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INTEGRATED SOIL FERTILITY MANAGEMENT FOR BEAN-MAIZE BASED FARMING SYSTEMS IN GITEGA PROVINCE, BURUNDI:

Understanding and enhancing the agronomic and economic benefits of organic and mineral inputs

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Summary

Securing sustainable food security remains a huge challenge in sub-Saharan Africa. Yet, there is an urgent need to do so as the region faces high population density, continuous cultivation of already depleted soils, limited availability of resources to farmers all of it leading to low crop productivity. In this region, soil acidity and low N and P supply capacities are common problems over large areas of agricultural land. These problems are aggravated by the lack of improved and resilient germplasm of the major crops, including maize, and various legume species. Hence, it provides the ideal testing ground to evaluate the Integrated Soil Fertility Management (ISFM) paradigm with its different options, thereby proving the conceptual 'staircase' of improving yield effects and profitability of fertilizer use. The current research is conducted in three action sites (Buraza, Makebuko and Mutaho districts) of the Consortium for Improving Agriculture-based Livelihoods in Central Africa (CIALCA) in Gitega Province.

Diammonium phosphate (DAP, 18-46-0) was used to remediate soil N and P deficiencies but its use is limited in rural areas because of its poor availability, its wrong application rates, high cost, lack of store rooms and good roads. Hence the region needs to find strategies that would enhance yield increments with concomitant increased agricultural net returns. The general objective of this work was to validate the ISFM concept on bean-maize based farming systems in Gitega Province, Central Burundi; thereby proving the underlying hypothesis of stepwise maximization of the profitability of DAP fertilizer use.

First, we carried out a field survey to evaluate the local farmers' knowledge on DAP fertilizer use and assess DAP effects on bean and maize production in two districts of Gitega Province: Buraza and Makebuko. We found a huge variability in plot sizes, plant densities, mineral DAP fertilizer rates on beans and maize production. This illustrates how farmers have different attitudes and this should be taken into account as a precondition for the establishment of profitable and sustainable nutrient management systems. Profitability of DAP use on local germoplasm under local farmers' practices was also assessed. Only 3 % and 40 % of farmers' fields provided profitable net returns for beans and maize, respectively. These results justify the need for ISFM.

Secondly, we assessed the applicability of the Compositional Nutrient Diagnosis (CND) approach under smallholder farming practices, and the frequency of nutrient deficiencies for maize cropping

in Buraza and Makebuko districts of Central Highlands of Burundi in the short rains of 2012 (2012SR). The trials were carried out on 76 fields for Buraza and 66 fields for Makebuko districts, hence totalling 142 fields covered in this study. In each field, two plots were demarcated to accommodate two treatments, a control without fertilizer and a treatment with 1kg of DAP fertilizer. Composite soil samples and maize ear leaves were collected from all plots and shipped to the International Center for Tropical Agriculture (CIAT) in Nairobi for analysis. Indophenol blue method was used for N-analysis and ICP-OES for the determination of other nutrients. A total of 284 samples was used in the CND computations. The maize simplex comprises eight nutrients *N, P, K, Ca, Mg, S, Mn and Zn* and the filling value R_9 which takes care of all other nutrients not included in this analysis. The occurrence of nutrient deficiencies showed that 1 kg of DAP resulted in alleviating some of them, especially in Buraza district. However, N and P remained the main limiting ones for maize productivity in both control and fertilized plots in Makebuko district. The persistent P-deficiency may be due to the strongly acid, P-fixing soils. Zn and Mn-deficiencies occurred mostly in both control and fertilized plots of Buraza district. Zn and Mn-deficiencies are expected to limit yields. We observed in this study that actually in Buraza district, the DAP fertilizer induced a smaller yield increase on average (29 %) compared to the one in Makebuko district (46 %) where these two nutrients are not limiting.

Next, we assessed the profitability of DAP fertilizer use on local and improved varieties of climbing bean (LR 2012) and maize (SR 2013) in smallholder farms of Buraza district in Gitega province in Central Burundi. Local varieties used were AMAKUTSA and ISEGA for bean and maize while G13607 and ZM 605-24C were improved varieties for climbing bean and maize. Fertilizer and variety effects were significantly larger when planted on time in a soil with larger total N (TN > 1.5 g kg^{-1}) and total C (TC > 16 g kg^{-1}) contents for beans while characterized by a moderate soil clay content (38 - 40 %) with high total C (TC ≥ 19 g kg^{-1}) content for maize. Large fertilizer and improved variety effects consequently resulted in large value cost ratios (VCR). For improved climbing beans, VCR values on average were 4.49 \$ $\$^{-1}$ which is more than the average of 3.19 \$ $\$^{-1}$ obtained from local climbing beans. The same trend was also observed for maize, where the value cost ratio for the improved maize on average, was almost twice the one of local maize. The use of DAP fertilizer (100 kg ha^{-1}) for the improved climbing bean and maize varieties resulted in larger grain yields, larger net benefits, larger value cost ratios and larger marginal rates of return than for local climbing bean and maize varieties.

Finally, we tested the application of DAP fertilizer with improved bush and climbing bean varieties, in rotation with a subsequent improved maize variety. Rotational effects of a bush and climbing bean variety were compared, and the profitability of DAP fertilizer assessed in bean-maize rotations in 59 smallholder farms of Mutaho district, Gitega Province in Central Burundi in 2 cropping seasons: LR 2012 for beans and SR 2013 for maize. The improved varieties used were MLB 122-94B and G13607 for bush and climbing beans and ZM 605-24C for maize, respectively. The use of DAP fertilizer (50 kg ha^{-1}) increased on average grain yields up to 1000 kg ha^{-1} for bush beans and 1800 kg ha^{-1} for climbing beans, respectively. Application of DAP fertilizer to the two bean varieties resulted in large yield differences when beans were planted on time in soils with a total C below 2.5 %. Such response was expected since the initial soil analysis indicated that the soils in which beans were cropped, were of low fertility, acidic, with small amounts of total N, total C and available P. The positive effect of DAP on maize grain yields was realized for about 60 % of the farmers. With the use of the same nutrients, maize following climbing beans out yielded maize following bush beans for about 48 % of the farmers. Large fertilizer and bean variety effects consequently resulted in a large value cost ratio. For climbing beans, VCR values on average were 4.25 \$ \$$^{-1}$, more than double the average of 1.83 \$ \$$^{-1}$ obtained from bush beans. The same trend was also observed for maize planted after beans, where the control maize plots on average yielded 4000 kg ha^{-1}. The value cost ratio was on average two times larger when maize followed climbing beans than when it followed the bush beans. Such profitability was realized when maize grain yields ranged between 1067 and 4622 kg ha^{-1}. These yields were obtained from fields with high total C (TC > 23 g kg^{-1}), low total N (TN < 2 g kg^{-1}) and high clay content (more than 37 % clay). Results from this study revealed that an improved climbing bean preceding an improved maize on soils enriched with DAP fertilizer is a promising alternative to the local smallholder farmers' practices.

In summary, the study confirmed the insufficient knowledge of smallholder farmers on how to use fertilizer according to their local conditions, which consequently leads to soil nutrient mining. There is a dire need for more trainings and awareness creativity emphasizing the use of fertilizer at their best advantage and development of site specific fertilizer recommendations instead of blanket. We noted that the use of fertilizer to the improved varieties was more profitable than for local varieties. In this way of implementing ISFM, we also found that use of fertilizer on climbing bean-maize rotation generated more rotational effects and was more profitable than that of bush bean-maize rotation. We therefore concluded that use of site specific fertilizer recommendations and high yielding improved grain legume varieties would be the most important factors to consider in initiatives to improve agronomic and economic productivity of legume-cereal rotations in such depleted soils.

Samenvatting

Het verzekeren van de voedselzekerheid in Sub-Sahara Afrika blijft een geweldige uitdaging. Tegelijk is er een dringende nood om hier iets aan te doen omdat de regio kampt met een hoge bevolkingsdichtheid, een permanente begroeiing op de reeds uitgeputte bodems en een beperkte toegang tot productiemiddelen (kunstmest, bestrijdingsmiddelen…) bij de boeren. Dit alles leidt naar een landbouw productiviteit die erg laag is. In de regio zijn bodemzuurheid en de lage N- en P-beschikbaarheid algemene problemen, wijd verspreid over grote delen van het landbouw areaal. Deze problemen worden versterkt door een gebrek aan verbeterde en robuuste variëteiten van de belangrijkste gewassen, met maïs en verschillende vlinderbloemigen als belangrijkste. Bijgevolg is de regio het ideale testgebied om het 'Integrated Soil Fertility Management (ISFM)' paradigma met al zijn opties te evalueren, in het bijzonder de vooropgestelde conceptuele, trapsgewijze verbetering van opbrengsten en rendement van kunstmestgebruik.

Diammoniumfosfaat (DAP, 18-46-0) is in het verleden voorgesteld om de bodemtekorten aan N en P te remediëren maar de toepassing is zeer beperkt in landelijke gebieden door een slechte beschikbaarheid van deze meststof, de vaak verkeerde toedieningshoeveelheden, de hoge kost en afwezigheid van de juiste infrastructuur. De regio is dus verplicht om strategieën uit te werken die de opbrengsten moeten verhogen met een gelijktijdige verhoging van de netto inkomsten. De hoofddoelstelling van dit werk was het valideren van het ISFM concept voor de op maïs gebaseerde landbouwsystemen in de provincie Gitega, in Centraal Burundi. Meer specifiek wordt de onderliggende hypothese van een trapsgewijze verbetering van de winstgevendheid van DAP kunstmest gebruik onderzocht.

Eerst werd een survey uitgevoerd in twee districten van Gitega, namelijk in Buraza en Makebuko, om te peilen naar de kennis van de boeren over DAP kunstmestgebruik en -effecten op de boon- en maïsproductie. We vonden een grote variabiliteit in de oppervlaktes van de percelen, de plantdichtheden en in de toegepaste DAP hoeveelheden voor de productie van maïs en boon. Dit tekent de verschillende attitudes van de boeren ten aanzien van kunstmestgebruik waarmee rekening moet worden gehouden bij het implementeren van winstgevende en duurzame systemen van nutriëntenbeheer.

Ten tweede onderzochten we de toepasbaarheid van de *‘Compositional Nutrient Diagnosis (CND)’* benadering onder gangbare praktijken bij kleine boeren om het voorkomen van nutriëntengebreken in maïs te identificeren in de districten Buraza en Makebuko, in de centrale hooglanden van Burundi in de zogenaamde ‘short rains’ van 2012 (2012 SR). De testen werden gedaan op 76 velden in Buraza en op 66 velden in Makebuko, in totaal dus op 142 velden. In elk veld werden twee percelen afgebakend om de volgende twee behandelingen uit te voeren: één perceel kreeg 1 kg DAP kunstmest, het andere werd onbemest gelaten. Mengmonsters van bodem en *‘ear leaf’* van maïs werden genomen in alle percelen en verzonden naar het *‘International Center for Tropical Agriculture (CIAT)’* in Nairobi voor analyse. Voor de N-analyse werd de Indofenolblauw methode gebruikt terwijl de andere nutriënten via ICP-OES werden bepaald. In totaal werden 284 monsters gebruikt voor de CND berekeningen. De maïs *‘simplex’* bevatte 8 nutriënten *N, P, K, Ca, Mg, S, Mn en Zn* en een ‘vulwaarde’ R_9 die alle andere elementen omvat die niet werden geanalyseerd. Een analyse van het voorkomen van nutriëntengebreken toonde aan dat DAP er in slaagde enkele ervan op te heffen, met name in Buraza. In Makebuko echter bleven N en P de belangrijkste beperkende nutriënten voor maïs productiviteit, zowel in de onbemeste als de bemeste percelen. De persistente P-gebreken konden worden toegeschreven aan de uiterst zure, fosfaat fixerende bodems. Zn- en Mn-gebreken kwamen vooral voor in zowel de controle als de bemeste bodems in Buraza. Zn- en Mn-gebreken zullen naar verwachting de opbrengst negatief beïnvloeden. Zo stelden we vast dat in Buraza het effect van DAP op meeropbrengst gemiddeld kleiner was dan in Makebuko – 29 % versus 46 %- . In het laatste district waren noch Zn, noch Mn gelimiteerd.

Vervolgens bepaalden we de winstgevendheid van DAP kunstmest gebruik voor lokale en verbeterde variëteiten van staakboon (in LR 2012) en maïs (in SR 2013) bij kleine boeren in Buraza (Gitega), in centraal Burundi. De gebruikte lokale variëteiten waren AMAKUTSA en ISEGA voor staakboon en maïs respectievelijk terwijl G13607 en ZM 605-24 C de verbeterde variëteiten waren voor staakboon en maïs. Voor boon waren de effecten van variëteit en kunstmest significant groter wanneer het planten tijdig gebeurde in bodems met een groter totaal stikstofgehalte (TN > 1.5 $g.kg^{-1}$) en groter totaal koolstofgehalte (TC >16 $g.kg^{-1}$). Voor maïs was dat het geval wanneer geplant werd in bodems met een middelmatig kleigehalte (38 - 40 %) en een hoog totaal koolstofgehalte (T C > 19 $g.kg^{-1}$).

De grote effecten die uitgingen van de meststof en de gebruikte variëteit leidden bijgevolg naar grote *value cost* verhoudingen (VCR). Voor de verbeterde staakbonen werden VCR waarden van 4.49 $\$.\$^{-1}$ opgetekend, hoger dan de gemiddelde VCR van 3.19 $\$.\$^{-1}$ die verkregen werd met de lokale variëteit. Dezelfde trends werden verkregen met maïs, waar de VCR van de verbeterde maïsvariëteit gemiddeld ongeveer dubbel zo groot was als die van de lokale. Het gebruik van DAP bij de verbeterde variëteiten van staakboon en maïs resulteerde in hogere graanopbrengsten, hogere netto winsten, hogere *value cost* verhoudingen en grotere marginale meeropbrengsten dan bij de lokale staakboon- en maïsvariëteiten.

Tenslotte testten we de effecten van DAP kunstmest op verbeterde variëteiten van 'bush' en staakboon, gevolgd in de rotatie door een verbeterde maïsvariëteit. De rotatie effecten van 'bush' en staakboon werden vergeleken in rotaties met maïs bij 59 'kleine' boeren in Mutaho district, in de provincie Gitega van centraal Burundi, in twee seizoenen: LR 2012 voor de bonen en SR2013 voor de maïs. De verbeterde variëteiten die werden gebruikt waren MLB 122-94B en G13607 voor 'bush' en staakboon en ZM 605-24C voor maïs, respectievelijk. DAP gebruik (50 kg.ha^{-1}) resulteerde in een gemiddelde stijging van de graanopbrengsten van 1000 kg.ha^{-1} voor 'bush' bonen en 1800 kg ha^{-1} voor staakbonen respectievelijk. De toediening van DAP kunstmest aan de twee boonvariëteiten resulteerde in grote opbrengststijgingen wanneer de bonen op het juiste tijdstip werden geplant in bodems met een totaal C-gehalte lager dan 2.5 %. Een dergelijke respons was verwacht, omdat de initiële bodemanalyses aantoonden dat de bodems waarin bonen werden geplant een lage bodemvruchtbaarheid hadden, zuur waren en kleine hoeveelheden aan totaal N, C en beschikbaar P hadden. Een positief effect van DAP op maïs opbrengsten werd gerealiseerd bij ongeveer 60 % van de boeren. Met eenzelfde bemesting deed de maïs het beter in 48 % van de gevallen, indien ze na staakbonen werd geplant dan wel na 'bush' bonen. De grote effecten van kunstmest en boonsoort leidde logischerwijze tot grote '*value cost'* verhoudingen. Voor de staakbonen waren de VCR waarden gemiddeld gelijk aan 4.25 $\$ \$^{-1}$, meer dan het dubbele van het gemiddelde voor 'bush' bonen van 1.83 $\$ \$^{-1}$. Eenzelfde trend werd genoteerd voor maïs geplant na bonen, waar de controle opbrengst van maïs gelijk was aan 4000 kg ha^{-1}. De '*value cost'* verhouding was gemiddeld twee keer groter wanneer de maïs werd geplant na de staakbonen dan wel na *'bush'* bonen. Dergelijke winstgevendheid werd gerealiseerd wanneer de maïsgraan oogsten varieerden tussen 1067 en 4622 kg ha^{-1}. Dit soort opbrengsten werd gehaald op velden met hoge totale koolstofgehaltes (TC > 23 g kg^{-1}), lage totale N (TN < 2 g kg^{-1}) en een hoog kleigehalte (meer dan 37 % klei). Uit deze studie blijkt dat een verbeterde staakboon voorafgaand aan verbeterde maïs bemest met DAP kunstmest een veelbelovend alternatief is voor de lokale praktijken van de kleine boeren.

Samengevat bevestigt deze studie het gebrek aan kennis bij de kleine boeren over hoe kunstmest te gebruiken, aangepast aan de lokale omstandigheden. Het gevolg is een continu uitmijnen van de bodems. Er is dus een dringende nood aan meer opleiding en bewustmaking waarbij de nadruk gelegd wordt op een gebruik van kunstmeststof die het meest voordelig is en op plaats-specifieke bemestingsadviezen in de plaats van de *'blanket'* aanbevelingen. We stelden vast dat het gebruik van kunstmest meer winstgevend was wanneer gecombineerd met verbeterde variëteiten dan wel met lokale variëteiten. In het kader van ISFM, stelden we ook vast dat het gebruik van kunstmest in staakboon-maïs rotaties grotere rotatie-effecten genereerde en meer winstgevend was dan dezelfde toepassing in 'bush' boon-maïsrotaties. Bijgevolg concludeerden we dat het gebruik van plaats-specifieke bemestingsadviezen en hoge-opbrengst-verbeterde variëteiten van granen en vlinderbloemigen de belangrijkste componenten zijn van initiatieven die het verhogen van de landbouwkundige en economische productiviteit van vlinderbloemige-graan rotaties beogen in de uitgeputte bodems van centraal Burundi.

Abbreviations

AE : agronomic efficiency

AIDS : acquired immune deficiency syndrome

BB-M : bush bean followed by maize

BIF : Burundese Francs

BLUP : Best Linear Unbiased Prediction

BNF : Biological Nitrogen Fixation

BRB : Banque de la République du Burundi

CB-M : Climbing Bean followed by Maize

CCAFS : Climate Change, Agriculture and Food Security

CIA : Central Intelligence Agency

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

CIAT : International Center for Tropical Agriculture

CIMMYT : International Maize and Wheat Improvement Center

CEC : Cation Exchange Capacity

CGIAR : Consultative Group for International Agriculture Research

CND : Compositional Nutrient Diagnosis

DAP : Diammonium Phosphate

DRC : Democratic Republic of Congo

EU : European Union

FAO : Food and Agriculture Organization

FAOSTAT : Food and Agriculture organization Corporate Statistical Database

F : Fertilized plots

GDP : Gross Domestic Product

GHI : Global Hunger Index

HIV : Human immunodeficiency virus

LCB : Local climbing bean

LM : Local maize

LRs : Long rainy season

ICB : Improved climbing bean

ICP-OES : Inductively coupled plasma optical emission spectroscopy

IFAD : International Fund for Agriculture Development

IM : Improved maize

ISABU : Institut des Sciences Agronomiques du Burundi

ISFM : Integrated Soil Fertility Management

ISTEEBU : Institut de Statistiques et d'Etudes Economiques du Burundi

KCl : Potassium chloride

MGY : Maize grain yield

MINAGRI : Ministère de l'Agriculture et de l'Elevage

MRR : Marginal rate of return

NASA : National Aeronautics and Space Administration

NB : Net benefits

NF : Non-fertilized plots

NPK : Nitrogen-Phosphate-Potassium

ns : Not significant

PNSEB : Programme National de Subvention des Engrais au Burundi

PV : Production value

Olsen P/P_{olsen} : Extractable P by 0.5M NaHCO3 (Olsen, 1954)

OM : Organic matter

SE : Standard error

SED : Standard error of difference

SMN : Secondary and micronutrients

SRs : Short rainy season

SSA : sub-Saharan Africa

TC : Total costs

TFPs : Technical and Financial Partners

TRMM : Tropical Rainfall Measuring Mission

UNDP : United Nations Development Program

USAID : United States Agency for International Development

U$: US dollar

VCR : value cost ratio

WFP : World Food Program

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PART I

Chapter 1

Introduction, hypotheses, research objectives and thesis outline

1.1. Agricultural productivity and fertilizer use in Burundi: A brief overview

Burundi is part of East and Central Africa and is landlocked between DRC, Tanzania and Rwanda (Figure 1.1). Total land area is 27,834 km^2, of which approximately 79.2 % is used for agriculture (Worldbank, 2014). In 2014, the country's population was 11 million, an increase of almost 3 % from 2012 with a population density of 421 person km^{-2} (Worldbank, 2014). Burundi is facing food insecurity due to social conflicts, climate change (drought, erratic rainfall patterns), decreasing soil fertility and high population density, with more than 90 % of the population being traditional farmers. Hence there is a large pressure on land due to rapid annual population growth rate being 3.14 % as of 2016 (Worldbank, 2014).

According to the 2014 Global Hunger Index report, the country has the highest level of hunger in sub-Saharan Africa (SSA). In the ranking food security of SSA countries, it ranks last at position 76, with a global hunger index score of 35.6. The Global Hunger Index (GHI) is a multidimensional statistical tool used to describe the hunger situation in a specific country and is updated once a year. The GHI is composed of the proportion of the undernourished as a percentage of the population, the prevalence of underweight children under the age of five and the mortality rate of the same age group (calculated average, in percentages). The 2015 UNDP Human Development Report ranks Burundi at place 184 out of 188 countries. Poverty is widespread, with 64.6 % of the population living on less than one dollar a day, particularly in rural areas.

Agriculture is considered as a backbone of Burundi's economy and is the second most important contributor to the gross domestic product (GDP) after the service industry. The agricultural sector accounts for 34.4 % of the GDP, with coffee as its main export product (CIA, 2015). However, during the past decade, the shares of the secondary and tertiary sectors have increased. With manufacturing and construction as its main subcomponents, the secondary sector covers the smallest overall share of the economy, 18.4 %. The tertiary sector includes services and transport and contributes about 47.2 % of GDP (CIA, 2015).

Moreover, agricultural productivity is low and constrained by socio-economic and agro-ecological factors, like the lack of market access and soil deterioration (Worldbank, 2014). Especially the decline in soil fertility as a result of soil nutrient mining and erosion, is precluding a secure food supply. Domestic food production is insufficient to meet the needs of the population: the country faces a significant food deficit of over 32 %. Some humanitarian initiatives such as the World Food Program (WFP) try to support food insecure and malnourished people through nutrition interventions, the provision of school meals, food assistance to victims of climatic shocks and the empowerment of communities to create assets and improve food production (WFP, 2015).

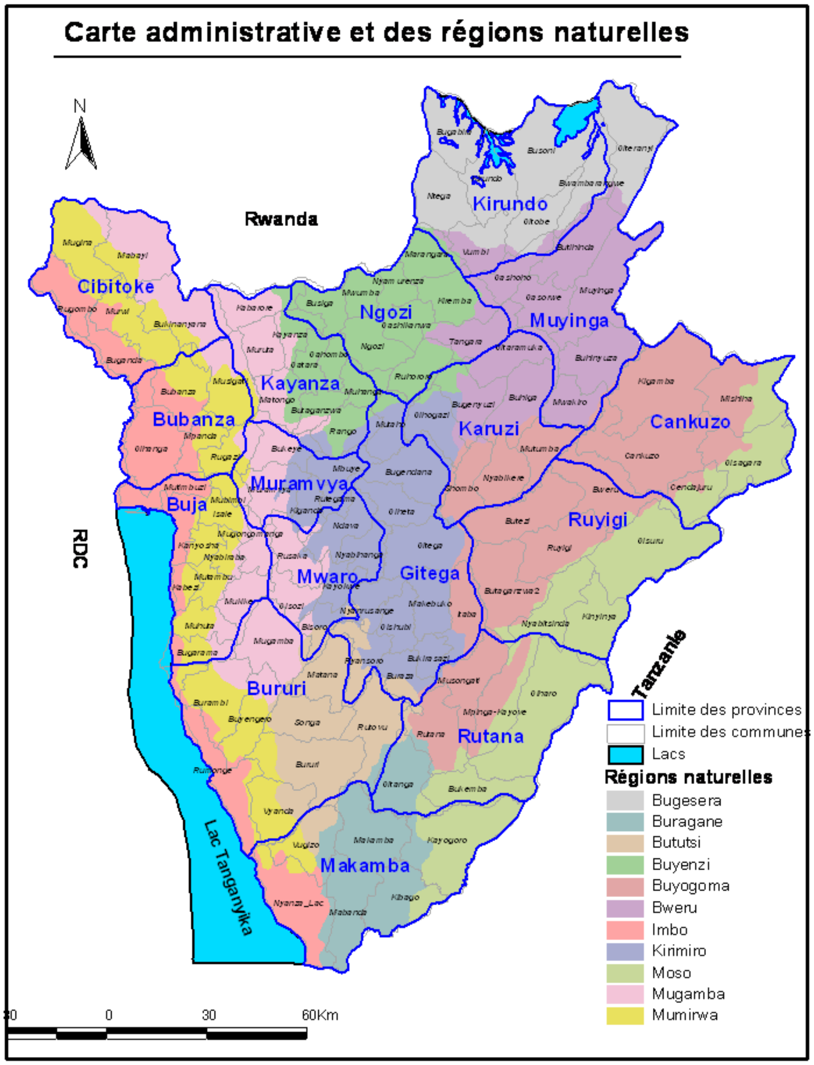


Figure 1.1. Administrative map of Burundi showing the different provinces (blue lines) and agro-ecological zones (areas differently colored) (ISTEEBU, 2014)

Important food crops in the country include cereals (maize, wheat and sorghum) and grain legumes (beans, soybeans, and groundnuts). Productivity of all these crops is generally low (Figure 1.2).

