Agroecosystems, 53, 219-227.

Turner D. and Barkus B. (1981). Nutrient concentrations in a range of banana varieties grown in the subtropics. Fruits, 36, 217-222.

Turner D.W. and Barkus B. (1983). Long-term nutrient absorption rates and competition between ions in banana in relation to supply of K, Mg and Mn. Nutrient Cycling in Agroecosystems, 4, 127-134.

Turner D.W., Korawis C. and Robson A.D. (1989). Soil analysis and its relationship with leaf analysis and banana yield with special reference to a study at Carnarvon, Western Australia. Fruits, 44, 193-203.

Tushemereirwe W.K., Gold C.S., Speijer P.R. and Holderness M. (1993a). Foliar diseases of banana in Uganda: results from a diagnostic survey. African Crop Science Journal, 1, 145-149.

Tushemereirwe W., Kangire A., Smith J., Ssekiwoko F., Nakyanzi M., Kataama D., Musiitwa C. and Karyaija R. (2003b). An outbreak of bacterial wilt on banana in Uganda. InfoMusa, 12, 6-8.

Tushemereirwe WK., Kangire A., Kubiriba J., Nakyanzi M. and Gold C.S. (2004). Diseases threatening banana biodiversity in Uganda. African Crop Science Journal, 12, 19-26.

Twyford I.T. and Walmsley D. (1973). The mineral composition of the Robusta banana plant: I. Methods and plant growth studied. Plant and Soil, 39, 227-243.

Twyford I.T. and Walmsley D. (1974). The mineral composition of the Robusta banana plant: II. The concentration of mineral constituents. Plant and Soil, 41, 459-470.

van Asten P.J.A., Wopereis M.C.S., Haefele S., Ould Isselmou M. and Kropff M.J. (2003). Explaining yield gaps on farmer-identified degraded and non-degraded soils in Sahelian irrigated rice scheme. Netherlands Journal of Agricultural Science, 50, 277-296.

van Asten P.J.A., Gold C.S., Okech S.H., Gaidashova S.V. and Tushemereirwe W.K. (2004). Problèmes liés à la qualité des sols dans les systèmes de production en Afrique de l'Est et leur lien avec les autres facteurs qui réduisent le rendement. InfoMusa, 13, 20-24.

van Asten P.J.A., Fermont A.M. and Taulya G. (2011). Drought is a major yield loss factor for rain-fed East African highland banana. Agricultural Water Management, 98, 541-552.

Van den Bosch H., Gitari J.N., Ogaro V.N., Maobe S. and Vlaming, J. (1998). Monitoring nutrient flows and economic performance in African framing systems (NUTMON): III. Monitoring nutrient flows and balances in three districts in Kenya. Agriculture, Ecosystems and Environment, 71, 93-80.

Vandeplas I., Vanlauwe B., Driessens L., Merckx R. and Deckers J. (2010). Reducing labour and input costs in soybean production by smallholder farmers in south-west Kenya. Field Crops Research, 117, 70-80.

Van Der Plas L. and Van Schuylenborgh J. (1970). Petrochemical calculations applied to soils -- with special reference to soil formation. Geoderma 4, 357-385.

Vander Zaag P. and Fox R.L. (1983). Fertility and management of Andepts of Rwanda. In: Fourth International Soil Classification Workshop, Rwanda 2-12 June 1981: Part I. Papers (F.H. Beinroth, H. Neel, H. Eswaran H. (eds.)). 471-484.

Vander Zaag P., Yost R.S., Trangmar B.B., Hayashi K. and Fox R.L. (1984). An assessment of chemical properties for soils of Rwanda with the use of geostatistical technique. Geoderma, 34, 293-314.

van der Zee S.E.A.T.M., Fokkink L.G.J. and van Riemsdijk W.H. (1987). A new technique for assessment of reversibly adsorbed phosphate. Soil Science Society of America Journal, 51, 599-604.

van der Zee S.E.A.T.M. and van Riemsdijk W.H. (1988). Model for long-term phosphate reaction kinetics in soil. Journal of Environmental Quality, 17, 35-41.

Vanlauwe B. and Giller K.E. (2006). Popular myths around soil fertility management in sub-Saharan Africa. Agriculture, Ecosystems and Environment, 116, 34-46.

Vanlauwe B., Tittonell 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.

van Straaten P. (2002). Rocks for Crops: Agrominerals of sub-Saharan Africa. ICRAF, Nairobi, Kenya, 338pp.

Van Wambeke A. (1982). Calculated soil moisture and temperature regimes of Africa. Soil Management Support Services, Technical Monograph nb3, 185pp.