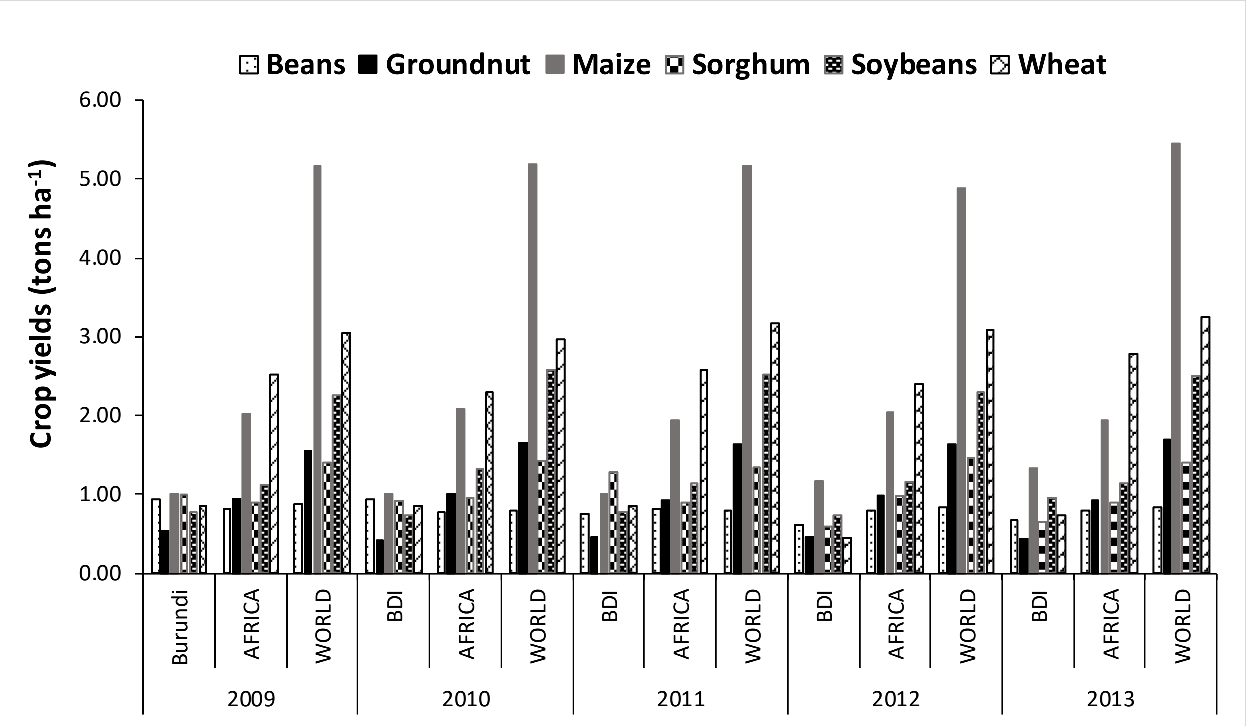
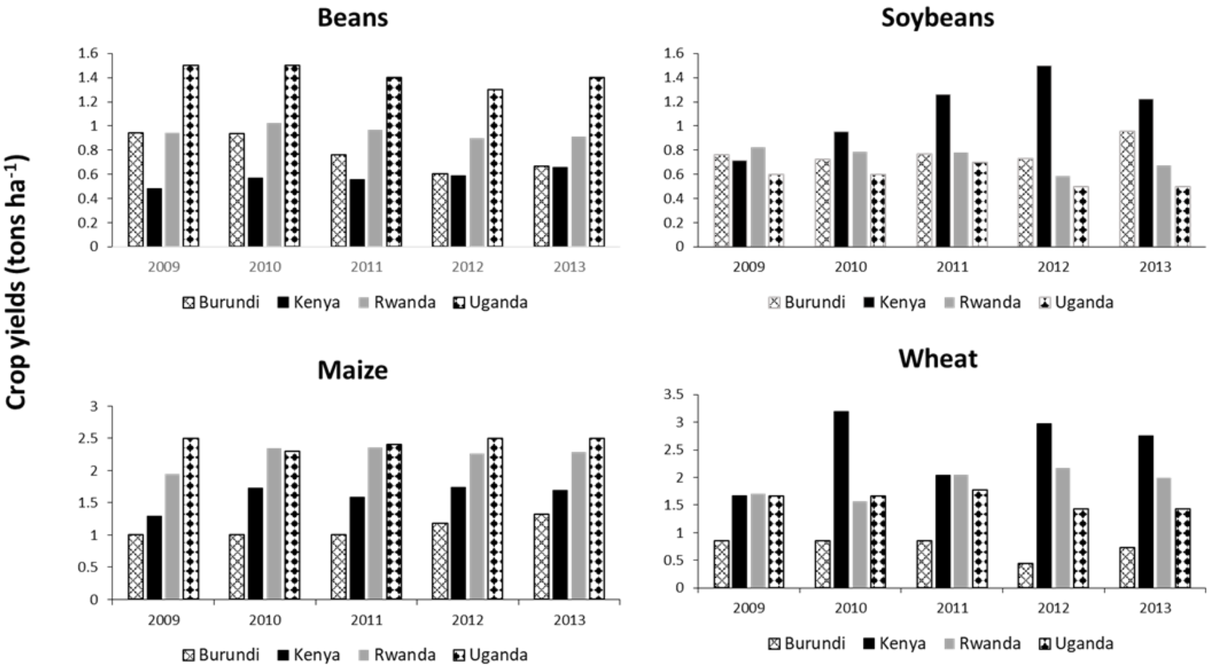


Figure 1.2. Productivity in tons.ha^{-1} of important cereals and grain legumes over the last five years in Burundi, Africa and at World level (2009-2013). BDI: Burundi. *Source: (FAOSTAT, 2014). Accessed 13th of October 2015*

Today, maize is the main staple of the country and plays a major role both as a cash and subsistence crop for most households. As per 2009, the maize gross production valued 42 (current) million US$ as compared to only 5 and 36 million US$ for wheat and sorghum, respectively. In 2013, the gross production value increased to 61 million US$ for maize, but has decreased to 4 and 15 million US$ for wheat and sorghum, respectively (FAOSTAT, 2014). For the grain legumes, although the yield of common beans has decreased over the last five years, its gross production value has increased from 189 million US$ in 2009 to 201 million US$ in 2013. However, the production remains well below compared to the production in the neighboring countries such as Rwanda, Kenya and Uganda (Figure 1.3).


Beans

Soybeans

Maize

Wheat

Figure 1.3. Productivity in tons.ha^{-1} of important cereals and grain legumes over the last five years in Burundi, Kenya, Rwanda and Uganda (2009-2013). *Source: (FAOSTAT, 2014). Accessed 04th of April 2018*

In 2005, the average maize grain yield was 1 ton ha^{-1} produced on approximately 116,000 ha. This increased to 1.3 ton ha^{-1} produced on 123,000 ha in 2013 (FAOSTAT, 2014). Even with this increase both in yield and total land area under maize, the country national production is deficient and large increases in yields are required to meet the food demands of an increasing population. The production of maize is at 162,000 tons per year, which is 10,000 tons short of the required annual maize consumption of 172,000 tons (www.indexmundi.com). The deficit is bridged by imports from neighboring countries. Generally, maize yields have stagnated at an average of 1.2 ton ha^{-1} (Worldbank, 2014) against a potential of 6 - 8 tons ha^{-1} produced in research stations (Manirakiza, 2004) and/or field experiments with adequate management. This implies among other factors the preparation of a good seedbed followed by early planting and the application of optimal soil fertility and plant protection management principles (Ofor et al., 2009; Vanlauwe et al., 2012). On small scale farmer's fields, yields are much lower. In Burundi, for instance, yields could be as low as 0.8 and 0.5 ton ha^{-1} season^{-1} for grains of maize (Manirakiza, 1999) and legumes (Ndarusigiye, 1990), respectively. For most households in Burundi, low yields can feed the family for only a few months in a year.

While in the other parts of the world, increase in food productivity has resulted from larger yields per unit of cultivated area (Nziguheba, 2001), in SSA, increase in food supply has been achieved at the expense of cropped land (Borlaug and Dowswell, 1995). This was not a problem until three decades ago, as the traditional agricultural systems depended on shifting cultivation to maintain food security with less work. Consequently, 4 million ha of forest was cleared annually (Quiñones et al., 1997). In the recent past however, population increase and subsequent land scarcity has resulted in continuous cultivation of the same plots of land. This has led to a gradual decline in soil fertility. In order to reverse this trend, it is important to return as much as possible all nutrients which are removed from the soil (either by crop harvests, leaching, erosion or volatilization). The current situation is however quite opposite in most smallholder farms where nutrient exports exceed nutrient imports at district and country scale (Stoorvogel et al., 1993). In Burundi, the average annual fertilizer application per farm is about 7.4 kg ha^{-1} NPK in 2013 (Worldbank, 2014). Indeed, fertilizer use in SSA is the lowest of the entire world since NPK fertilizer application ranges between 8 - 9 kg ha^{-1} and hence does not replenish the quantities of NPK removed (Chianu et al., 2011).

Recognizing the need to increase fertilizer use and hence food productivity, African leaders made a declaration to increase the use of fertilizer from the 8 to 50 kg ha^{-1} fertilizer during the African Summit held in Nigeria, Abuja, in June 2006. The average rate of 8 - 9 kg ha^{-1} of fertilizer use in SSA countries cannot guarantee the resilience of an agricultural system in case of adverse soil conditions.

In Burundi, all inorganic fertilizers are imported from outside and the quantity of fertilizer use is still low compared to the one used in the neighboring countries (Figure 1.4). The most common fertilizer in Burundi are urea (46-0-0), diammonium phosphate (18-46-0), potassium chloride and NPK (17-17-17). However, Potassium was not used in our trials because we wanted to focus on the commonly used DAP which is used for maize and beans in rural areas. So, rather than addressing potential nutrient deficiencies, we aimed at exploring the underlying reasons for poor or no response to DAP and its economics. K is also less deficient in Burundi soils and less important for beans and maize crops compared to N and P.

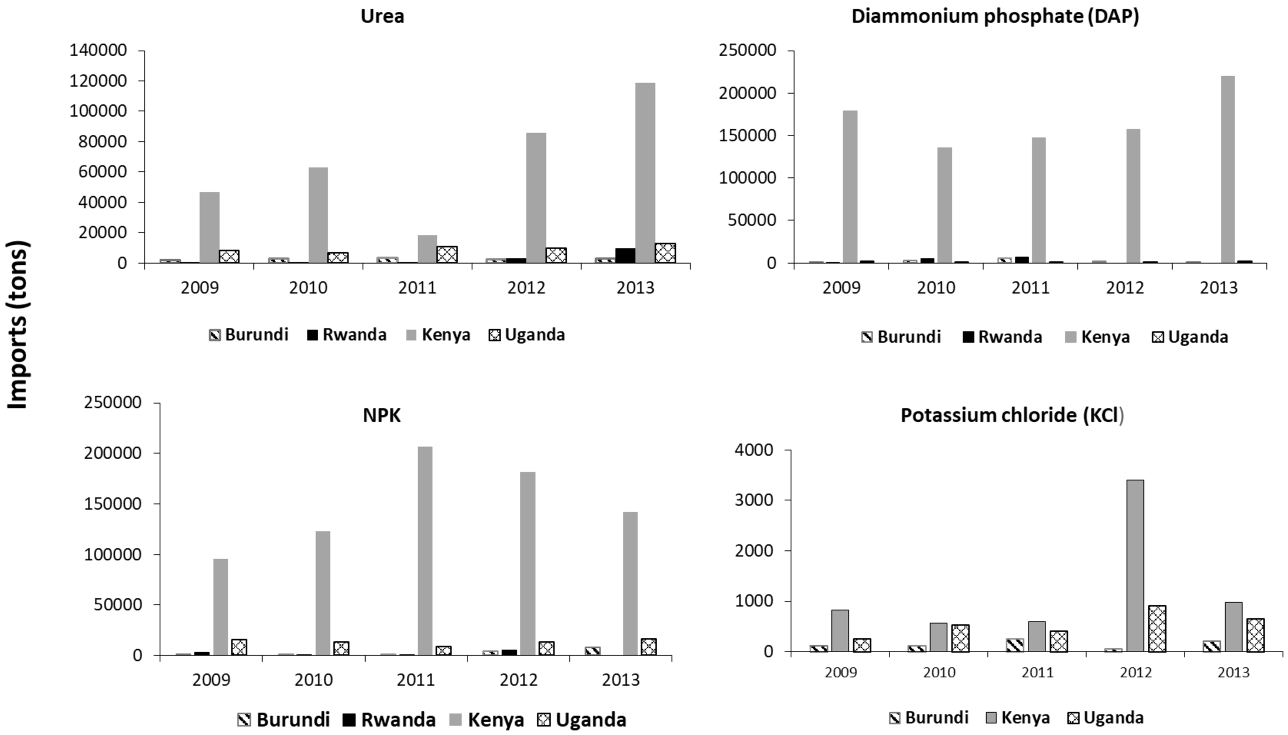


Figure 1.4. Evolution of fertilizer imports in Burundi, Rwanda, Kenya and Uganda (2009-2013). *Source: http://faostat3.fao.org/download/R/RF/E. Accessed on 4th April, 2018*

Fertilizer consumption in Burundi (Figure 1.5) have undergone a tremendous transition. In the 90's, the government played a significant role in fertilizer marketing through price controls. For easier accessibility by the farmer, fertilizer was channeled through private NGOs and parastatal farmers' organizations. Since 2013, fertilizer is subsidized by the government with support from the Netherlands and Germany and can so be sold below their market value (PNSEB, 2013).

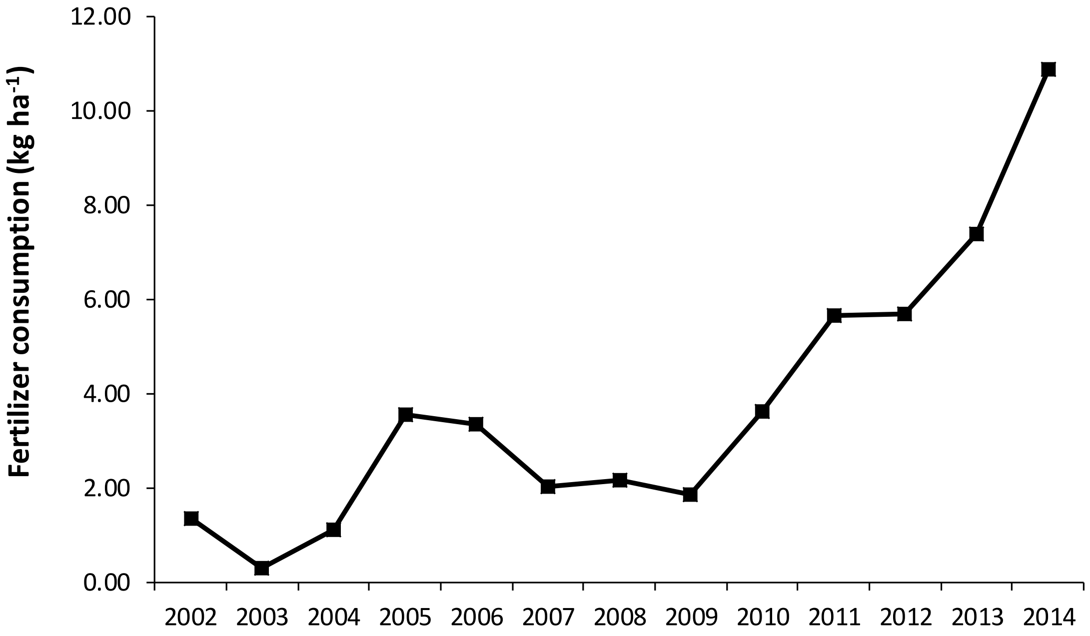


Figure 1.5. Fertilizer consumption (kg ha^{-1} of arable land) in Burundi (2002-2013). *Source: http://www.fao.org/faostat/en/#data/RFB. Accessed on 4th April, 2018*

Following the below scheme, farmers have to plan their needs for fertilizers per season and pay in advance the amount corresponding to the quantity and type of fertilizers needed through cooperatives or banks (Figure 1.6).

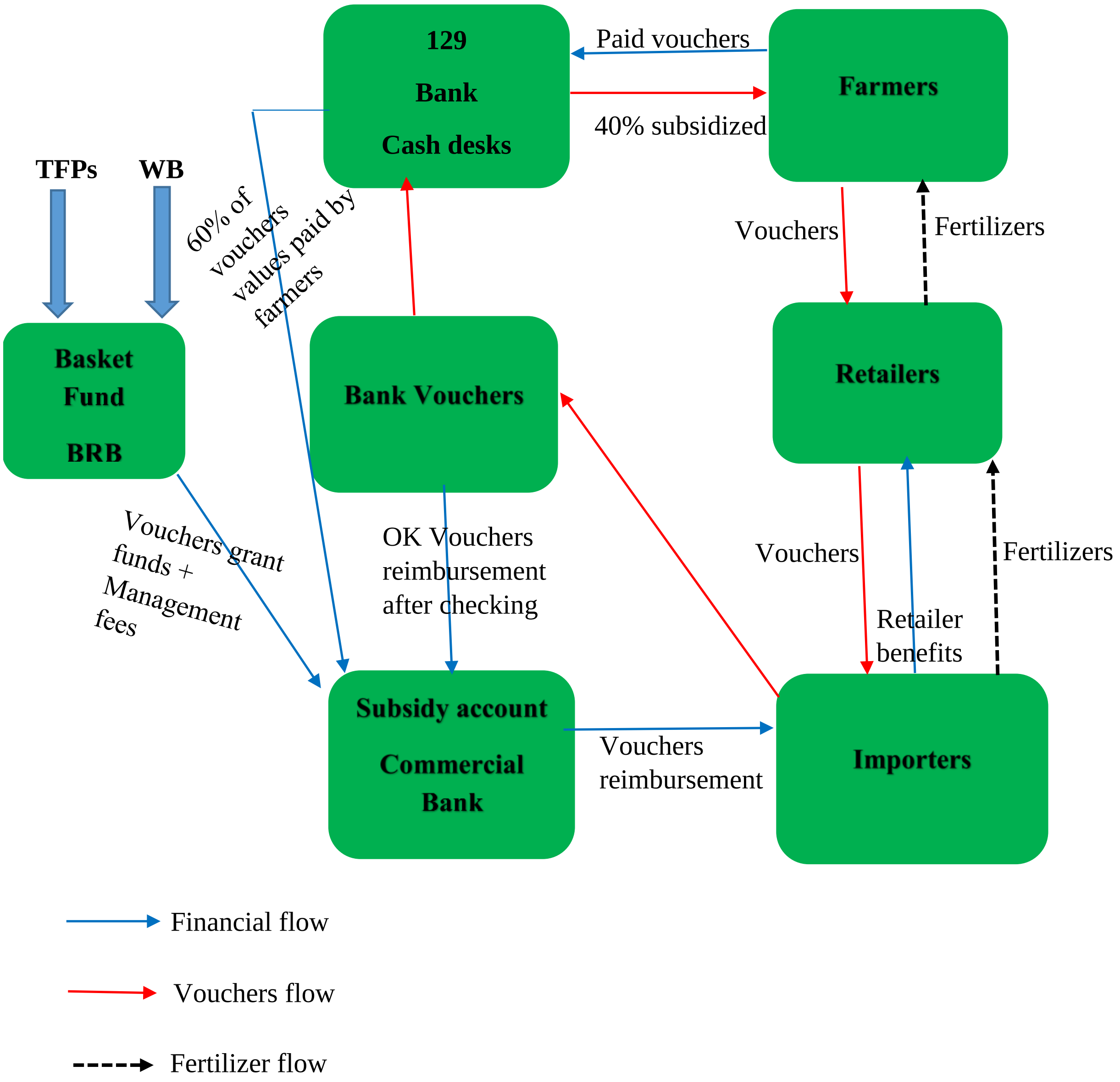


Figure 1.6. Scheme of fertilizer acquisition (provision and distribution) by farmers in Burundi (Dodiko, 2015). TFPs: Technical and Financial Partners (Netherlands and Germany); WB: World Bank; BRB: Banque de la République du Burundi

At the beginning of each season, the fertilizers are brought to the different districts to be distributed by extension services under the supervision of agronomists. Price fluctuation in Burundi is at 57.6% due to high transportation costs, delayed deliverance, high taxation, packaging materials and lack of customers (Kimana, 2009). The average regional price of fertilizers in Burundi (AMISTA, 2015) is given below for the years 2010 to 2015 and is quite variable between types of fertilizers (Figure 1.7). To compare, the average world market price for these three fertilizers was about half, i.e. 515 and 341 US$ ton^{-1} for DAP and urea respectively (www.indexmundi.com). Being a composite fertilizer with different formulation rates, we couldn't find the world market price of NPK (17-17-17).

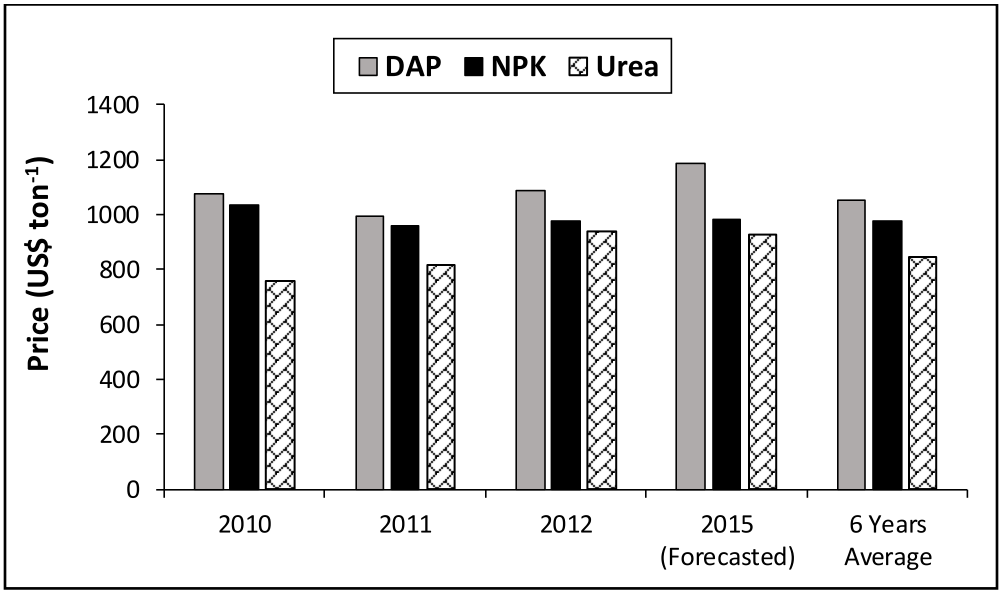


Figure 1.7. Yearly average price (US$ ton^{-1}) of fertilizers in Burundi (2010 - 2015). Source: AMITSA regional monthly price report-October 2015. Accessed 24th November 2015

Fertilizer consumption refers to the total quantity of each mineral fertilizer consumed per year during the period of 2009 - 2012. Fertilizer products include Nitrogen-Phosphate-Potassium fertilizers. Traditional sources of nutrients like animal manures or composts are not included. The evolution of fertilizer consumption (2009 - 2012) is described in Figure 1.8.

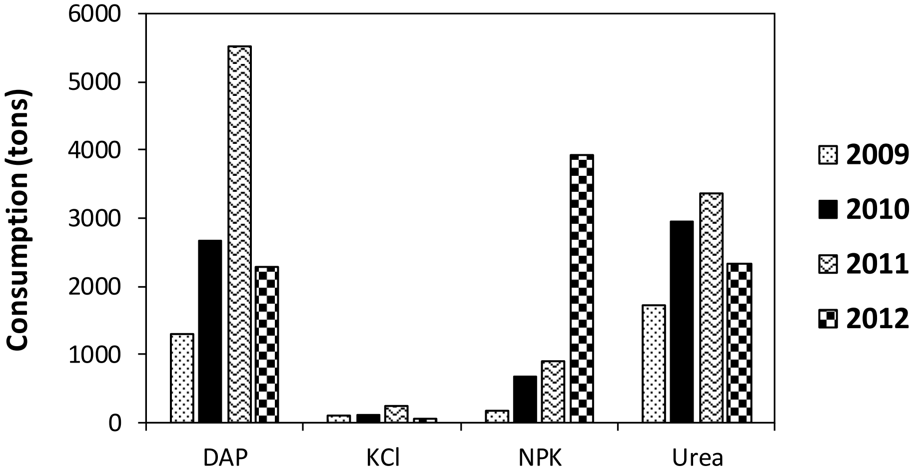


Figure 1.8. Fertilizer consumption in Burundi (tons) over the past four years. DAP- Di-ammonium phosphate; NPK-Nitrogen, phosphorus and potassium; KCl-potassium chloride; Urea. *Source:(FAOSTAT, 2014). Accessed 16th of October 2015.*

However, even with the subsidized fertilizers, investment remains quite indispensable. It is therefore of great importance that soil fertility replenishment technologies focus on maximizing the use efficiency of the limited available fertilizer inputs to achieve maximal crop yields (Vanlauwe and Zingore, 2011).

1.2. Gitega province: Study area description

1.2.1. Geographical conditions

This work is part of one of the outcomes of the Consortium for Improving Agriculture-based Livelihoods in Central Africa (CIALCA) project which was operating in Gitega Province as one of its mandate area. Mandate areas constitute geographical boundaries inside which CIALCA operates. They are defined as areas having similar agro-ecologic conditions and poverty profiles, a relatively good access to larger urban markets and where CIALCA's priority cropping systems are essential components of small farmers' livelihoods (Ouma.E et al., 2010). The study sites in the Central province of Burundi, Gitega, are situated between the latitudes 3°11' S and 3°48' S and the longitudes 29°46' E and 30°2' E, based on our GPS-coordinates. Gitega is located in the area of the central highlands, with alternating hills and flat land, covering an area of 1979 km^2 or 7.1 % of the total land area of Burundi. With a population of 725,223 inhabitants in 2008, Gitega is the second most populated province of Burundi with an average density of 366 inhabitants per km^2. The altitude varies between 1500 and 2000 m above sea level (masl). The main rivers present in Gitega, the Ruvubu and his affluent rivers, the Mubarazi and Ruvyironza, are draining towards the Nile (ISTEEBU, 2014).

The current study was carried out in 3 action sites (Mutaho, Buraza and Makebuko districts) of CIALCA in Gitega Province (Figure 1.9).

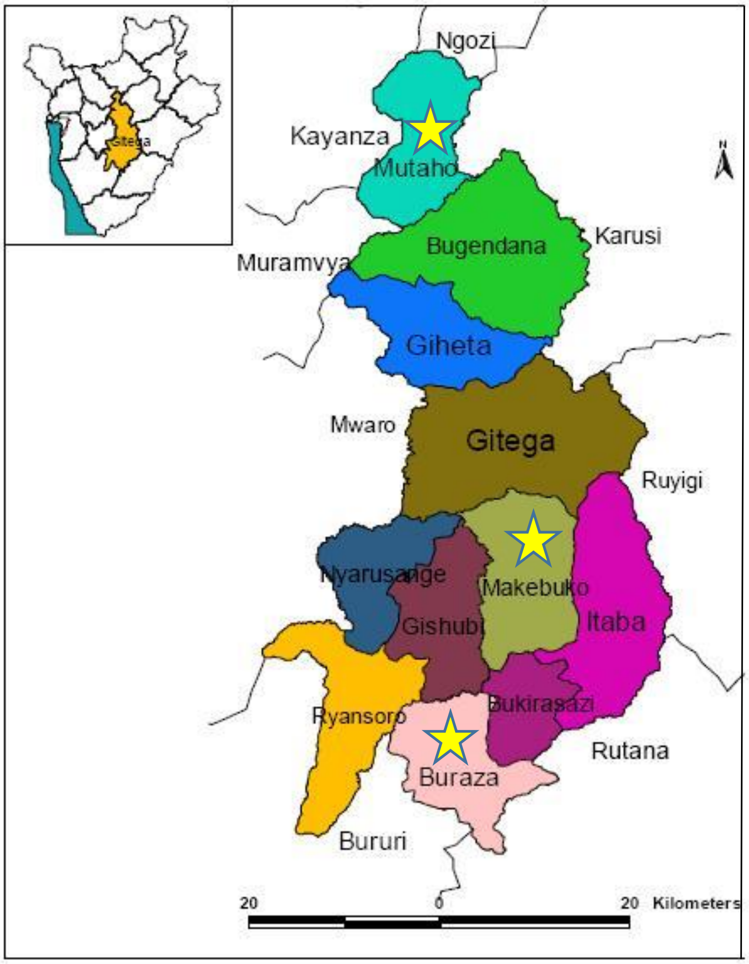


Figure 1.9. Map of Gitega Province showing the study districts: Buraza, Makebuko and Mutaho (ISTEEBU, 2014)

The criteria for selecting these districts were high level of poverty, a relatively high potential to increase productivity and a relatively good access to larger local urban markets. The choice was also guided by the fact that the main cropping systems practiced are based on maize and legumes, which are mandate crops of the current study (Ouma et al., 2010).

They differ in altitude, population density, soil group and distance to Gitega main market (Table 1.1).

Table 1.1. Main variation criteria between the selected districts

District	**Altitude (m)**	***Population density (#km^{-2})**	***Distance to main market de Gitega (km)**	****Soil group**
Buraza	1701-1927	299	55	Acrisols
Makebuko	1670-1743	350	24	Nitisols
Mutaho	1499-1618	432	42	Ferralsols

Source: Author, *(ISTEEBU, 2014) and ** (WRB, 2015)

I.2.2. Climate

The climate in Burundi is tropical highland climate because of its elevation. Rainfall follows a bimodal pattern in all districts. The climate has two main cropping seasons and an additional period in the marshland. Season A, from October to January with major crops like beans, maize and potatoes is called the Short Rainy Season (SRS). However, other crops are also cultivated, but in small proportions. Season B, from February to July with beans as main crop associated with sweet potato and cassava is referred to as Long Rainy Season (LRS). Season C, an additional period of cropping in the marshland from May to December with maize, beans, sweet potato and potato as important crops (ISTEEBU, 2015). The annual mean temperature is around 20 °C and the total annual rainfall ranges between 1300 - 1600 mm.

In some parts of Gitega Province, however, rainfall amounts and distribution can be quite variable (Figure 1.10).

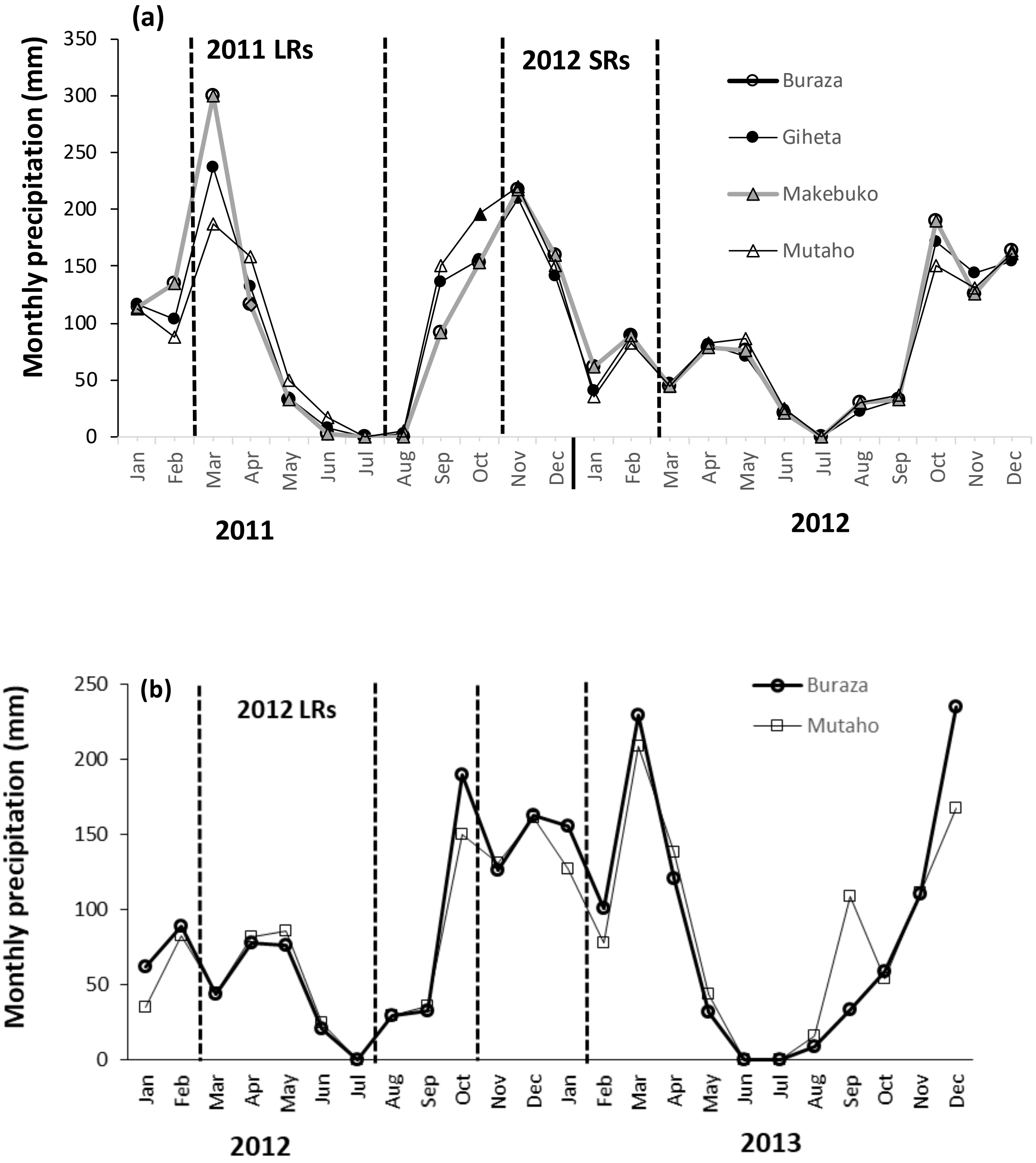


Figure 1.10. Rainfall distributions for (a) Buraza, Makebuko and Mutaho districts for the seasons of 2011 LRs to 2012 SRs-periods in which experiments under farmer practices (STEP I) were carried out and (b) Buraza and Mutaho for the seasons of 2012 LRs to 2013 LRs-periods in which experiments were conducted on the use of improved varieties, inorganic and organic fertilizers. The rainfall data were collected from the database of the CGIAR Research Program for Climate Change, Agriculture and Food Security (CCAFS), based in Cali, Colombia

At overall, the length of the growing periods in probabilities is reported by FAO as follows (Figure 1.11)

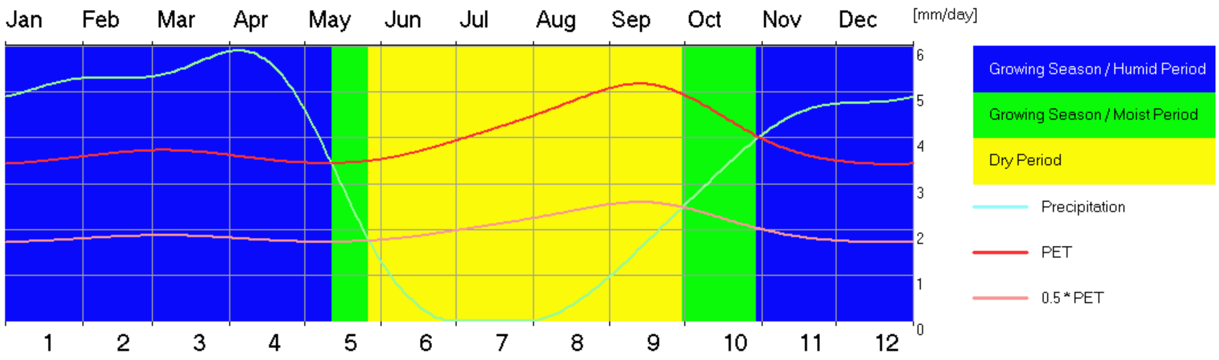


Figure 1.11. The length of the growing periods in Gitega province, Burundi. PET: Evapotranspiration; 0.5*PET: Growing season if Precipitation/PET > 0.5.

1.2.3. Geology and soils

Gitega is characterized by a wide range of soils. However, the dominant soil groups include Acrisols, Ferralsols and Nitisols (Sanchez et al., 1997; Batjes, 2011; Bationo et al., 2012).

According to the WRB (2015), Acrisols are strongly weathered acid soils with low activity clays with low base saturation in their argic horizon. These soils are found in areas with extensive weathering as well as areas experiencing tropical climates. Due to their highly weathered and low base status, Acrisols are often low in soil fertility and require complete fertilization and liming for any economical agricultural production. This kind of soils is common in most parts of Gitega and farming with low inputs can achieve little in crop production. Rotation of annual crops with improved pasture maintains the organic matter content (WRB, 2015) which may add charge to these soils, provided pH is raised.

Ferralsols are likewise dominated by low activity clays, mainly kaolinite and a large content of sesquioxides from Fe and Al. Ferralsols represent the common, deeply weathered, red or yellow soils of the humid tropics (WRB, 2015). These soils are poor with low amounts of weatherable minerals and as such, in low input systems, Ferralsols can become easily depleted of plant nutrients in the root zone. Ferralsols form a large part of the soils in Gitega in turn contributing to the low agricultural productivity in the region. However, most Ferralsols have good physical properties. Great soil depth, good permeability and stable microstructure make Ferralsols less susceptible to erosion than most other intensively weathered tropical soils. Most Ferralsols are friable and easy to work. They are well drained but may at times be sensitive to drought because of their limited available water storage capacity. Liming combats Al toxicity and raises the effective CEC. On the other hand, it lowers the anion exchange capacity, which may lead to collapse of microstructural elements and slaking at the soil surface. Therefore, frequent small doses of lime or basic slag are preferable to one massive application; 0.5 – 2 tons ha^{-1} of lime or dolomite are normally enough to supply Ca as a nutrient and to buffer the low soil pH of many Ferralsols. Unfortunately, liming is a rare practice in Gitega and as such agricultural productivity is greatly constrained. Fertilizer choice and the mode and timing of application determine to a large extent the success of agriculture on Ferralsols (WRB, 2015).

As for the third important group the Nitisols, these are the most productive soils in the humid tropics (WRB, 2015). Nitisols are deep, well-drained, red tropical soils with a large P-sorption capacity, stable micro structure that permits deep rooting and are thus quite resistant to erosion. Further, Nitisols have large amounts of weatherable minerals and appreciable amounts of organic matter. Management of these soils would require efforts to decrease their large P-fixing capacities. With regard to agriculture, most of these soils have good physical properties, but as a result of long-term leaching and nutrient exports without replenishment, their chemical properties are poor and nutrient stocks are small. The soil map of Burundi in Plate 1.1 gives the major soil types of the country.

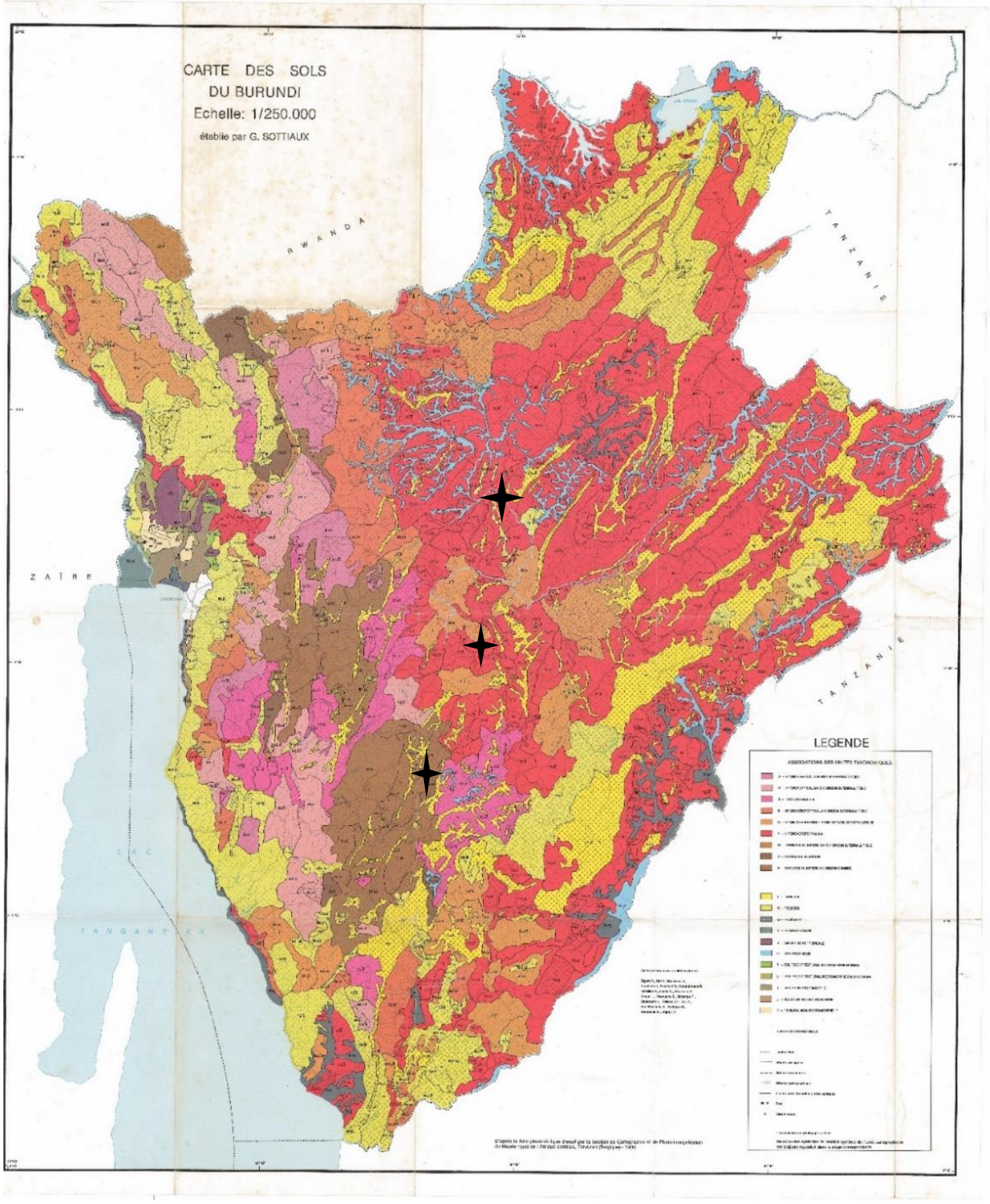
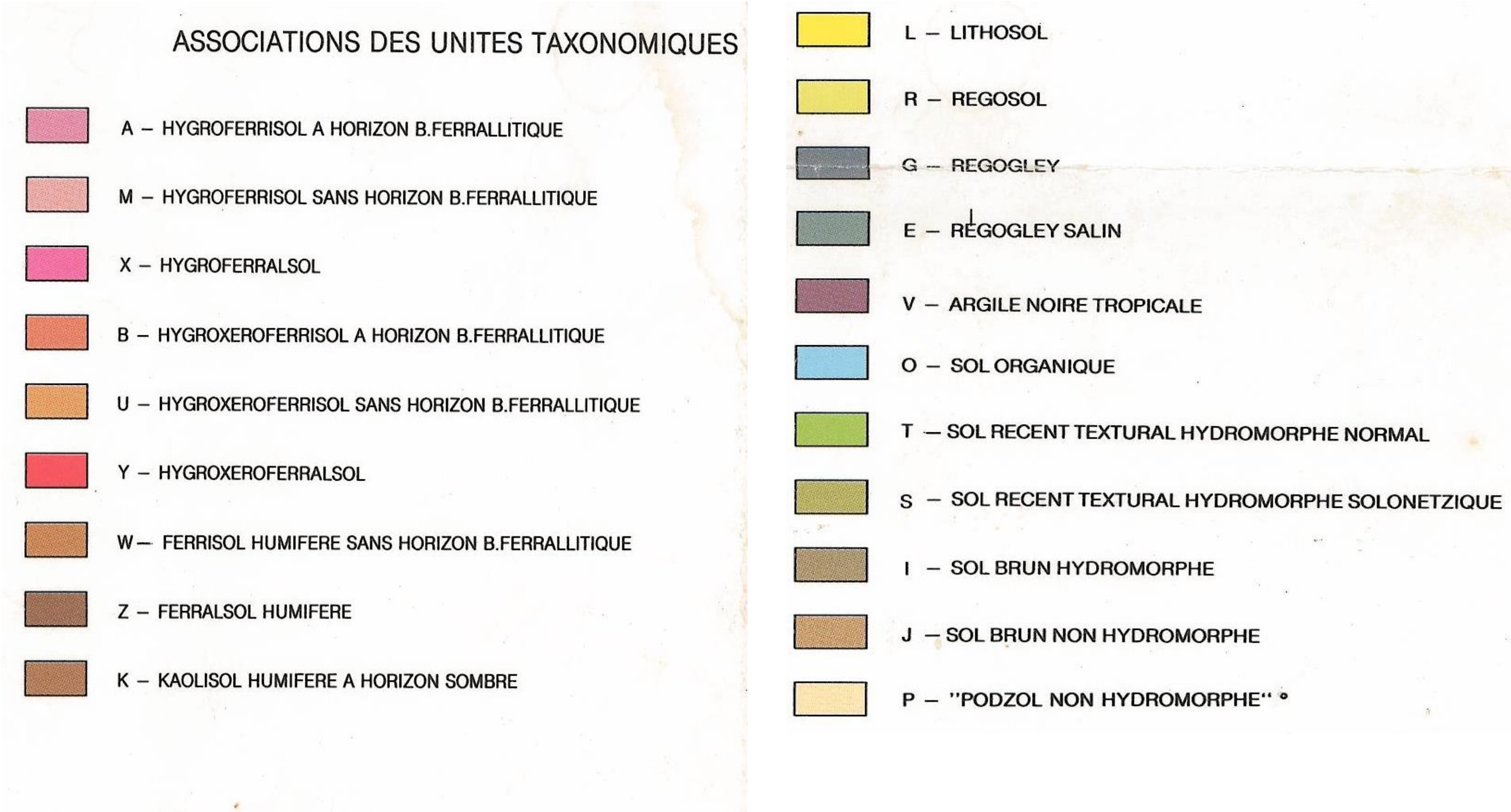


Plate 1.1. The soil map of Burundi at a scale of 1/250,000 (Sottiaux et al., 1988). Stars show the districts of the study area



ASSOCIATIONS DES UNITES TAXONOMIQUES

🟪 A – HYGROFERRISOL A HORIZON B.FERRALLITIQUE
🟪 M – HYGROFERRISOL SANS HORIZON B.FERRALLITIQUE
🟪 X – HYGROFERRALSOL
🟧 B – HYGROXEROFERRISOL A HORIZON B.FERRALLITIQUE
🟧 U – HYGROXEROFERRISOL SANS HORIZON B.FERRALLITIQUE
🟥 Y – HYGROXEROFERRALSOL
🟫 W – FERRISOL HUMIFERE SANS HORIZON B.FERRALLITIQUE
🟫 Z – FERRALSOL HUMIFERE
🟫 K – KAOLISOL HUMIFERE A HORIZON SOMBRE
🟨 L – LITHOSOL
🟨 R – REGOSOL
⬛ G – REGOGLEY
⬛ E – REGOGLEY SALIN
🟪 V – ARGILE NOIRE TROPICALE
🟦 O – SOL ORGANIQUE
🟩 T – SOL RECENT TEXTURAL HYDROMORPHE NORMAL
🟩 S – SOL RECENT TEXTURAL HYDROMORPHE SOLONETZIQUE
🟫 I – SOL BRUN HYDROMORPHE
🟫 J – SOL BRUN NON HYDROMORPHE
⬜ P – "PODZOL NON HYDROMORPHE" °

Plate 1.2. Legend of the soil map of Burundi (Plate 1.1)

1.2.4. Production systems

Gitega is characterized by poverty with an average of 68.2 % of the population living on less than a dollar a day (https://knoema.com/atlas/Burundi/Gitega?origin=knoema.es). The high poverty levels are partly attributed to low productivity of the agricultural sector, which is the major source of livelihoods for most households (IFAD, 2012). The farm sizes are too small, averaging 0.5 ha (Ouma et al., 2010). However, despite these confounding factors, 90 % of the arable land in this region is considered to be of high agricultural potential due to its favorable climatic conditions (Baramburiye, 2010). The farming systems in Gitega are mostly rain-fed and consist of subsistence mixed crop-livestock systems with perennial crops such as banana and coffee, complemented by sweet potato, cassava, beans and cereals (Dixon et al., 2001*)*. According to data obtained from FAOSTAT (2014), bananas and cassava are the top two crops in terms of productivity. Figure 1.12 reveals the average yields, in kilogram dry matter per hectare and per year, which are relatively low compared to intensive production systems. Farming is characterized by the use of rudimentary tools and the use of family labor. The produce serves mainly for self-consumption and the surplus is traded on the market (Ouma et al., 2010). However, the main trends are diminishing farm size, declining soil fertility, increasing poverty and hunger. In response, farmers work the land more intensively, but returns to labor are low (Dixon et al., 2001).

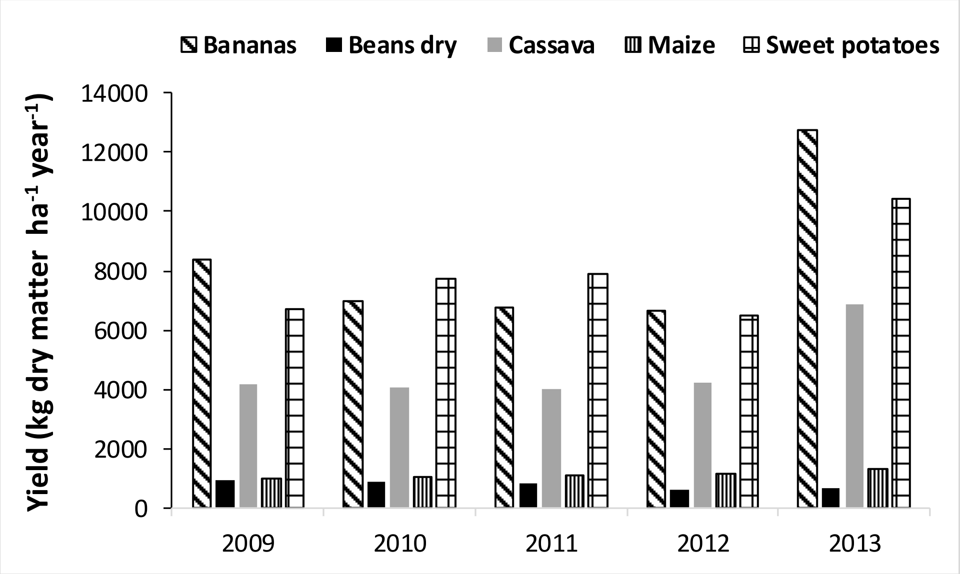


Figure 1.12. Average yields (kg dry matter ha^{-1} year^{-1}) of the most important food and agricultural commodities (2009-2013). *Source:* *http://www.fao.org/faostat/en/#data/QC*. *Accessed 4th April 2018*

Food crops are mainly for household consumption and represent 90 % of the cultivated area. They contribute 46 % of the GDP. In terms of volume of production, banana is the crop that yields the highest production per unit area compared to other food crops: 11960 kg ha^{-1} compared to 5550 to 6670 kg ha^{-1} for tubers, 1700 to 1870 kg ha^{-1} for cereals and about 850 kg ha^{-1} for grain legumes (Ministry of Agriculture and Livestock, 2011).