Velde B. (1992). Introduction to clay minerals - chemistry, origins, uses and environmental significance. Chapman and Hall, London, 198pp.

Verdoodt A. and Van Ranst E. (2003). Land evaluation for agricultural production in the tropics: a large scale land suitability classification for Rwanda, published by the Laboratory of Soil Science of Ghent University, Ghent, Belgium, 183pp.

Viers J., Dupre B., Braun J.-J., Deberdt S., Angeletti B., Ngoupayou J.A. and Michard A. (2000). Major and trace element abundances, and strontium isotopes in the Nyong basin rivers (Cameroon): constraints on chemical weathering processes and elements transport mechanisms in humid tropical environments. Chemical Geology, 169, 211-241.

Vizcayno-Soto G. and Côté B. (2004). Boundary-line approach to determine standards of nutrition for mature trees from spatial variation of growth and foliar nutrient concentrations in natural environments. Communications in Soil Science and Plant Analysis, 35, 2965-2985.

Voicu G., Bardoux M. and Voicu V. (1997). Mineralogical norm calculations applied to tropical weathering profiles. Mineralogical Magazine, 61, 185-196.

Voïnovitch I.A. (1988). Analyse des sols, roches et ciments: méthodes choisies. Masson, Paris, 455pp.

Voundi Nkana J.C.V., Demeyer A. and Verloo M.G. (1998). Chemical effects of wood ash on plant growth in tropical acid soils. Bioresource Technology, 63, 251-260.

Waggoner P.E. and Norvell W.A. (1979). Fitting the law of the minimum to fertilizer applications and crop yields. Agronomy Journal, 71, 352-354.

Wairegi L.W.I. (2010). Management practices and opportunities in the East African Highland Banana (Musa AAA-EA) production in Uganda. PhD-dissertation, Wageningen University, The Netherlands, 155pp.

Wairegi L.W.I., van Asten P.J.A., Tenywa M.M. and Bekunda M.A. (2010). Abiotic constraints override biotic constraints in East African highland banana systems. Field Crops Research, 117, 146-153.

Walker T.W. and Syers J.K. (1976). The fate of phosphorus during pedogenesis. Geoderma, 15, 1-19.

Walkley A. and Black I.A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil science, 37, 29-38.

Walmsley, D. and Twyford, I.T. (1976). The mineral composition of the Robusta banana plant: V. Sulphur, iron, manganese, boron, zinc, copper, sodium and aluminium. Plant and Soil, 45, 595-611.

Walworth J.L. and Sumner M.E. (1987). The diagnosis and Recommendation Integrated System (DRIS). Advances in Soil Science, 6, 149-188.

Walworth J.L., Letzsch W.S. and Sumner M.E. (1986). Use of boundary lines in establishing norms. Soil Science Society of America Journal, 50, 123-128.

Ward C.R., Taylor J.C. and Cohen D.R. (1999). Quantitative mineralogy of sandstones by X-Ray Diffractometry and normative analysis. Journal of Sedimentary Research, 69, 1050-1062.

Webb R.A. (1972). Use of the boundary-line in the analysis of biological data. Journal of Horticultural Science, 47, 309-319.

Weidler P.G., Luster J., Schneider J., Sticher H. and Gehring A.U. (1998). The Rietveld method applied to the quantitative mineralogical and chemical analysis of a ferralitic soil. European Journal of Soil Science, 49, 95-105.

White A.F., Blum A.E., Schulz M.S., Bullen T.D., Harden J.W. and Peterson M.L. (1996). Chemical weathering rates of a soil chronosequence on granitic alluvium: I. Quantification and mineralogical and surface area changes and calculation of primary silicate reaction rates. Geochimica et Cosmochimica Acta, 60, 2533-2550.

Whittig L.D. and Allardice W.R. (1986). X-Ray Diffraction techniques. In: Methods of soil analysis: part 1 - physical and mineralogical Methods (G.S. Campbell, R.D. Jackson, M.M. Mortland, D.R. Nielsen, A. Klute (eds.)), Soil Science Society of America, Agronomy Monograph nb 9, 2nd edition, 331-362.

Wilson L.R. and Jiranek J. (1995). Kaolin deposits of the Czech Republic and some comparisons with South-West England. Proceedings of the Ussher Society, 8, 357-362.

Wilson M.J. (1999). The origin and formation of clay minerals in soils: past, present and future. Clay Minerals, 34, 7-25.

Woods W.I. (1977). The quantitative analysis of soil phosphate. American Antiquity, 42, 248-252.