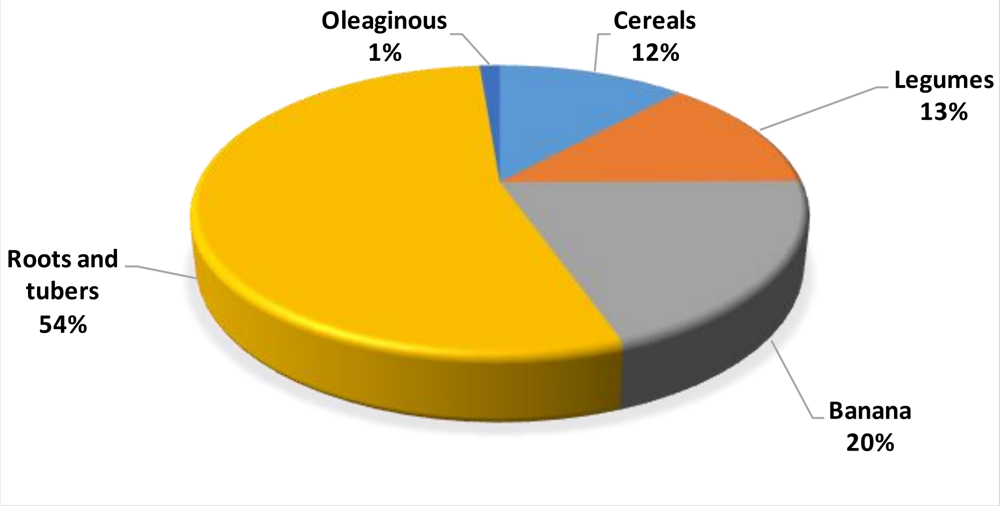


Figure 1.13. Proportion of banana in food production in Burundi (ENAB 2012-2013)

As for overall production, banana is the main cropping system crop with an annual production of around 2,235,700 tons $year^{-1}$ (in 2013), representing between 42 and 45% of the country's total food production. In macroeconomic terms, it is the main source of revenue for local governments through tax revenues on local beverages and food sold on the markets. These taxes were estimated at about 2.5 billion per year at the national level (Ministry of Agriculture and Livestock, 2011).

Cash crops include (coffee, tea, cotton, oil palm, sugarcane, tobacco) and stand for 10 % of cultivated land. They supply 4 % of GDP and provide 90 % of export earnings. The coffee alone provides about 80 %, the remaining10 % is tea (Baramburiye, 2010).

Maize *(Zea mays L.)* is one of the most important sources of food and income for farmers in the highlands of Burundi, and often the preferred crop for fertilizer use. Burundi’s maize seed sector has not been developed so far and farmers plant both local varieties and hybrids. Local landraces are poor yielding but have the greater advantage of being suited to the local conditions, are disease and pest resistant in addition to being more palatable to local tastes (Baramburiye, 2010). About ten new varieties have been developed and released in the country between 1980 and 2009 by

ISABU. The main varieties planted in Gitega are the ZM series mostly suited for the high mid-altitude zones.

Common bean (*Phaseolus vulgaris* L.) is a very important staple crop in the Great Lakes region of Central Africa because of its nutritional value, and wide utilization at the household level as well as in industry. It is the first source of protein and micronutrients, particularly iron and zinc, for many family households. In addition, it is a major source of revenue for the smallholder farmers who are the bulk of the poor population. The average per capita consumption of beans in Burundi of 60 kg year^{-1} is among the largest in the world (USAID, 2012). The report by FAOSTAT(2014) indicates that dry beans are part of the most produced crops in Burundi after banana, sweet potato, cassava and maize (Figure 1.11). However, the growth of the bean subsector faces several production challenges. These include, in order of importance, unpredictable weather, pests and diseases, the high cost of new improved varieties, lack of capital, and lack of adequate land (Ouma et al., 2010).

Burundi has a large potential to increase bean production but the potential has not yet been fully exploited despite the crop being planted by farmers for decades. National production is still relatively small as indicated in Figure 1.11 although its wide ecological adaptation means that it can be produced throughout the country. The reasons for the underutilized potential of the dry beans are the lack of a reliable market and limited knowledge of farmers on processing and other management practices (Ouma et al., 2010).

1.2.5. Constraints to agricultural productivity in maize-based cropping systems

Most parts of Gitega Province are considered to be of high agricultural potential. However, agricultural productivity is constrained by various factors, ranging from socio-economic to soil fertility. A few of these factors are detailed below.

Socio-economic constraints: Governance, policy and security levels (Vanlauwe et al., 2015) constrain agricultural productivity in the region. Similarly, population increase and subsequent pressure on the land has led to the exhaustion of nutrients as land is continuously cultivated with minimal nutrient application. Similarly, poorer farmers are constrained by labor, because in the quest to earn some of-farm income, they sell or lease their labor to wealthier farms in exchange of food and low wages (Ochieng et al., 2014). Further, rural-urban migration of the young (Sanginga and Woomer, 2009) in Burundi has been documented (IFAD, 2012) to negatively impact on the labor thus affecting productivity. These affect the capacity within the poorer farms to purchase soil fertility inputs and consequently produce low yields.

Agricultural productivity in this region is also greatly affected by the poor road infrastructure which curtails movement of inputs (fertilizer, seed, pesticides, etc.) and outputs (farm produce). Commercialization, improved market access and ability and risk to invest are critical for improving rural farm incomes and household food security. These are due to biophysical constraints (mainly rainfall) and depletion of soil fertility. Smallholder commercialization is highly influenced by factors of production as well as transaction costs (Vanlauwe et al., 2015).

Efforts to improve market infrastructure make it easier for farmers to gain access to inputs which increase the level of commercialization and productivity of crop enterprises (Shilpi and Umali-Deininger, 2008). Many smallholder farmers reside in remote agricultural areas with poor transport and market infrastructure which contributes further to the larger transaction costs. The civil conflict in Burundi destroyed the basic transport infrastructure that affects the transfer of commodities from farms to destination markets. In addition, the lack of a reliable market information system often leads to the exploitation of farmers by middlemen or brokers discouraging farmers' involvement in crop marketing.

Climatic conditions: Most agricultural production in Gitega is rain fed. Gitega is reported to have the most reliable rainfall distribution in most parts. Delay in the start of the rainy seasons and more specifically of the long rains affects crop productivity (TI and EAGC, 2009). Overdependence on rainfall has also been thought as one of the factors that negatively influence crop productivity.

Soil fertility**:** Low soil fertility is recognized as the major cause of low food crop production in SSA (Sanchez, 2002). Continuous cropping with small rates of fertilizer exacerbates an already bad situation due to nutrient mining. Traditional ways to replenish nutrient exports by using fertilizers are constrained by their limited accessibility to smallholders. In addition, the lack of up-to-date and site-specific fertilizer recommendations limits their efficiency for crop production.

1.3. Context and objectives of the study and thesis outline

1.3.1. Context of ISFM

The Consortium for Improving Agriculture-based Livelihoods in Central Africa (CIALCA), composed of international and national research and development partners, aims at reversing above trends and restoring soil productivity through adoption of Integrated Soil Fertility Management (ISFM) options.

ISFM is defined as "*a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs and improved germplasm, combined with the knowledge of how to adapt these practices to local conditions, aimed at maximizing agronomic use efficiency of the applied nutrients and improving crop productivity*" (Vanlauwe et al., 2010a). The goal of ISFM is to optimize crop productivity through maximizing of positive interactions that occur when fertilizer inputs - both mineral and organic - and improved germplasm, along the required associated knowledge, are integrated by smallholder farmers.

According to Vanlauwe et al. (2011), agronomic use efficiency comprises 'capture efficiency' and 'conversion efficiency'. 'Capture efficiency' is more related to the nutrients taken up and is in part regulated by an optimal supply of otherwise non-limiting nutrients and plant requirements for soil moisture, aeration and physical support. The 'conversion efficiency' is in part regulated by genotypic properties including those that determine biomass accumulation and harvest indices. It is also important to note that maximizing agronomic efficiency leads to maximal economic returns to inputs used, since both indicators are linearly related to specific input and output prices. Indeed, increasing productivity and profitability of an agricultural system in SSA is highly appreciable especially in smallholder farming systems. This is measured by farmers in terms of immediate quantity of outputs from their farms and not in terms of the benefits they obtain through soil fertility improvement in the long run. Considering the complexity of the agricultural systems in SSA, probably the most important component of ISFM would be to use the ISFM knowledge in accordance with the local conditions.

The ISFM steps as described by Vanlauwe et al. (2010), and visualizing a scenario of increasing complexity going from farmer's practice towards full implementation of ISFM, include the use of fertilizer and improved germplasm; combined application of organic and mineral inputs and adaptation to local conditions (Figure 1.14).

1.3.1.1. Fertilizer and improved germplasm

In terms of response to fertilizer, two soil types can be distinguished: (i) "responsive soils" that show acceptable responses to fertilizer (Path A, Figure 1.14) and (ii) "less-responsive soils" that are retrogressed or degraded and show little or no response to fertilizer (Path B, Figure 1.14). Investment in overall soil fertility rehabilitation through, for example, organic resource management will be required before yields will increase on non-responsive soils (Path C, Figure. 1.14).

A prerequisite to an efficient improvement of productivity through an enhanced supply of nutrients consists in the use of improved germplasm that is responsive to fertilizer and disease-resistant, use of the appropriate fertilizer formulation, rates and timely application. Farmers' access to these inputs and associated information on best practices is also of crucial importance. Therefore, the application of fertilizer to improved germplasm on responsive soils will boost crop yield and improve the profitability of fertilizer relative to current farmer's practice in SSA, which is characterized by traditional varieties receiving little nutrient inputs that are often inappropriately managed.

1.3.1.2. Combined application of organic and mineral inputs

Organic matter (OM) is a source of nutrients and trace elements and also an important contributor to the cation exchange capacity (CEC). The soil carbon stock accounts for a major part of the organic matter and is a good proxy indicative for the fertility of weathered tropical soils (Smaling and Dixon, 2006).

Farmers apply organic matter as a part of improving soil nutrient practices. Common farmer-available organic resources are: crop residues, green manure, animal manure and compost. Other practices consist of natural fallowing, improved fallows and relay or intercropping of legumes (and dual purpose legumes) (Place et al., 2003). The timing of applying plant residues and manure has to be carefully planned in the tropics because of its rapid decomposition in moist and warm climates.

With regard to the type of fertilizer, organic nutrients are commonly more affordable to smallholder farmers than mineral fertilizers. Therefore, it has been advocated that the combined application of mineral and organic inputs in sufficient quantities is a well-grounded practice for smallholder farming in the tropics, because neither of the two inputs is usually fully available and both inputs are needed in the long-term to sustain soil fertility and crop production (Vanlauwe et al., 2012).

Both mineral fertilizer and organic resources have benefits and disadvantages that are complementary, making it important to combine both sources of nutrients. Mineral fertilizers have high nutrient contents, but their rapid dissolution render them subject to losses through leaching and sorption. OM, however, has a slower release of nutrients and also regulates soil biological processes and fulfils a soil physical role as well. Mineral inputs are often too expensive for smallholders to be applied at optimal rates and organic inputs applied at rates that are feasible for small-scale farmers seldom release sufficient nutrients for optimum crop yield (Chianu et al., 2012).

In terms of profitability, positive returns are often found for mineral fertilizer inputs and for integrated mineral-organic systems (Place et al., 2003). However, to obtain the optimal uptake of fertilizer by the germplasm, one should take into account the type of soil, as explained in the third ISFM component.

1.3.1.3. Adaptation to local conditions

Farming systems are highly variable at different scales and the challenge is adjusting management for site-specific conditions. Adding nutrient inputs may result in highly variable crop responses across spatially heterogeneous farms. In smallholder farms as small as 0.5 ha, crop yields will vary enormously from poorly responsive fertile fields, to responsive or poorly responsive infertile fields. Farmers recognize the existence of soil fertility gradients. They tend to plant crops earlier and more densely, weed earlier and more frequently and apply nutrients in the most responsive fields of the farm, ensuring their most efficient use (Tittonell and Giller, 2013).

Besides the use of fertilizer and/or organic inputs, other accompanying measures such as application of lime on acid soils, water harvesting techniques on soils susceptible to crusting, or soil erosion control in hillsides were also included in the adaptation to local conditions. Again, for poor, non-responsive soils, investment in overall soil fertility rehabilitation will be required before profitability of DAP fertilizer will be enhanced (Path C, Figure. 1.14).

To conclude, the combinations of different ISFM components have resulted in substantial added benefits through higher resource-use efficiencies. However, the majority of research on ISFM has taken place on maize- and cassava- based cropping systems in the African Great Lakes region (Pypers et al., 2011; Vanlauwe et al., 2012; Vanlauwe et al., 2015). Yet, much organic and mineral fertilizer use by smallholders is directed towards higher value crops for which the effects of organics and ISFM remain under-researched. Also, responses to ISFM interventions were variable, highlighting the need for local adaptation and identification of interventions best suited for a particular production environment and household resource endowment. Unfortunately, the adaptation to local conditions is not part of our research due to logistic means. Some boundary conditions such as responsiveness of the land (soil type), time of planting, plant configuration, crop rotation system, weed management and history were also not included in the scheme of ISFM because the objective of this research was mainly to validate the ISFM paradigm on bean-maize-based systems thereby proving the concept of stepwise maximization of the profitability of DAP fertilizer but they cannot be ruled out. Figure 1.14 gives a schematic presentation of the ISFM concept.

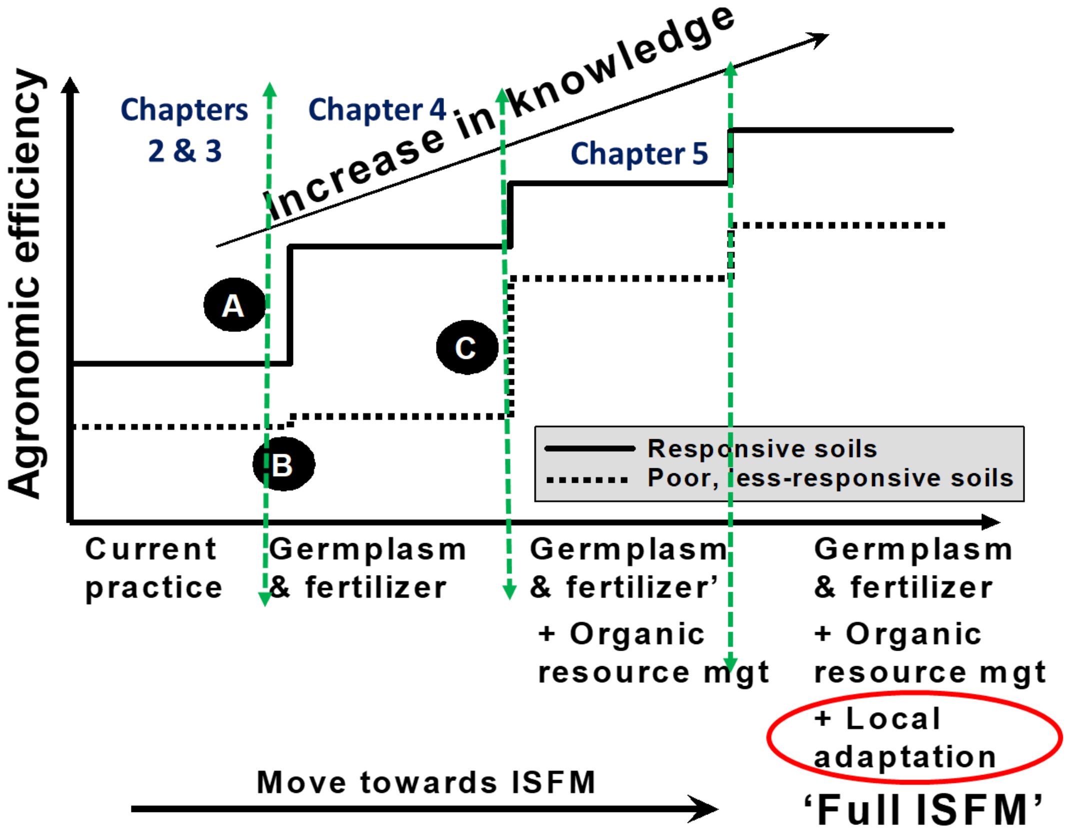


Figure 1.14. A schematic presentation of ISFM components culminating in complete ISFM towards the right side of the graph. Path A represents soils that show acceptable responses to fertilizer and are referred to as "responsive soils"; B represents soils that show minimal or no response to fertilizer due to other constraints besides the nutrients contained in the added fertilizer and are classified as "poor, less responsive soils". These soils would improve response (Path C) if these other constraints were removed (Vanlauwe et al., 2010a) . Green arrows show ISFM steps studied while red circle indicates that adaptation to local conditions is not part of our study due to logistic means.

The current research is conducted in three action sites (Buraza, Makebuko and Mutaho districts) of CIALCA in Gitega Province. This research evaluates ISFM options for maize-based farming systems, with a specific focus on understanding and enhancing the profitability of mineral and organic inputs used as affected by their management, the target crops, and soil conditions. This information will be summarized in a decision support framework for site-specific recommendations within these farming systems. This research responds to a real need in the Sub-Sahara-African-context where fertilizer recommendations have been shown repeatedly to be inadequate and beyond farmers reach.

I.3.2. Objectives and hypotheses

I.3.2.1. Objectives

The main objective of this study is to validate the application of the ISFM concept on bean-maize-based farming systems in Gitega Province, Central Burundi; thereby confirming the concept of stepwise maximization of the profitability of DAP fertilizer, as hypothesized in figure 1.15.

The research will meet the following specific objectives:

1. To document the current practices of the smallholder farmers related to fertilizer use in bean and maize production;
2. To diagnose nutrient deficiencies if any in maize in low input systems using the Compositional Nutrient Diagnosis (CND) approach, look into the effects of specific nutrient management interventions on crop productivity, and investigate how the variation in response is related to the biophysical conditions across the target intervention areas;
3. To evaluate the profitability of diammonium phosphate (DAP, 18-46-0) use on local and improved varieties of climbing bean and maize in smallholder farms of Buraza district in Gitega province, Central Burundi;
4. To evaluate effects of addition of organic inputs (manure and/or biomass generated by the use of improved bean varieties) on the profitability of DAP fertilizer in bean-maize farming systems.

I.3.2.2. Hypotheses

1. Current fertilizer effect is small due to poor varietal characteristics, poor management, and lack of appropriate accompanying measures;

2. Application of small rates of DAP fertilizer leads to nutrient mining and consequent nutrient deficiency in the plants;
3. The use of improved varieties and improved fertilizer management can substantially increase profitability of fertilizer, but important variability in response to fertilizer exists, and an important proportion of fields requires additional measures to increase the profitability of fertilizer;
4. Combining fertilizer and improved varieties with the use of organic inputs can further increase the profitability of fertilizer, but is neither essential nor sufficient in all fields. In non-responsive soils, other measures are required.

I.3.3. Thesis outline

This thesis is divided into 2 parts following the conceptual framework of ISFM (Vanlauwe et al., 2010a).

Part I covers chapters 1, 2 and 3. **Chapter 1** of the thesis gives a general introduction of the study region detailing the agricultural potential and the constraints to agricultural productivity in the region. This section also outlines the context of the study, hypotheses and the objectives upon which the study was based. **Chapter 2** holds the results from a preliminary survey prior to the experimental setup to document the current practices of the smallholder's farmers in bean-maize based systems. **Chapter 3** assesses (i) the applicability of the Compositional Nutrient Diagnosis (CND) approach under smallholder farming practices, and (ii) identifies the most limiting nutrient deficiencies for maize cropping in the Central highlands of Burundi. Some conclusions and recommendations from chapters 2 and 3 form the starting point of **Part II** of the thesis**.**

Part II comprises **chapters 4** and **5** and deals with the use of improved varieties and both organic and inorganic fertilizers in a way of increasing the yields of bean-maize based systems and the consequent economic returns. **Chapter 4** evaluates the yields and the profitability of DAP fertilizer use on the improved bean and maize varieties at a recommended rate (100 kg ha^{-1}). In **Chapter 5**, we compare rotational effects of bush and climbing beans and assess the profitability of DAP fertilizer use in bean-maize rotations. This will evaluate the benefits of rotational effects for bean-maize based systems.

Finally, in **Chapter 6**, the general conclusions of this study and research perspectives are presented. Figure 1.15 gives a schematic representation of the thesis structure.

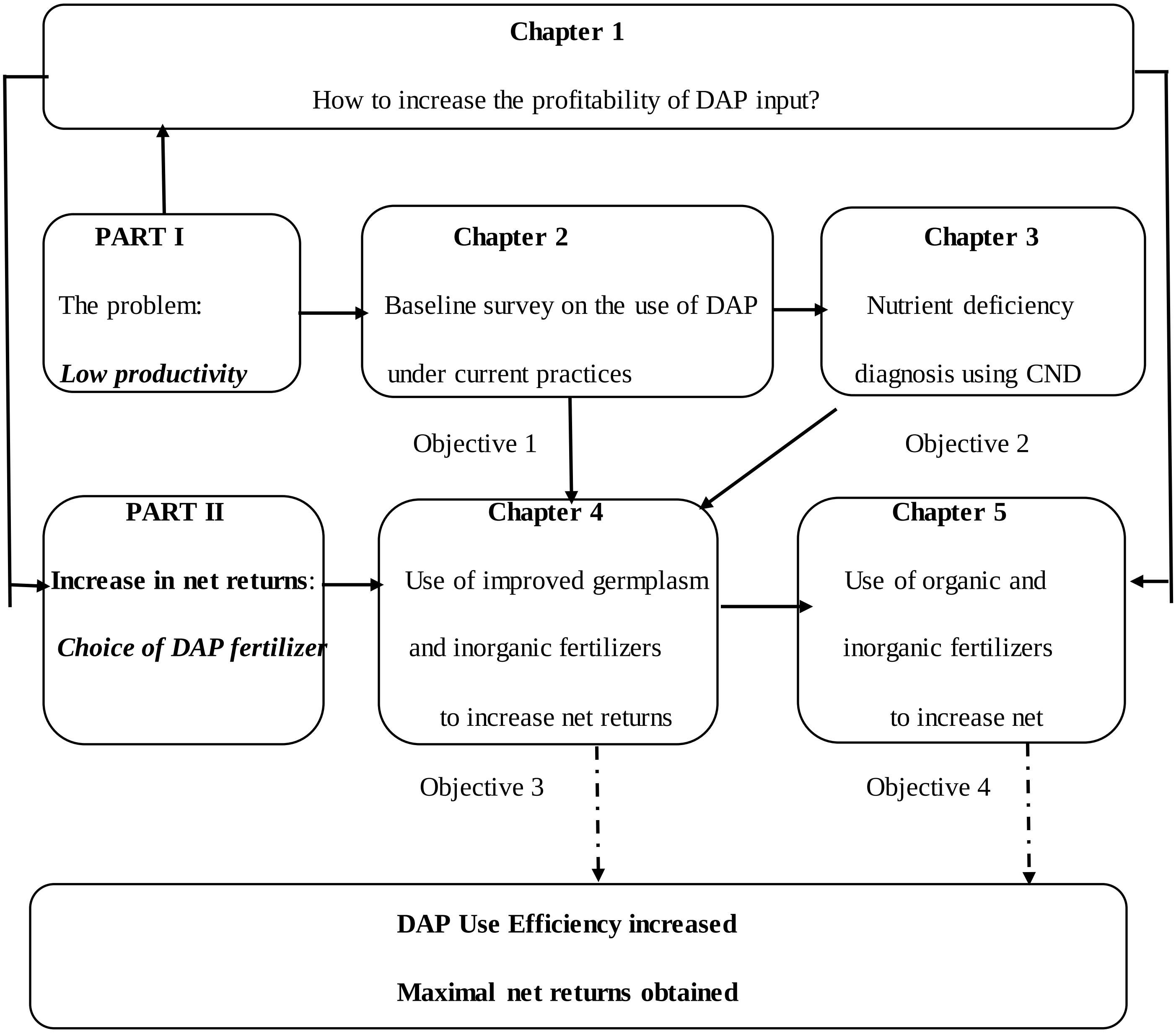


Figure 1.15. A schematic representation of the thesis structure

Chapter 2

Understanding local smallholder farmers' knowledge on the use of diammonium phosphate in bean-maize-based systems

2.1. Introduction

Traditional farming methods have led to severe nutrient depletion, low crop yields, and poverty, leaving many farm families disappointed (Chianu et al., 2012). The situation is aggravated by inadequate supplies of organic and inorganic fertilizers and hence a low use of fertilizers by farmers, in turn causing nutrient mining and low nutrient use efficiency. Weak agricultural extension as a result of lack of policy and institutional support leads to inappropriate fertilizer recommendations to deal with nutrient deficiencies. More recent constraints caused by climate change do not receive proper attention and together with this poor and declining soil fertility cropping systems, food security, nutrition, incomes, and livelihood resilience are threatened (Chianu et al., 2012).

The fertilizer shortage is mainly attributable to high transaction costs and inefficiencies throughout the fertilizer production–consumption chain (Jayne et al., 2003). Untimely availability and low quality also constitute a major constraint to fertilizer use. While most of the African countries have continued to import fertilizers, correct formulations to address the major limiting nutrients for specific areas and targeted knowledge on how best to apply them is often absent. The use of the correct type of fertilizer is of paramount importance for an efficient utilization as nutrients supplied should match crop requirements. Unfortunately, very often the small amount of fertilizer available in sub-Saharan Africa (SSA) is not the right type required by various crops. Sometimes, this mismatch between crop requirements and fertilizer formulations derives from an absence of the essential agronomic information allowing manufacturers and distributors to establish appropriate nutrient compositions for their products and provide relevant advice (Sanginga and Woomer, 2009). Smallholder farmers in Africa manage bean-maize cropping systems in diverse landscapes and agroecosystems but continue to register low yields (Nduwumuremyi et al., 2013). Low productivity of beans in bean-maize systems is due to many factors including low soil fertility (Nekesa et al., 1999), limited access to improved seed varieties and fertilizers, pests (Ogenga-

Latigo et al., 1993; Ampofo and Massomo, 1998), and diseases (Opio-Odongo et al., 1993), and undeveloped value chains (Ochieng et al., 2014).

Degradation of soil quality (physical and chemical) and inherent problems of weathered soils (nutrient deficiencies, low pH, toxicities) (Kumwenda et al., 1996; Folmer et al., 1998; Khomo et al., 2011) limit bean productivity across the tropics on smallholder resource-poor farms (Laker, 2005). Smallholder farmers face significant constraints to increase yields such as limited knowledge of how to diagnose problems that limit productivity; a lack of a clear understanding of interrelationships among technologies and management practices important for enhancing farm system productivity, stability, and resilience; and a lack of reliable and affordable access to relevant information, resources and technologies.

There have been some recent initiatives and innovations that provide options for reversing the vicious situation above. These include farmer adoption of proven technologies such as integrated soil fertility management, efficient improved germplasm and increased application of agro minerals and N fertilizers (Sanchez et al., 1997; Sanginga and Woomer, 2009; Chianu et al., 2012; Vanlauwe et al., 2015). Available innovations also exist in the areas of input–output market development, biological nitrogen fixation, the use of nutrient budgets for efficiency and to inform nutrient management policy, reintroduction of fertilizer subsidy, regulated repackaging of fertilizers into affordable sizes, and soil testing for efficient fertilizer recommendations. However, these innovations need a policy and institutional support to yield the required effects.

In Burundi, common beans (*Phaseolus vulgaris* L.) are grown for household consumption and income. Common beans serve multiple important roles in their cropping systems, food security, nutrition, incomes and livelihood resilience. As a significant source of protein, beans can help address poor nutrition, a major health problem among poor rural households. However, extension systems are weak. Agriculture is predominantly low input/low output, with production increases driven primarily by larger areas planted rather than higher productivity. Most households do not belong to any rural institution, limiting access to crop technologies, inputs and credit to informal systems (Cachomba and Menale, 2012). Grain legume research programs have identified and developed improved technologies and management practices that can substantially increase yields. However, adoption of these practices, particularly those addressing soil fertility remained modest for beans.

This study therefore aimed at investigating local farmers' knowledge on fertilizer use in Buraza and Makebuko districts of Gitega province, Central Highlands of Burundi. Specifically, we set out (1) to document local farmers' knowledge on the use of diammonium phosphate (DAP, 18-46-0) in bean and maize production; (2) to assess the effect of DAP in the small producer system and (3) to identify those factors explaining the ability of farmers to use the fertilizer to their best advantage.

2.2. Material and methods

2.2.1. Study area

The study was conducted over two seasons: a first season with maize starting from October 2011 to January 2012 and a second season with beans from February to June 2012 in Buraza (29˚ 53'50" E, 3˚ 45' 08" S) and Makebuko (30˚ 00'04" E, 3˚ 45'08" S) districts of Gitega Province in Central Burundi. The latter district was closer (Table 1.1, pge 13) to urban Gitega center while Buraza was away (55 km) from Gitega town. The climate in the study area is humid-tropical with bimodal rainfall patterns. The annual mean temperature varies between 15 - 20 °C (ISTEEBU, 2014) and the total annual rainfall ranges between 1300 - 1400 mm. Our study was conducted in the short rains (SR) with a total rainfall ranging from 400 to 450 mm for maize and during the long rains (LR) for beans with a total rainfall ranging from 600 to 650 mm (Table 2.1). The available rainfall data are estimates from the Tropical Rainfall Measuring Mission (TRMM) by National Aeronautics and Space Administration (NASA), with a resolution of 0.25 x 0.25 degrees.

Table 2.1. Location and main characteristics of the districts used for assessments of farmers' knowledge on DAP fertilizer use in Gitega Province (Burundi)

Variable	**Unit**	**District**	
		Buraza	***Makebuko***
Biophysical characteristics			
Altitude (MASL)	m	1701-1927	1670-1743
Annual mean temperature**	^{0}C	15-20	15-20
Topography			
Dominant soil group (WRB, 2015)		Acrisols	Nitisols
Socio-economic indicators			
Average farm size*	ha	0.5	0.5
Population density**	# km^{-2}	299	350
Family size*	#	6	6
Distance to Gitega main market**	km	55	24

Source: Author, * Ouma et al., (2010) and ** ISTEEBU (2014)

2.2.2. Household survey and field trials under bean and maize production

A combination of household survey techniques: baseline surveys and monthly researcher visits throughout the season were undertaken for beans and maize by a multidisciplinary team of researchers and technicians. Each district had a technician who was in charge of recording the agronomic footprint without interfering in overall field management. Prior to field selection, we had a meeting with farmers per district in order to inform them on what we are going to do and what we expect from them. We also visited their fields with a sheet per field describing its history. From the latter, we were able to select fields that we want and inform the selected farmers before the beginning of each season. A total of 71 and 131 farmers were randomly selected for beans and maize grown in LRs and SRs, respectively. A farmer was a smallholder farmer practicing mainly agriculture for subsistence with a very limited amount of resources towards various important livelihood goals and socio-cultural functions. At each step of growing season from field selection, land preparation up to the harvest, the technician was collecting data. He was also organizing meetings with farmers to get to know their cropping calendar so that he could be on time for collecting data and I was visiting all fields at least once in a month.

After pre-testing and revising a questionnaire, baseline surveys were conducted with sampled farmers one month before the onset of each season. Each selected farm had only beans or maize in the tested season. Most of baseline survey questions were “open”, in order not to limit farmers’ responses. The questionnaire of the survey was to provide a general overview on farmers’ fertilizer use behaviors in farming activities. It encompasses households’ demographics, educational level, farmland and crop, farmers’ association membership and distance to the homestead. All the questions were focusing on documenting farmers’ knowledge on fertilizer use.

In a further step we were concerned about the fertility status of the selected fields for bean and maize crops. The fertility status was assessed before the trial installation and was based on composite soil samples taken from the 0 to 20 cm layer in each farmer’s field. Soil samples were collected at random following “W” pattern per field. Composite soil samples were taken at eight locations in each farmer’s field, thoroughly mixed, then air-dried and sieved over a 2 mm screen before being shipped to the International Center for Tropical Agriculture (CIAT) in Nairobi for analysis.

Further interviews related to the observations of the bean and maize growth up to the harvest were held monthly by an agronomist and technicians. Bean and maize crops were grown with different farmers on different fields and seasons within Buraza and Makebuko districts. Farmers received 1 kg of DAP to be applied on maize and 1kg DAP for beans. In each farmer's field, two plots were demarcated to accommodate two treatments, a control without fertilizer, and a treatment with DAP, applied in the hill at different rates depending on the farmers' knowledge on the fertilizer use and mixed with soil before planting The DAP effect (kg ha^{-1}) defined as the yield difference between the fertilized and the control plots, was measured. Organic manure was applied as basal in the rows, then covered with soil and DAP was applied at the surface after mixing manure and surface soil, and then covered by soil to avoid volatilization before seeding. The time of planting: was set at the beginning of the planting season when farmers had adequate rain and soils are humid. All field operations during crop growth (plot demarcation and decision on planted area, DAP rates, planting time, spacing, etc.) were performed by farmers through participatory action research. Bean trials were set up in 45 farmers' fields for Buraza and 26 for Makebuko districts, respectively. Only fields with less than 10 % of slope were selected. Fields next to the scrubland, recently cleared and/or isolated fields were avoided. The trial establishment was performed at the onset of the season by the farmers. Overall, and as a consequence of this approach, variation was large both for plot size (ranging from 48 to 100 m^2) and hence for the DAP rates (ranging from 100 to 208 kg ha^{-1}). Also planting patterns were determined by the farmers and varied from 10 to 50 cm between planting lines, and from 5 to 30 cm between bean plants in all districts, leading to a range in planting density between 110,000 and 240,000 plants ha^{-1}. The local bean variety "*AMAKUTSA*" that was used in the trials is a climbing bean variety much appreciated by farmers for its large productivity (Ntukamazina et al., 2014). The growing period of this variety is 100 days on average.

The same approach was taken for a local maize variety grown on 89 farmers' fields for Buraza and 42 for Makebuko districts, respectively. The plot size was again determined by the farmers and ranged from 50 to 561 m^2. The rates of DAP applied in the fertilized plots hence ranged from 49 to 200 kg ha^{-1} in all districts. 1kg of Urea was supplied on maize as basal. The spacing varied from 50 to 100 cm between planting lines, and from 40 to 50 cm between maize plants, leading to a range in planting density between 20,000 and 70,000 plants ha^{-1}. The local maize variety "*ISEGA*" that was used in the trials is produced in Burundi, is early maturing (153 days) compared to other local maize varieties (182 days) and has a potential grain yield of 6.6 t ha^{-1}. The variety sells at a low price compared to the improved varieties (Manirakiza, 1999).

2.2.4. Statistical analyses

The survey data from the selected farmers growing beans and maize in Buraza and Makebuko districts were used for the analysis. Data of treatments with and without fertilizers were included in the assessment of documenting farmers' practices on the use of DAP fertilizer. However, most of the survey data collected from Mutaho district were erratic and could not be taken into account for analysis.

Data analysis started using descriptive statistics in Excel. Correlation analysis was used to evaluate the strength of a relationship between the rates of DAP applied by farmers and the farm and household characteristics. If the correlation was found, this can be either positive or negative depending on the numerical values found. We also used scatterplots that provide insights in the spread of the DAP effect and covariates which are soil parameters (pH, Olsen P and total N, total C and soil texture), delays in planting and DAP rates. They show how much DAP effect can be driven by one or more covariates and the correlation between the two variables can be set. If correlation exist, a linear regression analysis was runned in R software between DAP effect and its covariates to identify the coefficient of variance and the proportion (%) of explanatory of the covariate(s) in the model.

2.2.5. Economic analysis

A simple financial analysis was performed to assess the profitability of the treatments. The total cost (TC) of the operations included the costs for land preparation, seeds, application of DAP fertilizer input, staking for climbing bean, weeding, harvesting and post-harvest handling. Staking one hectare of climbing bean requires around 25,000 stakes, with a cost estimated at $ 350; corresponding to that used by Ruraduma et al. (2012). In this study, one stake was used for 4 plants (2 hills) and gave the highest yield (Ruraduma et al., 2012). Labor was valued at a wage of $ 0.17 per hour. One kg of fertilizer costed $ 0.80 and $ 0.53 for DAP and urea, respectively. Bean and maize grains were sold at 0.40 and 0.27 $ kg^{-1}, respectively. Opportunity cost for land were not included, as land was available in the area. This analysis was done for individual crops (bean and maize) and for crop type by using the farm gate prices of the inputs and outputs. Original prices were recorded in Burundese Francs (BIF) and converted to United States dollar ($). One $ was about 1500 BIF in February 2012.

Net benefits (NB), expressed in $ ha^{-1}, were calculated as the production value (PV) minus the total costs (TC). To assess profitability of fertilizer use, the value cost ratio (VCR, $ $$^{-1}$) and marginal rate of return (MRR, $ $$^{-1}$) were calculated as the ratio of the difference in PV between the treatment with fertilizer and the control, over the difference in TC, and the ratio of the difference in NB between the treatment with fertilizer and the control, over the difference in TC, respectively. To calculate the profitability for the crop type, PV, TC and NB were summed for the bean and subsequent maize crop, and then the VCR and MRR were calculated. The VCR should have a minimum of 2 (CIMMYT, 1988) for alternative practices to be profitable to farmers.

2.3. Results

2.3.1. Farmers' local knowledge on the use of diammonium phosphate in bean and maize production

2.3.1.1. Household and farming characteristics of the smallholder farmers of the study area

Selected household and farming characteristics of the smallholder farmers of Buraza and Makebuko districts are presented in Table 2.2 for both bean and maize crops.

Generally, male farmers are dominant in Buraza and Makebuko districts for bean and maize production. A large proportion of males (> 70 %) was observed in Makebuko compared to that of Buraza district. However, women farmers were more represented in Buraza compared to Makebuko district for both crops. Farmers involved in bean and maize production were relatively young (less than 60 years old) in both districts compared to the average. The dominant age category of these farmers was between 40 and 60 years for both crops. Large proportion of farmers growing beans were on average 46 and 50 years old in Buraza and Makebuko districts, respectively (Table 2.2). The trend was almost the same for farmers growing maize with an average age of 47 years old for both districts. Overall, most of the farmers (over 95 %) growing beans and maize did not have post primary education with more than 60 % of the farmers being illiterate in both districts. A large proportion of the surveyed farmers had farms that ranged between 0.1 to 0.5 hectares for beans (59 %) and from 1 to 1.5 hectares for maize (31 %). On average, 75 % of the farmers planted beans and maize closer to the homestead (less than 10 minutes) except for those (11.5 %) growing beans in Makebuko district. Maize as an easily stolen crop, tended to be grown more nearer the house than beans in both districts. The household members under the same roof were on average 5 in Buraza and 6 in Makebuko districts respectively for both beans and maize crops (Table 2.2).

Table 2.2. Household and farm characteristics of the surveyed farmers in the two districts of the study area

Variables	**Beans**			**Maize**		
	Buraza (n=45)	Makebuko (n=26)	Mean (%)	Buraza (n=89)	Makebuko (n=42)	Mean (%)
Gender (% respondents' farmers)						
Male	53	73	63	56	77	66.5
Female	47	27	37	44	23	33.5
Age (% respondents‘ farmers)						
20 – 40 years	42	23	32.5	31	36	33.5
40 – 60 years	45	54	49.5	55	48	51.5
> 60 years	13	23	18	14	16	15
Highest level of education (max. years spent)						
none	49	81	65	43	82	62.5
Primary school (6 years)	44	19	31.5	52	18	35
Secondary school (7 years)	7	0.0	3.5	5	0.0	2.5
Land area under crops (hectare/household) in 2012						
< 0.1	0.00	0.00	0.00	0.00	0.00	0.00
0.1-0.5	20	98	59	9	16.7	12.85
0.5 - 1.0	28.9	2	15.45	27	9.5	18.25
1.0 - 1.5	33.3	0.00	16.65	43	19	31
1.5 - 2.0	11.1	0.00	5.55	11	14.3	12.65
2.0 - 3.0	6.7	0.00	3.35	8	23.8	15.9
> 3.0	0.00	0.00	0.00	2.13	16.7	9.35
Association membership (% respondents' farmers)	64.4	15.4	39.9	84.3	16.7	50.5
Distance to homestead (% respondents‘ farmers)						
less than 10 minutes	75.6	11.5		78.7	95.3	
10 - 20 minutes	20	34.6		15.7	2.4	
above 20 minutes	4.4	53.9		5.6	2.4	
Average household size	6	5		6	5	

Mean (%): mean of the proportion of the farmers per each variable and per district for both districts

2.3.1.2. The rates of DAP applied as affected by household characteristics

The rates of DAP applied on beans were on average not statistically different ($P > 0.05$) between Buraza and Makebuko districts. However, the rates of DAP applied on maize were on average statistically different ($P < 0.001$) between the two districts.

Table 2.3. Average and ranges of DAP application rates (kg ha^{-1}) used in beans and maize fields per district in Gitega province, Central Burundi

DAP rate (kg ha^{-1})	**Beans**		**Maize**	
	Buraza (n=45)	Makebuko (n=26)	Buraza (n=89)	Makebuko (n=42)
Mean	151.55 (±4.12)^{a}	147.99 (±5.41)^{a}	118.08 (±3.77)^{a}	58.84 (±4.67)^{b}
Min	100	100	49.02	17.83
Max	208.33	208.31	200	162.34

Means with standard error (SE) between brackets. n: number of bean fields per district. Means with the same superscript letters in the row for the same crop are not significantly different at 95 % probability level $P < 0.001$.

A correlation analysis was conducted to identify which of the above mentioned household and farm characteristics (Table 2.4.a & b) might explain the large variability in the rates of DAP applied by farmers in bean and maize fields. No correlation was found for beans between DAP rates and their covariates.

Table 2.4.a. Correlation analysis results between DAP rates and the selected household and farm characteristics of the individual 71 bean fields of the study area

	DAP rates	*Age*	*School level*	*Association membership*	*Crop area*	*Field position*	**SF appreciation*	*Distance home*
DAP rates	1							
Age	0.049	1						
School level	0.125	-0.435	1					
Association membership	0.083	-0.006	-0.064	1				
Crop area	-0.0389	0.194	-0.065	-0.419	1			
Field position	-0.072	0.210	-0.065	0.455	-0.317	1		
SF appreciation	-0.134	0.112	-0.035	-0.081	0.182	-0.042	1	
Distance home	-0.080	0.003	-0.169	0.173	-0.488	0.312	-0.134	1

*SF appreciation=Soil fertility appreciation by farmers

A similar correlation analysis as for beans was conducted for maize. A negative correlation was found between DAP rates and crop area (Table 2.4.b).

Table 2.4.b. Correlation analysis results between DAP rates and the selected household and farm characteristics of the individual 131 maize fields of the study area

	DAP rates	*Age*	*School level*	*Association membership*	*Crop area*	*Field position*	**SF position*	*Distance home*
DAP rates	1							
Age	0.066	1						
School level	0.255	-0.257	1					
Association membership	-0.460	-0.112	-0.300	1				
Crop area	**-0.540**	0.106	-0.329	0.482	1			
Field position	-0.494	-0.027	-0.273	0.403	0.532	1		
SF position	-0.239	0.084	-0.104	0.278	0.384	0.198	1	
Distance home	0.148	-0.030	0.154	-0.137	-0.072	-0.117	-0.151	1

*SF appreciation=Soil fertility appreciation by farmers

2.3.2. Diammonium phosphate effect on bean and maize production

2.3.2.1. Beans

The rates of DAP applied were categorized into three classes (Table 2.5) per district. DAP effect was evaluated based on the three classes of DAP rates and its interaction between districts. The DAP effect (kg ha^{-1}) is defined as the difference between bean yield with fertilized plot with DAP and the control plot. A significant treatment effect was observed between the three DAP classes ($P < 0.001$). The DAP effect was also statistically different between districts ($P < 0.05$). However, the interaction between different classes of DAP rates and districts was found not significant ($P > 0.05$).

Table 2.5. DAP effect (kg ha^{-1}) on local bean yield

District	**# samples**	**DAP classes**	**DAP effect (kg ha^{-1})**		
			Mean	Min	Max
Buraza					
(n=45)	20	100-150	190.70	76.39	330.36
	22	151-200	287.67	114.58	479.17
	3	201-250	395.50	297.62	527.78
Makebuko					
(n=26)	15	100-150	333.99	156.25	609.38
	9	151-200	437.31	208.33	552.08
	2	201-250	361.11	361.11	361.11
$SED_{District}$			41.54*		
$SED_{DAPclasses}$			60.17***		
$SED_{(District*DAPclasses)}$			ns		

#: number of the fields; DAP effect: Yield difference between the fertilized plot with DAP and the control plot; SED: standard error of difference (only presented when significant at $P \leq 0.05$); ***: significant at $P < 0.001$; *: significant at $P < 0.01$; ns: not significant ($P > 0.05$).

Based on comparisons of the DAP effects obtained within the same class between Buraza and Makebuko districts, we observed that firstly, the responses to DAP application rates ranging from 100 to 150 kg ha^{-1} and from 151 to 200 kg ha^{-1} were significantly ($P < 0.001$) larger in Makebuko than in Buraza district. In the former district, the DAP effect was 71 % (143 kg ha^{-1}) and 51 %

(150 kg ha^{-1}) larger for the two classes respectively. Secondly, the DAP effect induced by the rates of DAP ranging from 201 to 250 kg ha^{-1} is on average 10 % (34 kg ha^{-1}) larger in Buraza than in Makebuko district (Table 2.5).

The average soil pH in Buraza and Makebuko districts ranged from 5.4 to 5.6. No significant differences were observed for pH, Olsen P and total C between districts. However, the total N content in the top soils of Buraza is significantly larger than in Makebuko districts (Table 2.6).

Table 2.6. Physico-chemical properties of top soil (0 – 20 cm) sampled from 71 bean fields in two districts of Gitega province (Burundi)

Parameters measured	**Unit**	**Buraza (n = 45)**		**Makebuko (n = 26)**	
		Mean	Range	Mean	Range
pH_w		5.64 (±0.14)	3.00-8.30	5.36 (±0.11)	4.12-6.29
Olsen P	mg kg^{-1}	11.49 (±0.96)	0.59-27.84	10.16 (±0.99)	4.15-27.41
TC	g kg^{-1}	23.9 (±0.9)	10.3-39.6	21.5 (±0.76)	15.7-28.9
TN	g kg^{-1}	3.0 (±0.1)^{a}	1.00-5.50	2.0 (±0.07)^{b}	1.1-2.9

Values are means of soil parameters determined from samples with standard error of the difference (SED) between brackets at 95 % probability level. Means with the different superscript letters in the row are significantly different at 95 % probability level. SED: standard error of the difference between treatment means in pairwise “t test’.

A scatterplot was likewise drown in Figure 2.1.a to evaluate how much the DAP effect can be affected by its covariates such as soil parameters (pH, Olsen P, total C and total N). We included as well “delay in planting” and “DAP rates” as parameters but no other parameters related to bean crop management because they were standardized and cannot explain variation. Bean yield increase seem to be driven mostly by the rates of DAP and the delay in planting ($P < 0.05$).

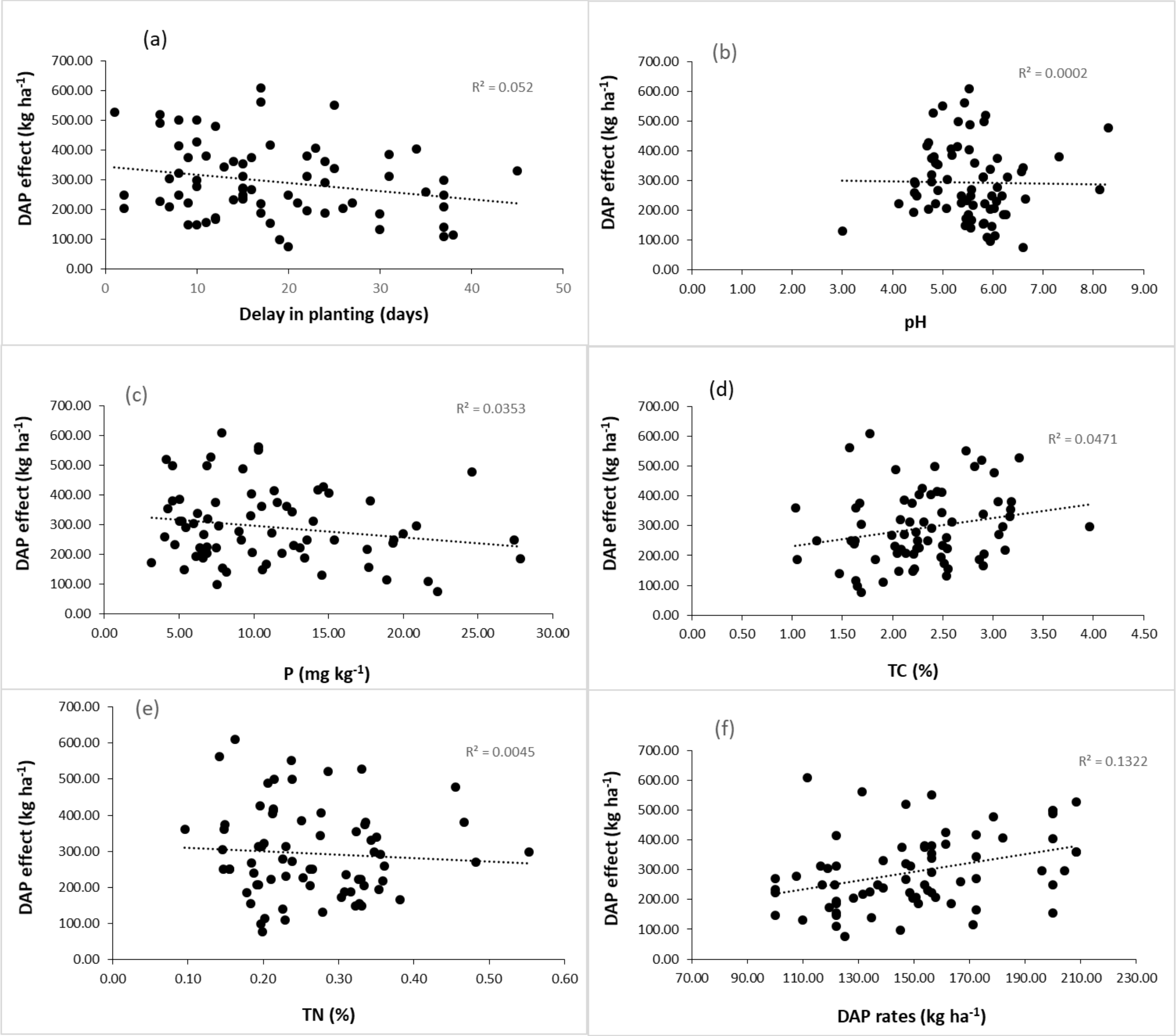


Figure. 2.1. a. Relationship between DAP effect on beans and delay in planting (a), soil parameters (b, c, d, e and f with b=pH; c= Olsen P; d= TC; e=TN and f=DAP rates)

A linear regression analysis (Table 2.7) was then runned between DAP effect and significate covariates to check the regression coefficient and evaluate the proportion of the explained variance. Positive correlation was found between DAP effect and DAP rates. The DAP effect increases with DAP application rates while decreases with the delay in planting. The more you grow beans in time the more bean yield increase with DAP application. DAP effect is explained at large scale by DAP rates (Table 2.7).