Wopereis M.C.S., Tamelokpo A., Ezui K., Gnakpenou D., Fofana B. and Breman H. (2006). Mineral fertilizer management of maize on farmer fields differing in organic inputs in the West African savanna. Fields Crops Research, 96, 355-362.

Wortmann C.S., Bosch C.H. and Mukandala L. (1994a). Foliar nutrient analyses in bananas grown in the Highlands of East Africa. Journal of Agronomy and Crop Science, 172, 223-226.

Wortmann C.S., Karamura E.B. and Gold C.S. (1994b). Nutrient flows from harvested banana pseudostems. African Crop Science Journal, 2, 179-182.

Wortmann C.S. and Kaizzi C.K. (1998). Nutrient balances and expected effects of alternative practices in farming systems in Uganda. Agriculture, Ecosystems and Environment, 71, 115-129.

Yamaguchi J. and Araki S. (2004). Biomass production of banana plants in the indigenous farming system of the East African Highland - a case study on the Kamachumu Plateau in Northwest Tanzania. Agriculture, Ecosystems and Environment, 102, 93-111.

Yamoah C.F., Burleigh J.R. and Malcolm M.R. (1990). Application of expert systems to study of acid soils in Rwanda. Agriculture, Ecosystems and Environment, 30, 203-218.

Zake J.Y.K. (1995). Overcoming soil constraints in crop production. In: Sustaining soil productivity in intensive African agriculture (Y. Ahenkorah, E. Owusu-Bennoah, G.N.N. Dowuona (eds.)), Technical Centre for Agricultural and Rural Cooperation (CTA), 57-66.

Zech W., Senesi N., Guggenberger G., Kaiser K., Lehmann J., Miano T.M., Miltner A. and Schroth, G. (1997). Factors controlling humification and mineralization of soil organic matter in the tropics. Geoderma, 79, 117-161.

Zingore S., Murwira H.K., Delve R.J. and Giller K.E. (2007). Soil type, management history and current resource allocation: three dimensions regulating variability in crop productivity on African smallholder farms. Field Crops Research, 101, 296-305.

Scientific achievements

Scientific achievements

Peer-reviewed papers

Delstanche S., Opfergelt S., Cardinal D., Elsass F., André L., Delvaux B. (2009). Silicon isotopic fractionation during adsorption of aqueous monosilicic acid onto iron oxides. Geochimca et Cosmochiomica Acta, 73, 923-934.

Opfergelt S., de Bournonville G., Cardinal D., André L., **Delstanche S.**, Delvaux B. (2009). Impact of soil weathering degree on silicon isotopic fractionation during adsorption onto iron oxides in basaltic ash soils, Cameroon. Geochimica et Cosmochimica Acta, 73, 7226-7240.

Research papers presented on conferences

Delstanche S., Opfergelt S., Cardinal D., André L., Delvaux B. (2006). Adsorption of silica on synthetic iron oxides fractionates stable silicon isotopes. AGU Fall Meeting, San Francisco, December 11-15, poster.

Opfergelt S., **Delstanche S.**, Cardinal D. André L. (2006). Silicon isotopic fractionation in a tropical soil-plant system. AGU Fall Meeting, San Francisco, December 11-15, poster.

Opfergelt S., Cardinal D., **Delstanche S.**, Delvaux B. André L. (2007). Towards a better understanding of continental silicon cycle using Si stable isotopes. Congrès des doctorants, Paris IPGP, March 26-29, oral communication.

Delstanche S., van Asten P.J.A., Gaidashova S., Delvaux B. (2008). Mineral and organic contribution to nutrient pool in black anthropogenic soils from the African Great Lakes Region. EUROSOIL 2008, Vienna, August 25-29, poster.

Delstanche S., Jassogne L., Bizimana S.,Gaidashova S., Muliele Muku T., Nibasumba A., Van Damme J., van Asten P., Titeux H., Delvaux B., Bielders Ch., Baret Ph. (2010). Challenges and opportunities for sustainable banana-based systems for the African Great Lakes Region. Thematic day on the 'History and future of soil research in Congo, Rwanda and Burundi' by the Soil Science Society of Belgium, Brussels, December 1st, poster.

Delstanche S., van Asten P.J.A., Delvaux B. (2010). Drivers of soil fertility in smallholder banana systems in the African Great Lakes Region (Rwanda, SW Uganda). Thematic day on the 'History and future of soil research in Congo, Rwanda and Burundi' by the Soil Science Society of Belgium, Brussels, December 1st, poster.