Table 2.7. Linear regression analysis results for the individual 71 bean fields of the study area for the effect of DAP (kg ha^{-1}) for local beans as explained by soil parameters, delay in planting and DAP rates.

Significate variable	**Regression coefficient**	**Square of partial correlation**	**R^2**	**% of explained variance**	**p-value**
Intercept	121.61(±73.45)				0.100
DAPrates	1.47(±0.45)	0.37	0.14	70.39	0.002
DelayPb	-2.65(±1.33)	-0.24	0.06	29.61	0.049

*DAPeffect=121.61+1.47 DAPrates-2.65 DelayPb ($P<0.05$); Adjusted R^2 of the model is 0.29

2.3.2.2. Maize

Based on the large variability of DAP rates, only two distinct classes of the rates of DAP were obtained (Table 2.8). The DAP effect was hence evaluated based on these two classes, between districts and the interaction between DAP classes and districts. Significant differences were obtained for the DAP effect between the two classes of DAP rates ($P < 0.0001$). The DAP effect was also statistically different between districts ($P < 0.005$)

Table 2.8. DAP effect (kg ha^{-1}) on local maize yield

District	**# samples**	**DAP classes**	**DAP effect (kg ha^{-1})**		
			Mean	Min	Max
Buraza					
	28	0-100	915.13	109.38	1500
	61	101-200	1206.87	227.27	2500
Makebuko					
	38	0-100	1443.61	475	2265.63
	4	101-200	1989.09	1081.08	2567.57
$SED_{District}$			110.91***		
$SED_{DAPclasses}$			255.41**		
$SED_{(District*DAPclasses)}$			ns		

#: number of the fields; DAP effect: yield difference between the fertilized plot with DAP and the control plot; SED: standard error of Difference (only presented when significant at $P \leq 0.05$); ***: significant at $P < 0.001$; **: significant at $P < 0.01$; ns: not significant.

Different responses were obtained within the same class of DAP rates between Buraza and Makebuko districts (Table 2.8): (i) the DAP effect derived from an application of less than 100 kg DAP ha^{-1} on maize was larger in Makebuko (on average, 58 %) than in Buraza district; and (ii) the response to DAP application rates between 101 to 200 kg ha^{-1} was also on average 65 % (781 kg ha^{-1}) larger in Makebuko than in Buraza district.

A significant difference was found (Table 2.9) for soil total N content ($P < 0.001$) between Buraza and Makebuko districts. For all other characteristics, the figures are quite comparable while in some cases significant differences appear as reported. Their impact should hence not be overestimated. For example, the silt content of soils in Buraza is significantly larger than that in Makebuko district, but the soil texture is clay loam in all cases. (Table 2.9).

Table 2.9. Physico-chemical properties of top soil (0 – 20 cm) sampled from 131 maize fields in two districts of Gitega province (Burundi)

Parameters measured	**Unit**	**Buraza (n = 89)**		**Makebuko (n = 42)**	
		Mean	Range	Mean	Range
pH$_w$		5.31 (±0.08)	4.12-8.03	5.41 (±0.04)	4.04-7.14
Olsen P	mg kg^{-1}	9.15 (±0.87)	1.95-71.26	13.09 (±1.25)	2.37-93.93
TC	g kg^{-1}	22.0 (±0.7)	9.0-49.1	21.5 (±0.2)	10.2-31.0
TN	g kg^{-1}	2.1 (±0.1)^a	1.1-3.8	1.7 (±0.0)^b	1.1-2.7
Sand	%	40.98 (±0.18)	35.75-44.94	40.94 (±0.09)	38.21-44.88
Clay	%	38.67 (±0.42)	33.13-47.91	38.95 (±0.22)	30.74-49.05
Silt	%	17.67 (±0.38)^a	11.10-27.14	15.98 (±0.13)^b	10.92-22.09
Silt +Clay	%	28.17 (±0.32)	17.67-38.67	27.46 (±0.26)	15.98-38.95
Textural class		Clay loam	Loam clay-Clay loam	Clay loam	Loam clay- Clay loam

Values are means of soil parameters determined from samples with standard error of the difference (SED) between brackets at 95 % probability level. Means with the different superscript letters in the row are significantly different at 95 % probability level. SED: standard error of the difference between treatment means in pairwise “t test’.

A similar scatterplot as for beans was drown in Figure 2.1.b to evaluate whether the DAP effect can be related to soil parameters (pH, Olsen P, total C, total N, clay, sand and silt), delay in planting and rates of DAP applied, as part of the maize crop management parameters. No correlation was found between DAP effect and selected covariates (*P* > 0.05) and consequently the linear regression analysis could not be runned without significate covariates to DAP effect.

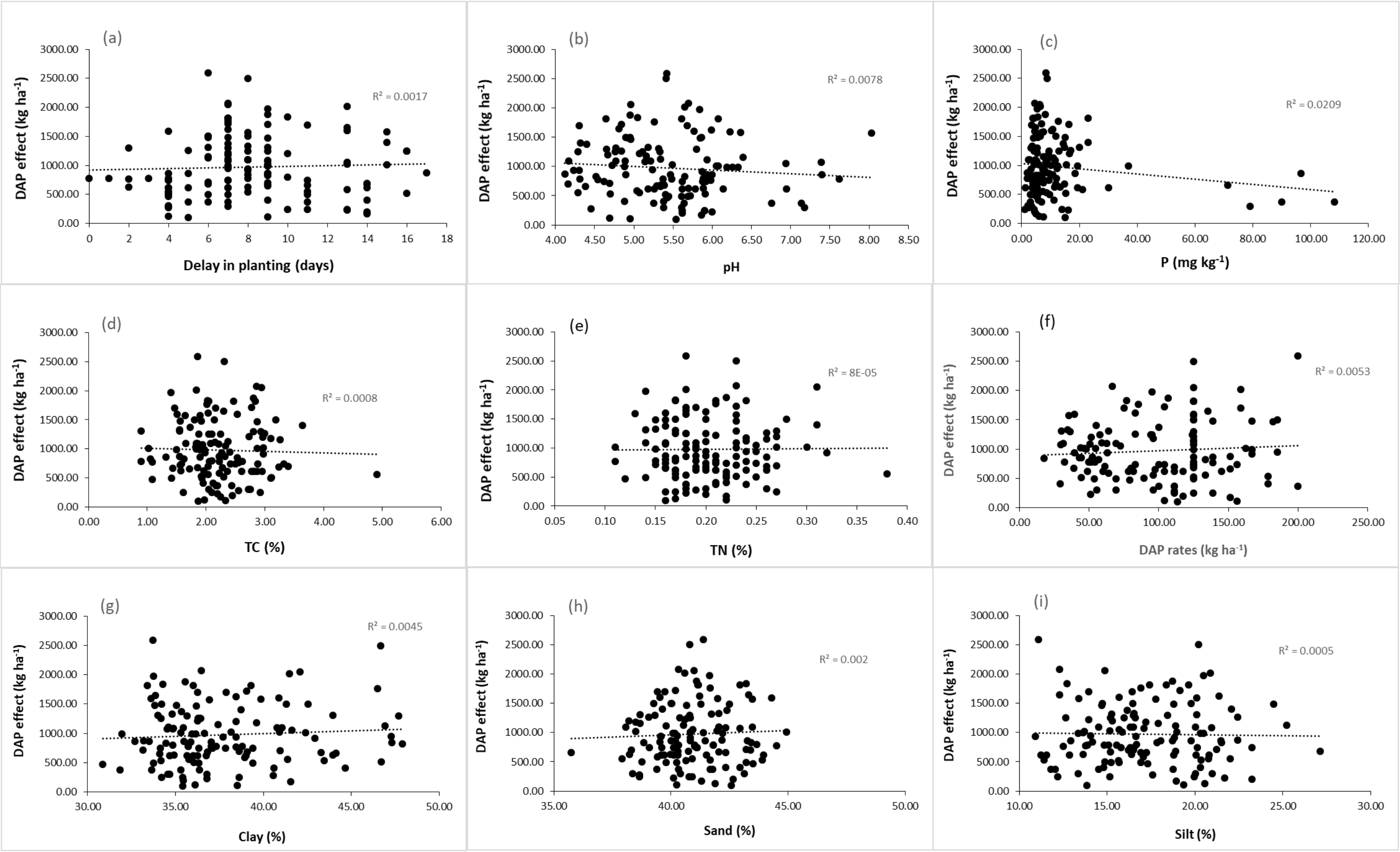


Figure. 2.1. b. Relationship between DAP effect on maize and delay in planting (a), soil parameters (b, c, d, e, f, g, h and i with b=pH; c= Olsen P; d= TC; e=TN; f=DAP rates; g=Clay; h=Sand and i=Silt)

2.3.3. Economic analysis

The economic returns from the application of DAP fertilizer to local climbing bean and maize crops were not profitable (VCR<2) but positive for local varieties. In the LR2012, the net benefits were on average, slightly different and significant ($P < 0.05$) for LCB (\$ 169 ha^{-1} \$ 196 ha^{-1}) between the control and the fertilized treatments. In the SR2012, the trend of the net benefits was also the same ($P < 0.05$) for LM (\$ 511 ha^{-1} \$ 570 ha^{-1}) for the same treatments. The slight differences in net benefits between the control and the fertilized treatment plots were due to the fact that the value of the bean yield increment due to DAP application was larger than the cost of DAP fertilizer. Fertilizer use increased total costs (TC), slightly increased NB (on average) but significantly ($P < 0.05$) when applied to LCB and LM. However, the Value Cost Ratio for LM was on average two times larger than that of LCB (1.95 versus 0.99 respectively) (Table 2.10) although they were not profitable. In general, the VCR is considered profitable when it is larger than 2 (CIMMYT, 1988).

Table 2.10. Financial analysis, including total costs (TC), net benefits (NB), value cost ratio (VCR), and marginal rate of return (MRR) from the application of DAP fertilizer to local climbing bean (n = 71) and maize (n = 131) varieties in Buraza and Makebuko districts

Crop type	**TC**		**NB**		**VCR**	**MRR**
	Control	DAP	Control	DAP		
	………………………$ ha^{-1}……………..				………$ $$^{-1}$……..	
LCB (LR2012)	208.35	328.55	168.58	195.95	0.99	-1.87
LM (SR2012)	189.84	269.08	510.64	570.06	1.95	0.95

LCB: local climbing bean; LM: local maize; LR: Long rains; SR: Short rains; TC: total cost (\$ ha^{-1}); NB: net benefit (\$ ha^{-1}); VCR: value cost ratio (\$\$$^{-1}$); MRR: marginal rate of return (\$\$$^{-1}$)

The VCR has been profitable respectively by 3 % (n = 2) of farmers using LCB and 40 % (n = 52) for those growing LM (Figure 2.2). DAP fertilizer induced large differences in net benefits between LCB and LM. The Value cost ratio and marginal rate of return were also two times larger for LM than for LCB ($P < 0.001$) for both treatments.

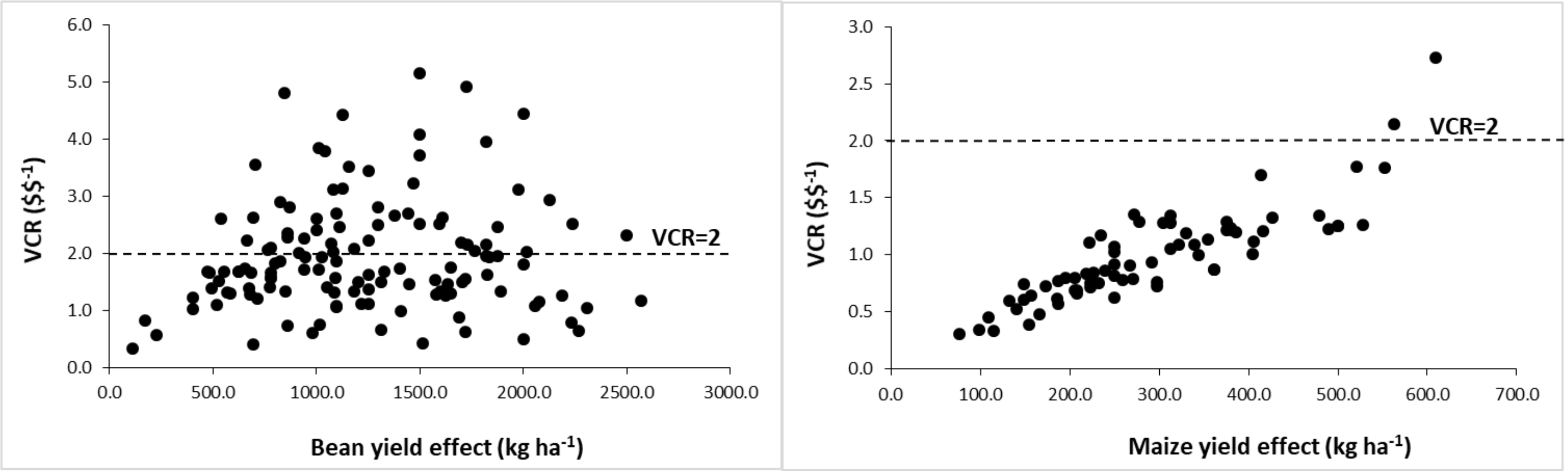


Figure 2.2. The relationship between the value cost ration (VCR) and the yield effect (yield with fertilizer minus yield without fertilizer) for local bean and maize varieties in Buraza and Makebuko districts of the study area

2.4. Discussion

2.4.1. Farmers' local knowledge on the use of diammonium phosphate in bean and maize production

Most farmers surveyed in this study were male. The average age of the interviewed farmers ranged between 40 and 60 years (Table 2.2) and indicated that most of them were mature people with a capacity to work. More than 50 % of the farmers selected for beans and maize in Buraza district had some formal education and were member of an association while this was not the case for the selected farmers in Makebuko district. The average land and household size of a farm is an indication of population density in each district and hence a direct contributor to food insecurity and poverty. More than 70 % of the bean and maize fields in Makebuko district were close to the homestead, and consequently had easy access to better management practices.

Regarding the large variability in rates of DAP applied by farmers within a same area and crop (Table 2.3), the understanding of their local knowledge is important. Such knowledge includes complex practices and decisions made by local people based on experience built over time; it is dynamic, continually changing and rarely systematically analyzed (Boven & Morohashi, 2002). This needs to be considered when targeting improved integrated soil fertility management interventions i.e.in Burundi to assess how it influences farming decisions (Brokensha, Warren, & Werner, 1980). In this study, the rates of DAP applied could be explained based on the different household and farming characteristics of the farmers. A large proportion of farmers (75 %) applied less than 200 kg ha^{-1} on bean and maize fields when close to the homestead and on the small crop area (> 0.5 ha) (Tables 2.2, 2.5 and 2.8). The home fields are recognized to be fertile as they always receive maintenance fertilization (Vanlauwe et al., 2015) by manure generated from crop residues, kitchen waste, livestock, compost to sustain crop yields, and require less labor to transport manure (Misiko et al., 2011). The home fields are mostly used to produce food for home consumption including beans. Most farmers prefer to apply larger amounts (> 100 kg ha^{-1}) on maize (Table 2.8) generally grown on large crop areas compared to beans to maximize crop response to fertilizer in such depleted fields (Vanlauwe and Giller, 2006).

2.4.2. Diammonium phosphate effect on bean and maize production

In the bean growing season, a large proportion of farmers (Table 2.5) applied less than 150 kg DAP ha^{-1} on the bean fields, resulting in a smaller DAP effect (on average 191 kg ha^{-1} in Buraza and 331 kg ha^{-1} in Makebuko districts, respectively) (Table 2.5), hence these fields can be described as “fertile, non-responsive soils”. The bean response to DAP fertilizer may be limited by other nutrient deficiencies which are not provided with DAP and while they are not identified here, they cannot be overlooked. Besides access to nutrient resources, poor households with very small farms, often selling their labor to other households, are thus applying less or no agro-inputs and spend less labor on their home fields. Moreover, these fields are expected to remain fertile, as they receive inputs generated from crop residues, kitchen waste, manure from livestock and compost to sustain crop yields (Vanlauwe et al., 2015).

A large DAP effect was obtained in 51 % of bean fields (Table 2.5) that received more than 150 kg DAP ha^{-1}. In Buraza district, yield increments of 97 and 205 kg ha^{-1} were on average obtained with the second (151 - 200 kg DAP ha^{-1}) and the third (201 - 250 kg DAP ha^{-1}) DAP classes, respectively (Table 2.5) on beans when compared to the yield obtained with the first DAP class (DAP rates lesser than 150 kg ha^{-1}). The more DAP was applied, the more gain in bean yield was obtained in Buraza district. However, this seems not to be the case in Makebuko district where the bean yield increment (103 kg ha^{-1}) obtained with the second DAP class (151 - 200 kg DAP ha^{-1}) was larger than that obtained with the third DAP class (201 - 250 kg DAP ha^{-1}) where the yield increment was on average 27 kg ha^{-1} also compared to the yield obtained with the first DAP class (DAP rates lesser than 150 kg ha^{-1}). This result was confirmed by the output from a linear regression analysis between DAP effect and soil parameters (pH, Olsen P, total N and total C), delay in planting and DAP rates where only DAP rates and delay in planting came out as significate predictors of DAP effect. The bean yield increment increases with increase in DAP application rates in due time and this denotes how our soils can still be described as “responsive soils” and need maintenance fertilization to sustain good crop yields.

These trends were different in the case of maize. Overall, the proportion of farmers who had applied less (n = 65) or more (n = 66) than 100 kg DAP ha^{-1} on maize fields was almost the same. However, a yield increment (545 kg ha^{-1}) between the two DAP classes (Table 2.8) obtained in Makebuko district was larger than that obtained (292 kg ha^{-1}) in Buraza district.

For both crops, the DAP effect was always larger in Makebuko than in Buraza district (Tables 2.5 & 2.8). This may be explained by differences in soil types (Table 2.1) and properties (i.e. lower total N in Makebuko compared to Buraza district), disproportionality between fields with large

DAP rates (i.e. large proportion of farmers (> 50 %) applied smaller DAP rates in Makebuko compared to Buraza district (Tables 2.5 & 2.8). We may not rule out the proximity of Makebuko district to the extension services located in Gitega Town (Table 2.1) which may help farmers get easy access to improved technologies.

The increment in crop yields was on average increasing with the application of DAP. This denotes good soil responsiveness to DAP fertilizer use although they are often of poor fertility status (Tittonell et al., 2007).

2.4.3. Economic analysis

Low grain yields obtained from the control under local climbing beans resulted in small net benefits. This was not the case for its corresponding fertilized treatment where the net benefit was increased by 16 %. On the other side, high yield increment on local maize with DAP application resulted in increase of net benefit by 12% (Table 2.10).

Large fertilizer effect consequently resulted in small value cost ratios. The VCRs were not profitable (VCR< 2). For local climbing beans, VCR value on average was 0.99 $ $^{-1}$ while 1.95 for local maize (Table 2.10).

The application of DAP under farmer practices was only profitable (VCR ≥ 2) to 3 % and 40 % farmers growing local climbing beans and maize, respectively. The net benefits were significant and different between the control and DAP fertilizer treatments ($P < 0.05$) across all cropped fields for both climbing bean and maize varieties (Table 2.10).

The use of DAP fertilizer for the local climbing bean and maize varieties resulted in small grain yields, small net benefits, small value cost ratios and small marginal rates of return. It is essential to carefully advice smallholder farmers on the use of fertilizers and possibly related technologies to achieve durable yield improvements, but intensification can only proceed if farmers have access to markets to buy improved seeds, commercialize their produce at a reasonable price and purchase inputs. Farmers are encouraged to adopt the Integrated Soil Fertility Management to improve soil fertility and be assured of net returns to investments (Kimani et al., 2004).

2.5. Conclusion

This study improved our understanding of how local knowledge of the smallholder farmers influences the use of DAP fertilizer in bean and maize production as a precondition for the establishment of profitable and sustainable nutrient management systems.

The huge variability in plot sizes, plant densities, mineral DAP fertilizer rates on beans and maize production in Buraza and Makebuko districts illustrates how farmers have different attitudes towards the use of fertilizer. Such information will facilitate collaboration between farmers, extension workers, researchers and decision makers to improve crop intensification of family farms by using appropriate integrated soil fertility approaches suitable to transform subsistence farms into market oriented farms in Burundi. From this study, we noticed that there is still need for targeting and carefully advice farmers on judicious use of fertilizer, and possibly additional measures (investments in combined organic and inorganic inputs) may be need for a better increase in crop productivity. In other words, this study justifies the need for ISFM.

Chapter 3

Compositional nutrient diagnosis to determine nutrient deficiencies in maize cropping under farmer practices in the central highlands of Burundi

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3.1. Introduction

Soil fertility depletion is since many years recognized as the major cause of low food crop production in sub-Saharan Africa (SSA) (Sanchez, 2002). Traditional ways to replenish nutrient exports by using fertilizers are constrained in SSA by their limited accessibility to smallholders. In addition, the lack of up-to-date and site-specific fertilizer recommendations limits their efficiency for crop production. The need for intensification of agriculture in SSA has recently gained support, in part because of the growing recognition that enhanced farm productivity is a major entry point to break the vicious cycle underlying rural poverty and food insecurity (Vanlauwe et al., 2010). One of the Abuja Fertilizer Summit's recommendations (2006) acknowledges that sustainable intensification necessitates an increased use and good management of external nutrient sources (Abuja Fertilizer Summit, 2006). When soils are degraded, restoration of soil fertility through balanced fertilisation and organic matter additions is necessary to achieve high crop productivity. Also other components to manage soil fertility in SSA, such as manure, crop rotations, and improved fallows are most effective when strategically combined with fertilizers (Zingore, 2011).

The economy of Burundi is predominated by agriculture. About 90 % of population depends on subsistence farming, marginally self-sufficient in food production (FAOSTAT, 2014). Maize is an important subsistence crop next to beans and bananas. It is the most important cereal in terms of total food production and total area under cultivation. In 2013, the maize cultivation covered a total area of 123,000 hectares at a total production of 162,400 tonnes of grain, or an average maize grain yield of only 1.3 tons ha^{-1} (FAOSTAT, 2014). The potential maize grain yield of 6.6 tons ha^{-1} is far from being reached. The principal factors responsible for the yield gaps in the maize growing zones of Burundi are thought to be both abiotic (acidic soils, low N and P especially at mid and high altitudes, poor cultural practices and low input supplies) and biotic (streak disease, stem borers, low yielding varieties, weeds etc.) (Manirakiza, 1999). Most relevant to this study is that continuous cultivation without the supply of adequate inputs accelerates soil nutrient depletion.

Integrated Soil Fertility Management (ISFM) aims at maximising agronomic use efficiency of the applied inputs by integrating the use of improved germplasm, fertilizers and appropriate organic resource management coupled with adaptations of these practices to local circumstances, and is currently promoted to improve crop productivity (Vanlauwe et al., 2010).

ISFM hence implies the development of more profitable fertilizer recommendations that target primary nutrient deficiencies. To do so, relying on soil analysis is a possibility, though it is often cumbersome and interpretation not always straightforward. More recently, a renewed interest in plant tissue analysis has emerged due to drastic improvements in high-throughput analysis by ICP - OES or ICP - MS. This allows rapid assessment of plant nutrient disequilibria by analysing leaves or other plant parts collected at strategic growth stages when they are directly reflecting the availability and uptake of nutrients (Beverley, 1987). Compositional Nutrient Diagnosis (CND) is an empirical procedure developed by Khiari et al. (2001a) which allows the determination of critical nutrient norms based on a high yielding subpopulation. Khiari et al. (2001b) developed a mathematical procedure to separate a large population of crop data into low-and high-yield subpopulations as a basis for the CND approach. We adopted this method to determine the nutrient norms and diagnose nutrient deficiencies in maize cropping systems in Burundi.

The objectives of this work were (i) to assess the applicability of the CND approach under smallholder farming practices, (ii) to map the frequency of nutrient deficiencies for maize cropping, (iii) look into the effects of specific nutrient management interventions on crop productivity, and (iv) investigate how the variation in response is related to the biophysical conditions across the target intervention areas of the central highlands of Burundi.

3.2. Materials and methods

3.2.1. Study area

The study was carried out from October 2011 to February 2012 in Buraza and Makebuko districts of Gitega Province in Central Burundi. Similarly, a detailed background of the two districts referred to this study is given in Chapter 2, sub-section 2.2.1.The general soil, biophysical, topography and socio-economic characteristics of the fields restricted to these districts are described in Table 3.1.

Table 3.1. Main characteristics of the fields restricted in this study (n = 142)

Variable		**Buraza (n = 76)**		**Makebuko (n = 66)**	
	Unit	Mean	Range	Mean	Range
Soil properties					
pH$_{water}$		5.35	4.12-8.03	5.55	4.04-7.49
Olsen P	mg kg^{-1}	8.66	1.95-23.07	13.11	1.98-93.93
Total C	%	2.19	0.90-4.91	2.19	0.77-3.43
Total N	%	0.20	0.11-0.38	0.18	0.08-0.28
C/N ratio		10.74	8.18-12.92	12.42	9.63-12.25
Clay	%	38.33	33.18-47.91	39.29	30.74-49.05
Silt	%	17.79	11.10-27.14	16.70	10.92-22.50
Silt + Clay	%	56.12	50.82-68.21	56.00	50.50-66.25
Textural class		Clay loam	loam clay-clay loam	Clay loam	loam clay-clay loam
Biophysical characteristics					
Altitude (meters above sea level)	m		1701-1927		1670-1743
Annual mean temperature**	^{0}C		15-20		15-20
Topography					
Dominant soil group (WRB, 2015b)			Acrisols		Nitisols
Socio-economic indicators					
Average farm size*	ha	0.5		0.5	
Population density**	#km^{-2}	299		350	
Family size*	#	6		6	
Distance to Gitega main market**	km	55		24	

Source: Author, *Ouma et al., (2010) and **ISTEEBU (2014)

3.2.2. Experiment layout and management

The trials were carried out on 76 fields for Buraza and 66 fields for Makebuko districts, hence totalling 142 fields. Each of the selected farmers availed a field for the trial. The selection of fields, the soil sampling and handling, the trial establishment and its supervision were conducted as in Chapter 2, sub-section 2.2.2. The composite soil samples were shipped to the International Center for Tropical Agriculture (CIAT) in Nairobi for analysis. Soil pH was determined in a 1:2.5 w/w soil-water suspension (Metson, 1956). Extractable P was determined according to Olsen *et al*. (1954), using a buffered $NaHCO_3$ extraction (0.5 M $NaHCO_3$ + 0.01 *M* EDTA, pH 8.5) and measured colorimetrically (Riley, 1962). Soil texture was assessed using the hydrometer method (Bouyoucos, 1962). Total C and total N were analysed by Gas Chromatography (GC), following oxidative digestion of samples under a controlled oxygen supply at high temperature (approx. 900 °C) in a C/N analyser (Carlo Erba EA1110 elemental analyser) (Dumas, 1826). Analysis results are presented in Table 3.1.

The experimental plot size was determined by the farmer and ranged from 50 to 342 m^2. Each farmer was supplied with 1 kg of DAP. The DAP was applied at different rates ranging from 49 to 200 kg ha^{-1} in Buraza district and from 18 to 162 kg ha^{-1} in Makebuko district, in accordance with local farmer practices. This influenced the rate of nutrients applied in the fertilized plots: the rates of N applied ranged from 9 to 36 kg ha^{-1} in Buraza district and 5 to 29 kg ha^{-1} in Makebuko district. Likewise, the rates of P applied ranged from 12 to 46 kg ha^{-1} in Buraza district and 6 to 37 kg ha^{-1} in Makebuko district.

Farmers planted local maize variety "*ISEGA"* and managed all fields following their local practices. "*ISEGA*" variety is characterized by its early maturity (153 days) compared to other local varieties (182 days) in the study area and a potential yield of 6.6 metric ton per hectare. The variety sells at a low price compared to the improved varieties (Manirakiza, 1999a). The spacing was determined by farmers and ranged between 50 and 100 cm between lines and between 40 to 50 cm within lines with 2 to 4 seeds per hill. Plant density ranged from 18,421 to 75,000 plants ha^{-1}. Maize was top-dressed with Urea (46-0-0) as basal at a rate of 50kg ha^{-1}.

Maize ear leaves were collected at tasselling stage (± 60 days after planting) from all plots. In each plot, three ear leaves were collected from randomly selected plants. Sampled ear leaves were oven-dried at 65 °C for 48 - 72 hours and ball-milled. For N-analysis, ground ear leaf samples were digested in hot sulphuric acid solution in the presence of Se as catalyst followed by colorimetric N analysis by a Technicon auto analyser using the indophenol blue method (Mulvaney, 1982). For the determination of other nutrients (P, K, Ca, Mg, S, Mn and Zn), ball-milled samples were digested with nitric acid and the nutrient content in the digests determined by inductively coupled plasma optical emission spectrometry (ICP - OES, Optima 3300 DV, Perkin- Elmer, Norwalk, USA).

Maize was harvested at maturity in a net plot (middle rows in each plot), and grain yield was assessed at 12 % moisture. The net plot was excluding the two outside bordering rows and ranged from 34 to 188 m^2 (0.0034 - 0.0188 ha) resulting in 96 - 659 plants m^{-2} (18,421 - 75,000 plants ha^{-1}).

3.2.3. Data analysis

3.2.3.1. Effect of DAP fertilizer on maize grain yield

Data analysis was done using descriptive statistics in Excel software (Microsoft Office, 2013) to assess the effect of DAP fertilizer on maize grain yield. To enable understand the spread of the maize grain yield data, a scatterplot with the yield in the treatment with DAP versus control yields was drawn for each district. Statistical significances between fertilizer treatment, districts and their interactions were tested with the Student *t* test with $P < 0.05$. The effects of various factors and their interactions were compared by computing the standard error of difference. The variation in fertilizer effect between farms and districts were also carried out and expressed as a cumulative frequency distribution curve. Maize grain yield (MGY) was determined as the shelled dry weight expressed at 15 % moisture content in tons per hectare. The effect of DAP fertilizer is defined as the maize grain yield difference (ton ha^{-1}) between the fertilized and control plots.

3.2.3.2. Compositional nutrient diagnosis (CND) on maize

The CND approach has been adopted as a robust mathematical basis to define a minimum yield target useful for discriminating between high and low yielding subpopulations (Khiari et al., 2001a). The S^9, *i.e.,* ninth dimensional ($d+1$) maize simplex (S^d) comprises eight nutrients *N, P, K, Ca, Mg, S, Mn and Zn* and the filling value R_9 which takes care of all other nutrients not included in this analysis. A total of 284 samples was used in the CND computations with Excel software (Microsoft Office, 2013).

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

Where 100 is the dry matter concentration (%); N, P, K….are nutrient proportions computed as:

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

The nutrient proportions become scale invariant after they are devided by geometric mean (G) of the d+1 components including R_d (Aitchinson, 1986), as follows:

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

The dataset was arranged in descending order of maize grain yield. Secondly, the measured ear leaf nutrient concentrations were converted into row-centered log ratios, denoted as V_x for nutrient X (Aitchison and Egozcue, 2005).

Row-centered log ratios are computed as:

$V_N = \ln(\frac{N}{G})$, $V_P = \ln(\frac{P}{G})$, $V_K = \ln(\frac{K}{G})$ ….., $V_{Rd} = \ln(\frac{Rd}{G})$, and (4)

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

Where V_x is the CND row-centered log ratio expression for nutrient X. This operation is the control to insure that V_x computations have been conducted properly. By definition, the sum of tissue components is 100%, as in Eq. (1), and the sum of their row-centered log ratios, including the filling value must be zero, as in Eq. (5).

• The yield cut-off value separates high from low-yielding subpopulations. This was obtained at the largest inflection point of the nine (eight nutrients plus a filling value) cubic cumulative variance ratio functions as outlined by Khiari et al. (2001a). The yield cut-off so obtained was used in stepwise CND computations.

• The CND norms (V_x^*) which are threshold nutrient log ratios were calculated as the means and standard deviations for the nutrient log-ratios (Vx) of the high-yielding subpopulation:

Let $V_N^{*,}$ V_P^*, VK*… V_{Rd}^* and SD_N^*, SD_P^*, SD_K^*… $SDRd^*$ be the CND norms as means and standard deviations of row-centered log ratios of d nutrients, respectively.

• The CND indices (Ix), which are deviations from the CND norms:

The row-centered log ratios of independent specimens are standardized as follows:

$$I_N = \frac{(V_N - V_N^*)}{SD_N^*}, \quad I_P = \frac{(V_P - V_P^*)}{SD_P^*}, \quad I_K = \frac{(V_K - V_K^*)}{SD_K^*}, \quad \ldots\ldots\ldots\ldots, \quad I_{Rd} = \frac{(V_{Rd} - V_{Rd}^*)}{SD_{Rd}^*} \qquad (6)$$

Where I_N, I_P, I_K… I_{Rd} are the CND indices.

- The CND imbalance index (CNDr^2), a measure of nutrient imbalance of a sample and computed as the sum of the squared CND indices of individual nutrients and filling value. The CND nutrient imbalance index of a diagnosed specimen is its CND r^2 and is computed as follows:

$$r^2 = I^2_N + I^2_P + I^2_K + \ldots.. + I^2_{Rd} \qquad (7)$$

Each specimen is thus characterized by its radius, r, computed from the CND nutrient indices. The sum of d+ 1 squared independent, unit-normal variable produces a new variable having a chi-square distribution with d+1 degrees of freedom (Ross, 1987). Because CND indices are independent unit-normal variables, the CND r^2 values must have chi-square distribution. The chi-square distribution function provides an advantage for CND as a generic support model for small databases.

- The critical CNDr^2 imbalance index (Critical CNDr^2), being the minimum CNDr^2 nutrient imbalance index to reach the high yield target. This is derived from assigning the proportion of the low yielding subpopulation at the yield cut-off as an exact probability of the cumulative chi-square distribution function with nine degrees of freedom (Khiari et al., 2001a).

- The CND nutrient sufficiency ranges define the deficient and/or excessive nutrient concentrations in the low yielding subpopulations. These ranges were obtained from the conversion of individual critical nutrient indices into concentration ranges with a lower and an upper boundary. Moreover, the obtained CND sufficiency ranges were compared with values published in Reuters and Robinson (1997). The use of nutrient sufficiency ranges offers significant advantages over the use of critical values by providing a range of values where a nutrient is not limiting (Campbell, 2000). The occurrence of nutrient deficiencies in each study area was determined by comparing the CND index of each sample with the nutrient sufficiency ranges. When the CND nutrient index (I_X) fell below the lower limit of the sufficiency range it was considered deficient. The limiting nutrients in each farmer's field were then ranked according to increasing CND index with the lowest CND index identifying the most limiting nutrient to maize productivity. The nutrient limitations in each study area were subsequently ranked using the average rank across all farmer fields. The occurrence of a nutrient limitation by one of the eight nutrients and the filling value was also determined for the whole database.

3.3. Results

3.3.1. Effect of DAP fertilizer use on maize grain yield

The productivity of maize in Buraza and Makebuko districts, is first evaluated in a scatterplot that show the spread of yield data (Figure 3.1). The yield increment as affected by DAP fertilizer was positive for more than 90 % of farmers' fields in Buraza and Makebuko districts.

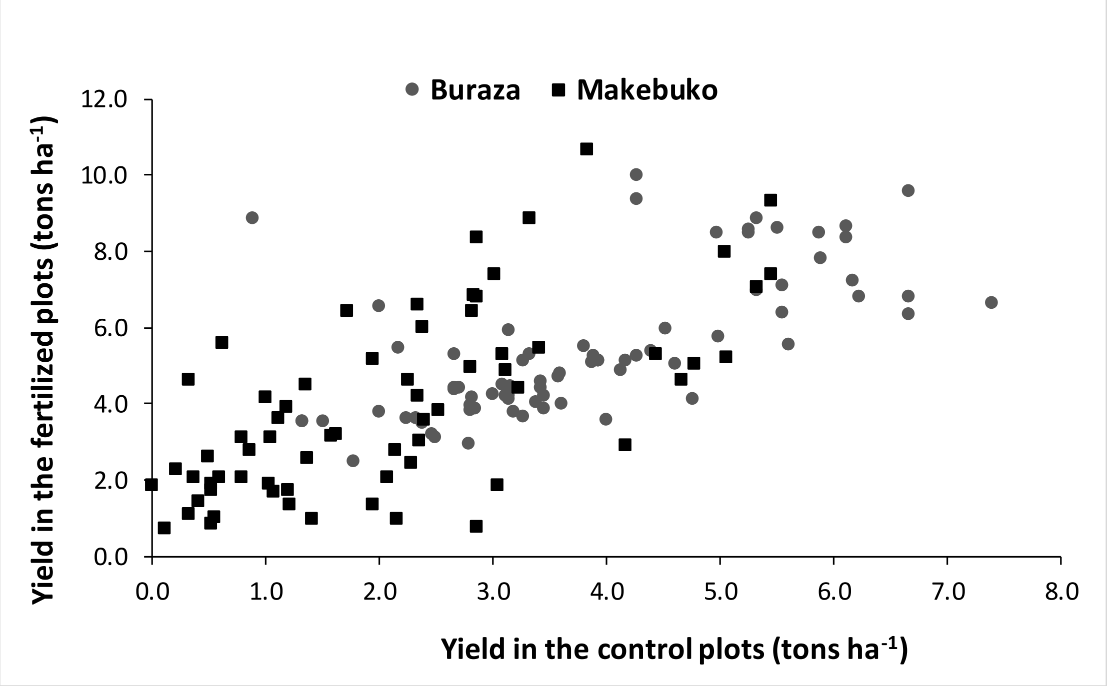

Figure 3.1. Distribution of maize grain yield data in the treatment with DAP versus control yields (tons ha^{-1})

Next the average yield increase in bean and maize production for each district is summarized in Table 3.2. The average grain yield for Buraza district is 3.85 tons ha^{-1} in the control plots and 5.45 tons ha^{-1} with fertilizer applied. The fertilizer-induced yield increase is on average 29 % (1.60 tons ha^{-1}) in Buraza district. For Makebuko district, the grain yields were on average 2.13 tons ha^{-1} in the control plots and 3.97 tons ha^{-1} in the fertilized plots. The yield increase due to fertilizer application hence is on average 46 % (1.84 tons ha^{-1}) in Makebuko district. The response to fertilizer was significantly ($P < 0.001$) larger in Makebuko than in Buraza district. Maize grain yields were on average significantly ($P < 0.001$) different between the districts and for both treatments but their interaction was not significant ($P \geq 0.05$) (Table 3.2).

Table 3.2. Mean grain yields (tons ha^{-1}) of local maize for both control and fertilized plots of the individual 142 fields in the study

Treatment	**Buraza (n = 76)**	**Makebuko (n = 66)**
	Overall mean grain yield (tons ha^{-1})	
Control	3.85	2.13
DAP	5.45	3.97
SED	0.27	0.34
SED fertilizer (F)	0.25***	
SED district (D)	0.27***	
SED F x D	ns	

SED: standard error of difference (only presented when significant at $P \leq 0.05$); *** significant at $P \leq 0.001$; ns: not significant.

The variation in fertilizer effect, expressed in a cumulative frequency distribution curve (DAP vs Control, Figure 3.2.) between the different farmers is larger for Makebuko district than in Buraza district. For about 96 % of the farmers, fertilizer effects are positive. Fertilizer effects on maize grain yields are larger in Makebuko district than in Buraza district for about 66 % of farmers (Figure 3.2). Only in very few cases (8 %), a negative effect of fertilizer addition was obtained.

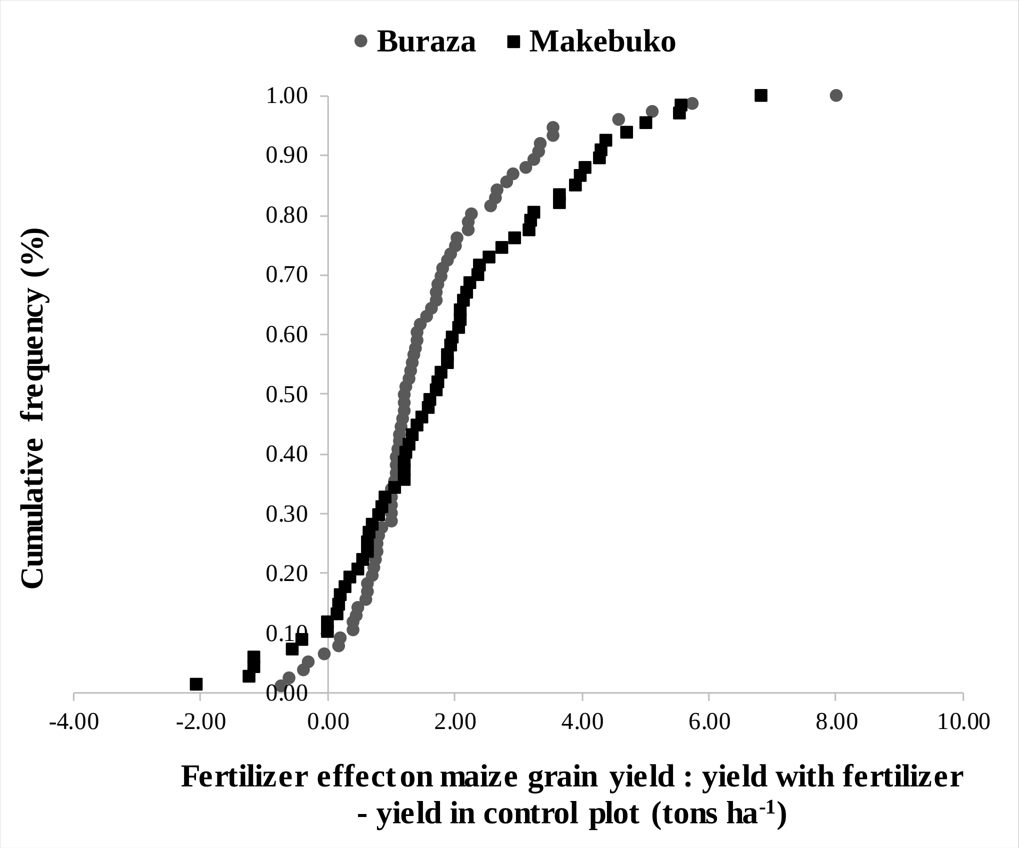

Figure 3.2. Distribution of fertilizer effect on maize grain yield: yield with fertilizer - yield in control plot (tons ha^{-1}) for Buraza and Makebuko districts (n = 142), respectively

3.3.2. Compositional maize nutrient diagnosis

3.3.2.1. High yield cut-off and nutrient concentrations of the high and low-yield subpopulations

The yield cut-off was determined after examining the cubic functions fitted to the cumulative variance of the eight nutrients and the filling value versus yield. It was obtained at the largest inflection point for Zn at a value of 3.9 tons ha^{-1} as shown in Table 3.3. This value was used as the yield cut-off that separates the high from the low-yielding subpopulations. Based on this yield cut-off, 133 of 284 samples were assigned to the high yielding subpopulation, holding 47 % of the observations. Logically, fertilized plots were dominant in the high-yield subpopulations, contributing 68 % of the 133 high yielding plots. Likewise, the control plots were predominant in the low-yield subpopulation. They contributed 66 % of the 151 low-yielding plots.

Table 3.3. Inflection points (-b/3a) of the cubic relationship between the cumulative variance ratio functions (Fic (Vx)) of row centered log ratios of each nutrient (Vx) versus yield, in a maize ear leaf survey population (n = 284) conducted during the 2012 short rains

(V_x)	*F_i^c (V_x) = aY^3+ bY^2+ cY+ d*	*-b/3a (tons ha^{-1})*	*R^2*
Macronutrient			
V_N	$0.2566Y^3-2.8002Y^2-7.1027Y+103.01$	3.637	0.991
V_P	$0.2201Y^3-2.4573Y^2-6.4249Y+94.188$	3.721	0.995
V_K	$0.1233Y^3-0.4399Y^2-18.24Y+110.37$	1.189	0.993
V_{Ca}	$0.0944Y^3-0.0705Y^2-19.099Y+108.47$	0.249	0.995
V_{Mg}	$0.2651Y^3-2.954Y^2-6.7186Y+105.62$	3.714	0.993
V_S	$0.2299Y^3-2.4071Y^2-8.533Y+104.26$	3.490	0.993
Micronutrient			
V_{Mn}	$0.0622Y^3+0.0849Y^2-17.591Y+107.34$	-0.455	0.998
V_{Zn}	$0.2065Y^3-2.4201Y^2-6.153Y+99.874$	**3.906**	0.996
Filling value			
V_{Fv}	$0.0755Y^3+0.0934Y^2-18.48Y+103.01$	-0.414	0.997

F_i^c (V_x): Cumulative variance ratio functions, Vx: row-centered log ratio for each nutrient, R^2: coefficient of determination, -b/3a: inflection point for each nutrient X. The inflection point of 3.9 tons ha^{-1} (value in bold) obtained from Zn is the selected yield cut-off value separating high from low-yield subpopulations.

The average maize grain yield of the high-yield subpopulations is 5.74 tons ha^{-1} which is significantly different ($P \leq 0.001$) from the one of the low-yield subpopulations at 2.32 tons ha^{-1} (Table 3.4). In addition, the concentrations of N, P, Ca, Mg, S and Mn were significantly different ($P \leq 0.05$) between the high and the low-yield subpopulations. Zn was consistently not significantly different between the high and the low-yield subpopulations.

Table 3.4. Means of maize grain yield and ear leaf nutrient concentrations of the high and low yielding subpopulations

Grain yield (tons ha^{-1})	**High yield subpopulation**	**Low yield subpopulation**	**p-value**
	5.740	2.318	0.0001
Macronutrient (%)			
N	2.070	1.860	0.0001
P	0.198	0.179	0.0001
K	2.058	1.951	0.0001
Ca	0.577	0.474	0.0001
Mg	0.235	0.234	0.0143
S	0.169	0.166	0.0385
Micronutrient (mg kg^{-1})			
Mn	50.395	44.190	0.0001
Zn	15.512	15.663	0.0023

P-value at $P \leq 0.05$ denotes a significant difference between the maize ear leaf nutrient concentrations between high and low-yield subpopulations.

3.3.2.2. CND norms

The CND norms (Vx*) calculated as the means and standard deviations of the row-centered log ratios from the high-yielding subpopulation are presented in Table 3.5.

Table 3.5. Compositional nutrient diagnosis (CND) norms (V_x^*) derived from the high yield maize subpopulation (n = 133)

CND norm	**Macronutrient**						**Micronutrient**		**Filling value**
	V^*_N	V^*_P	V^*_K	V^*_{Ca}	V^*_{Mg}	V^*_S	V^*_{Mn}	V^*_{Zn}	V^*_{Fv}
Mean	1.99	-0.38	1.99	0.66	-0.23	-0.52	-4.07	-5.26	5.83
STD	0.18	0.22	0.24	0.28	0.27	0.14	0.31	0.31	0.15

V^*_x: CND norm for nutrient x (mean of nutrient ratios obtained from the high yielding subpopulation), STD: standard deviation of nutrient ratios obtained from the high yielding subpopulation.

3.3.2.3. Critical nutrient imbalance index (critical CNDr^2)

The determination of the CNDr^2 critical threshold indicates that the 53 % of the low yielding subpopulation corresponds to a χ^2 value of 7.5 (Figure 3.3). Therefore, this is the critical CNDr^2 for qualifying a sample in the high-yielding subpopulation (Figure 3.3).

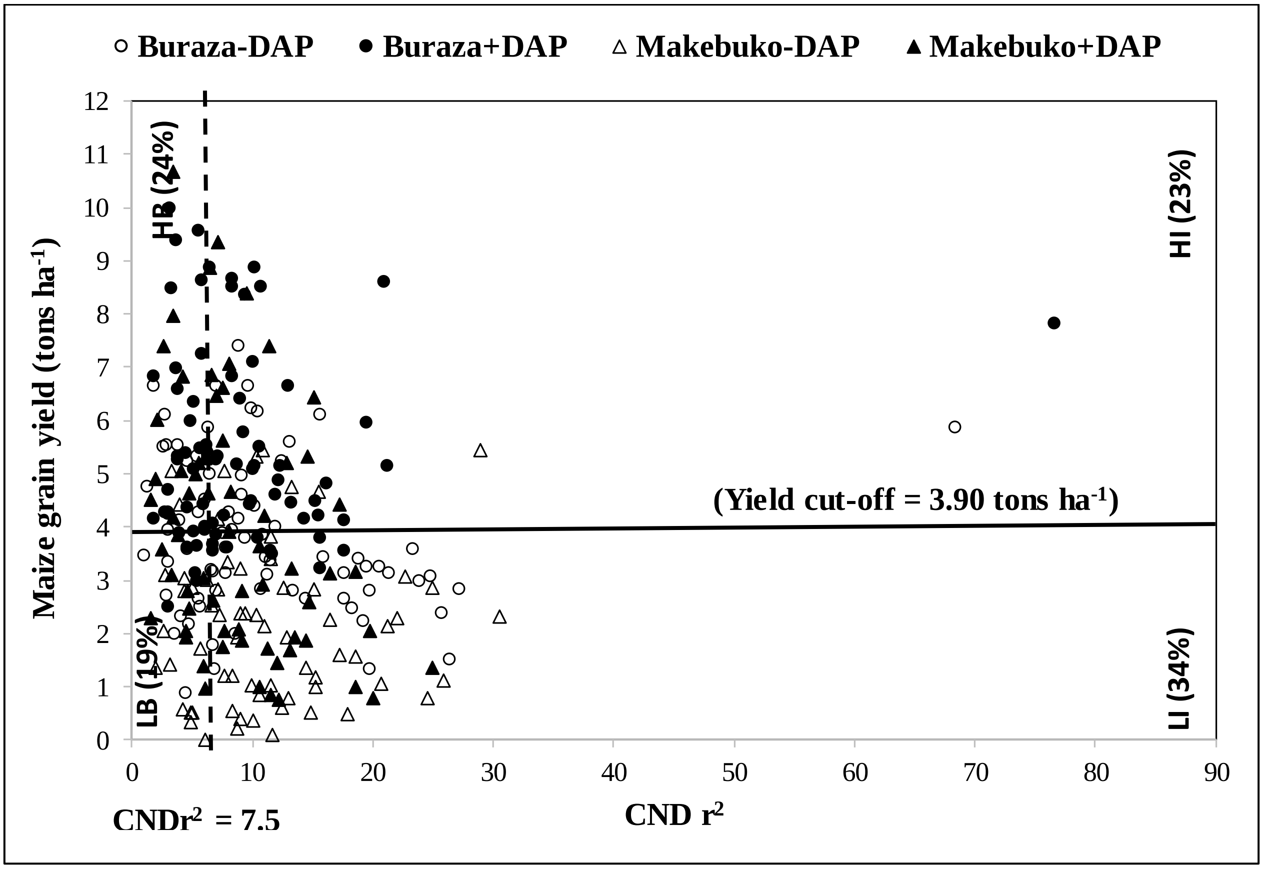

Figure.3.3. Partioning of high-and low maize yield subpopulations according to their nutritional balance indexes. The yield cut-off and the critical CND balance index (Critical CNDr^2) are used as the delimiters of the four quadrants. HB: high yield and balanced, LB: Low yield and balanced, LI: Low yield and imbalanced, HI: High yield and imbalanced, Buraza – DAP: Buraza control (without DAP) plots, Buraza + DAP: Buraza fertilized plots, Makebuko – DAP: Makebuko control (without DAP) plots and Makebuko + DAP: Makebuko fertilized plots

3.3.2.4. CND nutrient sufficiency ranges

The critical *CND* I_x^2 indices were related to the MGY for partitioning the population according to the Cate-Nelson procedure. As per the control procedure (Khiari et al., 2001a), the squared individual nutrient indices must sum up to the critical *CNDr*^{2}, which in this case was 7.5. The critical CND index ranges were then assigned as the nutrient sufficient ranges, obtained from the square root of the critical *CND* I_x^2 indices. A comparison of CND sufficiency ranges and published values is presented in Table 3.6.

Table 3.6. A comparison of maize CND sufficiency ranges and the published reference

	CND		**REFERENCE**		
Nutrient	Lower	Upper	Lower	Upper	Toxic
Macronutrient (%)					
N	2.04	2.72	2.6	3.1	> 3.75
P	0.20	0.26	0.3	0.4	> 0.5
K	2.29	3.07	2.1	2.6	> 4.0
Ca	0.58	0.78	0.2	0.5	> 0.9
Mg	0.25	0.33	0.2	0.3	> 0.5
S	0.16	0.22	0.16	0.22	> 0.8
Micronutrient (mg kg^{-1})					
Mn	55.7	74.4	20.0	150.0	> 200
Zn	16.8	22.5	28.0	51.0	> 100

% and mg kg^{-1} are units for nutrient range concentrations; references are from Reuters and Robinson (1997)

Most of the CND sufficiency ranges obtained in our study were in line with those of Reuters and Robinson (1997) except for some differences in the lower boundary of Ca ranges being three times than the 0.2 % published value while the upper boundary only varied by 60 %. Moreover, the CND sufficiency ranges for P and Zn, were smaller than the published reference (Table 3.6).

3.3.2.5. Occurrence of nutrient deficiencies in maize cropping in the highlands of Burundi

The occurrence of nutrient deficiencies followed a different ranking across both districts (Figure 3.4). In Buraza district, the most frequently occurring deficiencies were Zn (18 %), Mn (16 %) and N (10 %) respectively, while in Makebuko district P, N and Mg were found to be the most limiting nutrients in 21, 17 % and 13 % of the plots, respectively.

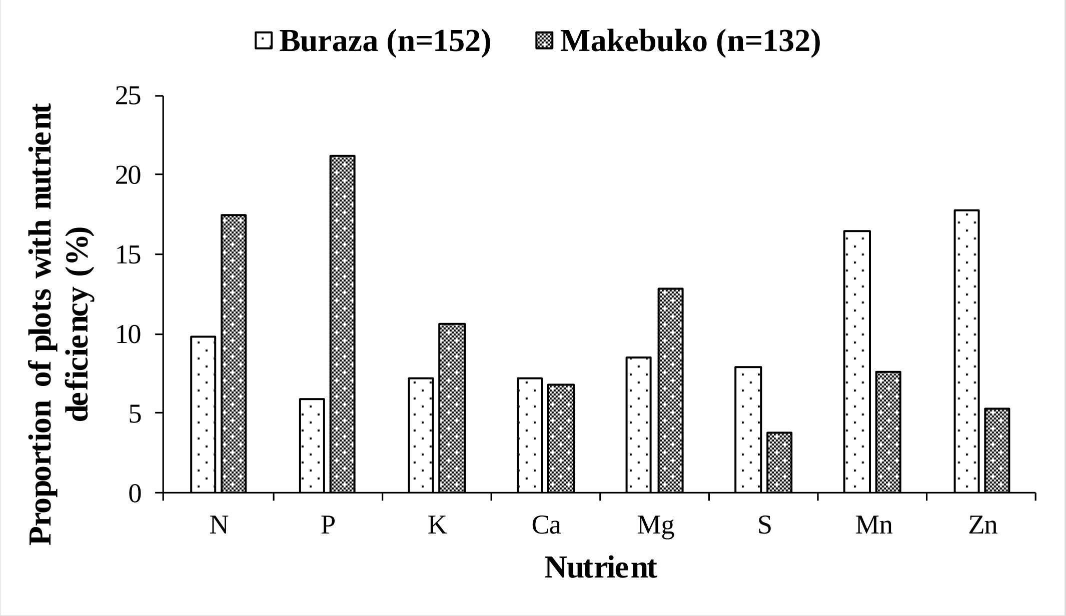

Figure. 3.4. Frequency of plots showing a specific nutrient deficiency in the study area

The contribution of DAP addition in remediating N- and P-deficiencies was limited since N- and P-deficiencies persisted in both control and fertilized plots across all districts. There were no larger responses to DAP for lower values of CND indices for N and P nutrients (Figure 3.5).

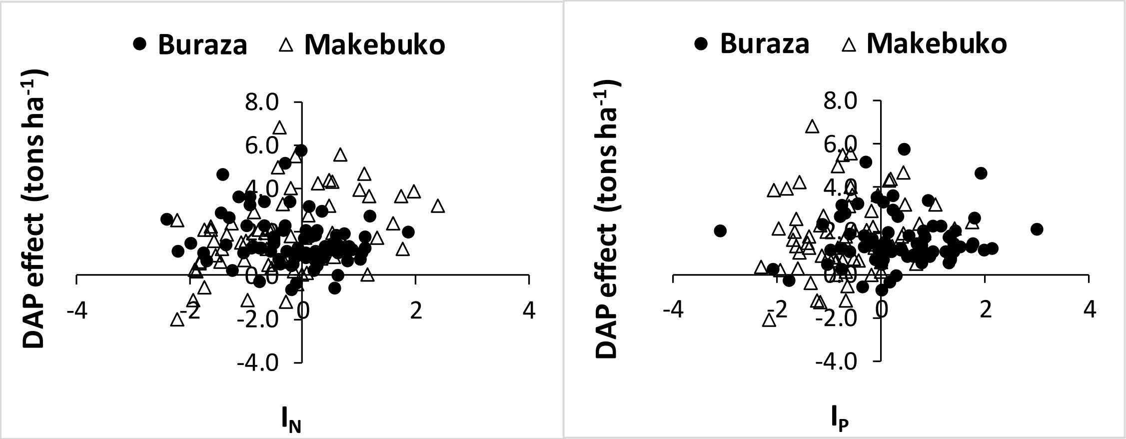

Figure 3.5. Relationship between DAP effect (yield with fertilizer minus yield without fertilizer) in tons ha^{-1} and CND indices for N and P nutrients (I_N and I_P).

Overall, N was deficient in 13 to 18 % of the control plots, compared to 7 to 17 % of the fertilized plots in Buraza and Makebuko districts, respectively. P was deficient in 4 to 23 % of the control plots, compared to 8 % to 20 % of the fertilized plots again, across all districts. It is clear that N and P-deficiencies persist after the DAP treatment while it is becoming less prevalent (Table 3.7).

From all 284 surveyed plots, only 37 (13 %) did not show any nutrient deficiency. Only 6 % of the control plots (n = 16) did not show any nutrient deficiency while with the DAP-treatment this proportion was increased to 7 % (n = 21) of the fertilized plots (Table 3.7).

Table 3.7. Frequency of nutrient deficiencies in Buraza and Makebuko districts ranked according to frequency of occurrence

District/ Ranking*		**1**		**2**		**3**		**4**		**5**		**6**		**7**	
		Nut	%	Nut	%	Nut	%	Nut	%	Nut	%	Nut	%	Nut	%
Buraza (n = 152)	NF (n=76)	Zn	21	Mn	20	N	13	Ca, Mg & S	7	K	5	P	4	Fv	3
	F (n=76)	Zn	14	Mn	13	Mg	11	K & S	9	P, Ca & Fv	8	N	7		
Makebuko (n = 132)	NF (n=66)	P	23	N	18	Mg	14	K	12	Mn	9	S	8	Ca	6
	F (n=66)	P	20	N	17	Mg	14	K	9	Ca & Zn	8	Mn	6	Fv	5

* 1, 2, 3, 4, 5, 6 and 7: Ranking order from the most to the least limiting nutrient; Nut: nutrient; NF: Non-fertilized plots; F: Fertilized plots; %: proportion of plots showing nutrient deficiency for each treatment and per district.

3.4. Discussion

3.4.1. Effect of DAP fertilizer use on maize grain yield

The observed variation in maize grain yield can be attributed to the DAP fertilizer use. The large maize grain yield increase observed in the fertilized plots above those obtained from the control plots pinpoints the need for soil nutrient replenishment for sustainable maize production in Burundi (Muthuri, 2017). While maize grain yields were significantly different between the districts and fertilizer had significant effects in both districts, the interaction between district and fertilizer was not significant. Moreover, DAP effect can also be explained by management issues, soil acidity or other parameters which were not measured in this study but cannot be ruled out.

3.4.2. Compositional maize nutrient diagnosis

3.4.2.1. Partitioning between high and low yielding subpopulations

Our decision to retain 3.9 tons ha^{-1} as a reasonable yield cut-off for maize in the studied region was to produce narrow nutrient sufficiency ranges. It also led to a large number of samples in the low-yielding subpopulation. Walworth and Sumner (1987), cited by Khiari *et al.*, (2001b) stated that it is desirable to maximize the number of specimens unequivocally belonging to the low-yielding subpopulation in the survey population. The proportion of low yield specimens for a yield target of 3.9 tons ha^{-1} is 53 % and the corresponding critical $CNDr^2$ value is 7.5. As shown by the CNDr^2 distribution function, the higher the proportion of low yield subpopulation, the lower the critical CNDr^2.

Moreover, Khiari et al. (2001b; Khiari et al., 2001c) showed for sweet corn and potato crops that the higher the yield target, the narrower the range in leaf nutrient concentrations. Khiari et al. (2001c) also reported that higher yield targets would increase the proportion of low-yielding specimens in a population and produce narrower nutrient sufficiency ranges.

The high-yielding subpopulations are dominated by fertilized plots coupled with large concentrations of N and P in the maize ear leaves. This clearly indicates that these nutrients limit maize production in Central Burundi (Niyuhire et al., 2017). The soil total N and available P were somehow below the critical requirement (Table 3.1) explaining the high yield response obtained in the fertilized plots.

3.4.2.2. CND sufficiency ranges and nutrient deficiencies in highland maize cropping of Burundi

Most of CND nutrient sufficiency ranges in Buraza and Makebuko districts were in line with already published references. The discrepancies observed between both approaches (CND and literature references) can be explained by differences in soil type, climate, maize variety, crop management and nutrient supply (Njoroge et al., 2017).

Since 1 kg of DAP was given to farmers to be used following their local practices and on variable plot sizes, the rates of DAP applied were different within district and between districts. Thus, the rates of N and P applied were also different among farmers and districts. The occurrence of nutrient deficiencies showed that 1 kg of DAP resulted in some removal of N and P deficiencies especially in Buraza district. However, N and P remained mainly limiting for maize productivity in both control and fertilized plots in Makebuko district. The persistent P-deficiency is not a surprise and may be due to the strongly acid, P-fixing soils (Table 3.1), and has already been observed by PANSEB (2013), Nziguheba *et al*., 2015 and many others in Central Africa. The work of PANSEB showed the soil fertility maps of Burundi for each nutrient and the required rates of nutrient per major crop in Burundi. We arrived at similar findings while I could not access the raw data. The nutrients retained for this work were N, P, K, S, Ca, Mg, Zn, Cu and B. Soil total N was determined using Kjeldahl acid digestion method while atomic emission spectrometry (ICP), using Mehlich 3 was adopted for Olsen P, available K, Ca, Mg, Na, Mn, Fe, Cu, B, S and Zn. The major crops described in the former report were maize, beans, Irish potato, rice, wheat and cassava. The major nutrient deficiencies found for maize in Gitega Province were N **(**Low to very low), Olsen P (< 5.0 $mg.kg^{-1}$). The optimum for P should be between 20.1 and 100 $mg.kg^{-1}$. 85% of Burundian soils were characterized by P deficiency. K was slightly (90-120 $mg.kg^{-1}$) low to very low (< 60 $mg.kg^{-1}$). The optimum for K should be between 120.1 à 390.1 ppm. Available S was slightly low (10.1-20.0 $mg.kg^{-1}$). The optimum for S should be between 20.1 à 50.0 $mg.kg^{-1}$. 71% of Burundian soils are deficient in S. Available Ca and Mg were low for Gitega (200-400 $mg.kg^{-1}$); the optimum should be between 800.1- 2000.0 $mg.kg^{-1}$. Zn content was ranging from low (0.51-1.0 $mg.kg^{-1}$) to very low (< 0.50 $mg.kg^{-1}$). 62% of Burundi soils are deficient in Zn.

Nziguheba et al . (2015) reported that P deficiency occurs in many soils of Central Africa, due not only to P-depletion through crop harvest and erosion but mainly to the prevalence of highly P-fixing soils in the region. The highlands are dominated by acid P-fixing soils belonging to the orders of Ferralsols, Acrisols, and Nitisols (Sanchez et al., 1997; Bationo et al., 2012). Hence phosphorus becomes the major limiting nutrient for maize production in many soils. While the use of large amounts of P fertilizers could be the most plausible way to overcome P limitation, their high cost limits the accessibility to smallholder farmers (Nziguheba *et al.*, 2015). Managing these soils would require a combination of inputs including fertilizers, liming and organic inputs, in line with the Integrated Soil Fertility Management principles (Vanlauwe *et al*, 2015).

It is remarkable that Zn and Mn-deficiencies occurred in both control and fertilized plots of Buraza district. Zn and Mn-deficiencies are expected to limit yields. We observed in this study that actually in Buraza district, the DAP fertilizer induced a smaller yield increase on average (29 %) compared to the one in Makebuko district (46 %) where these two nutrients are not limiting. Mn-deficiency can induce poor tasselling and delays anther development resulting in Mn-deficient plants producing fewer and smaller pollen grains with reduced cytoplasmic contents (Sharma et al., 1991). Yet, Zn-deficiency is not extreme and hence does not preclude a crop response to DAP. Reasons for the striking differences in nutrient deficiencies between Buraza and Makebuko districts could be due to the differences in soil type, crop management, population density and altitude (Table 3.1) but remain to some extent elusive. Low Zn in the harvested yield also negatively affects human health through the low concentrations of Zn in people's diet (Alloway, 2009). Zn-deficiencies were also found by Nziguheba et al. (2009) when assessing nutrient deficiencies in maize in the West African Savanna by using Diagnosis Recommendation Integrated System (DRIS). An addition of Zn and Mn to the experimental design could had allowed a fair assessment of the nutrient norms for these elements. However, information is not sufficient to establish the scale of these deficiencies and a strategy to address these deficiencies is lacking.

Application of secondary and micronutrients (SMNs) can have significant effects on crop yields in SSA but has received less attention than the macronutrients N, P, and K, as illustrated by the fact that most fertilizer subsidy programmes primarily focus on NPK fertilizers. This may be due in part to a commonly expressed belief that there is no need to address other nutrients while the continent is still struggling to adopt macronutrient fertilizers. But indeed the reverse is more likely to be true: where SMN deficiencies exist, they can limit response to NPK fertilizers (Vanlauwe *et al.*, 2015).

Our findings highlight the need, to emphasize on the primary and micro-nutrient deficiencies per district for a better site specific fertilizer recommendation to maize production; especially in areas where management has often induced substantial differences in nutrient status among fields, for site specific fertilizer recommendations, where fertilizer is either relatively expensive and/or scarce.

3.5. Conclusion

The application of the CND approach to our dataset revealed the most obvious nutrient deficiencies in maize: Zinc and Manganese for Buraza district; Nitrogen and Phosphorus for Makebuko district. A clear difference between the districts emerged, where in Buraza district Zn and Mn-deficiencies were the most prominent issue while they were totally not an issue in Makebuko district. In the latter district, nitrogen and phosphorus were the most important limiting nutrients, phosphorus ranked first in the control plots while the same was true for nitrogen in the fertilized plots. Strategies for soil fertility improvement should include measures to replenish Zn and Mn alongside the macronutrients N and P based on the different most striking nutrient deficiencies identified per district. We can assume that the usefulness of the CND approcah could be corroborated by relating norms to the response to nutrients supplied. The development of site-specific fertilizer recommendations will increase farm productivity and profitability. This will improve the livelihoods of the smallholder farmers in Burundi. Given the usefulness of the CND approach, it is necessary to conduct a validation study that could establish norms for a wide range of nutrient ratios, including both macro and micronutrients, which can be referred to while conducting CND analysis in the Central Africa.

PART II

Chapter 4

Profitability of diammonium phosphate use on local and improved varieties of bean and maize in smallholder farms of Central Burundi

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4.1. Introduction

Food insecurity in sub-Saharan Africa (SSA) is mainly constrained by low agricultural productivity (Norton et al., 2014). Low soil fertility, limited availability of resources to farmers, nutrient mining and drought are the main causes of low agricultural productivity in SSA (McCann, 2005; Mucheru-Muna et al. 2010). Studies by Sanginga and Woomer (2009) indicate that low soil fertility and nutrient depletion continue to represent huge obstacles in securing required harvests in Africa. Nutrient depletion is reflected in food deficits and hence in continuous food aid, specifically in SSA. This concern led the African governments to pursue different agricultural policies and strategies, among others promoting adoption of new technologies, to boost agricultural production, and therefore reduce poverty (Jayne et al., 2003). However, and despite their potential to increase agricultural productivity, technologies such as the use of fertilizers, improved varieties and the application of pesticides have not been significantly adopted by farmers, especially in SSA (Beddington, 2010).

In Burundi, joint efforts from the Government and its development partners are underway to pursue these agricultural policies and strategies to enhance agricultural production to ensure food security.

Improving food security through increased food production capacities is one of the major action points of the country's Poverty Reduction Strategies framework II (Burundi, 2012). Key government institutions involved are "The Institut des Sciences Agronomiques du Burundi" (ISABU) and "the Ministry of Agriculture and Livestock" (MINAGRI) together with other stakeholders such as the European Union (EU) and FAO. The non-governmental organizations are supporting the Government in its efforts to revitalize the agricultural sector through the introduction of best farming techniques to increase productivity. These organizations help at farm level in the dissemination and supervision of best farming practices and techniques as transferred by the agricultural research institute and other stakeholders. The most commonly disseminated techniques include the use of improved farm inputs such as seeds, fertilizers and pesticides, soil fertility management through erosion control techniques and others (Ahishakiye, 2011).

However, most of the rural population in Burundi deals with a poor purchasing power, and a large cost and restricted availability of fertilizers in the countryside. Hence, the small amount of fertilizer available is used mostly on cash crops (Wodon et al., 2008). Moreover, farmers prefer using improved seeds, but most of the times do not use the recommended quantity of seeds as they are often out of reach in terms of cost and market availability. The distance to where input sources can be purchased is also a major constraint (Ochieng et al., 2014).

Beans and maize as mentioned in chapter 2 are among the most important subsistence crops in terms of food production. The report by FAOSTAT (2014) indicates that dry bean (*Phaseolus vulgaris* L.) is the third most produced crop in Burundi after banana and sweet potato. Beans are a major source of food and revenue for smallholder farmers who make up the bulk of the poor population (Ochieng. et al., 2014). The average per capita consumption of beans in Burundi of 60 kg year^{-1} is among the highest in the world (FAOSTAT, 2014). However, the growth of the bean subsector faces several production challenges. These include, in order of importance, unpredictable weather, pests and diseases, the high cost of new improved varieties, lack of capital, and lack of adequate land (Birachi et al., 2011). Maize is also an important subsistence crop next to beans and bananas. It is the most important cereal in terms of total food production and total area under cultivation (FAOSTAT, 2014). In 2013, the maize cultivation covered a total area of 123,000 hectares at a total production of 162,400 tonnes of grain, or an average maize grain yield of only 1.3 tons ha^{-1} (FAOSTAT, 2014).

This chapter assesses the profitability of diammonium phosphate (DAP, 18-46-0) use on local and improved varieties of climbing bean and maize in smallholder farms of Buraza district of Gitega province in Central Burundi.

4.2. Material and Methods

4.2.1. Study area

The study area as described in chapter 2, was conducted in Buraza district (3°45′08″ S, 29°53′50″ E), Gitega Province in Central Burundi. All the characteristics related to climate, rainfall, temperature and soil type are the same within the first season (LR 2012) for beans and the subsequent season (SR 2013) for maize, respectively.

4.2.2. Experiment layout and management

The field experiment was conducted over two seasons, assessing the profitability of DAP fertilizer use to an improved climbing bean variety planted in LR 2012, and an improved maize variety planted during SR 2013. Before trial establishment, the fertility status of the selected fields was characterized based on composite soil samples taken from the 0 to 20 cm layer in each farmer's field. Composite soil samples were taken at eight different locations in each farmer's field, thoroughly mixed, then air-dried and sieved over a 2 mm screen before being shipped to the International Center for Tropical Agriculture (CIAT) in Nairobi for analysis. Analysis results are presented in Table 1.

Table 4.1. Selected physico-chemical properties of top soil (0 - 20cm) samples from 63 climbing bean and 39 maize fields in Buraza district of Gitega province (Burundi)

Soil parameters measured	Unit	Climbing bean fields (n = 62)	Maize fields (n = 39)
pH_w		5.49 (±0.06)	5.58 (±0.11)
Olsen P	mg kg^{-1}	8.65 (±1.33)	10.69 (±2.54)
TC	g kg^{-1}	20.3 (±0.06)	21.7 (±0.08)
TN	g kg^{-1}	2.0 (±0.01)	2.0 (±0.01)
Clay	%	38.70 (±0.53)	38.17 (±0.53)
Sand	%	41.67 (±0.27)	41.84 (±0.31)
Silt	%	15.69 (±0.35)	15.41 (±0.40)

Values are means with standard error between brackets.

The trial establishment was performed at the onset of each season by the farmers and supervised by a team of an agronomist and technicians. All field operations during crop growth were performed by farmers while observations during growth and at the harvest were taken by the agronomist and technicians. Climbing beans and maize were planted on different fields. Local varieties were supplied by farmers while improved varieties and DAP fertilizer were given by the research team. The experiment design was a latin-square (species randomized in the x-direction and fertilizer application in the y-direction).

4.2.2.1. Climbing beans

Trials were carried out in 62 randomly selected fields of Buraza district. The slope threshold of the selected fields was 10 %, in the selected fields ranging from 0.2 up to 7.5 %. Fields next to the scrubland, recently cleared and/or isolated fields were avoided. In each field, four plots were demarcated to accommodate a local and an improved climbing bean variety each receiving two treatments, a control without fertilizer, and a treatment with DAP, applied at two bags (2 bags of 50 kg) per hectare (18 kg N ha^{-1} and 20 kg P ha^{-1}). The DAP was applied per hill mixed with soil as a single dose just before planting.

The plot size measured 36 m^2 (6 m x 6 m). The spacing was 40 cm between plants and 50 cm between planting lines within two seeds per hill. Local ("*AMAKUTSA*") and improved (G13607) climbing bean varieties, commonly recommended for the middle and high altitudes (Ntukamazina, 2008), were used in the first season (LR 2012).

4.2.2.2. Maize

Maize was planted in the SR season (SR 2013) in 39 randomly selected fields within Buraza district. The slope of the fields where trials were installed ranged from 1.2 to 7.6 %. In each field, four plots were demarcated to accommodate a local or an improved maize variety, each receiving two treatments, a control without fertilizer, and a treatment with DAP applied at two bags (2 bags of 50 kg) per hectare (18 kg N ha^{-1} and 20 kg P ha^{-1}). Local "*ISEGA*" and improved "*ZM605-24C*" maize variety, commonly recommended for the middle and high altitudes, were used for the experimentation. "*ZM605-24C*" is an open pollinated maize variety from CIMMYT Zimbabwe, The DAP was applied as a single dose just before planting. Urea ($CO(NH_2)_2$) (50 kg ha^{-1}) was broadcast as basal in two fractions, the first half was applied before planting whereas the second half was applied at silking stage in both treatments. In the fertilized plots, the first half of the urea was mixed with DAP before planting. The spacing was 50 cm between plants and 75 cm between planting lines within two seeds per hill.

At maturity, climbing beans and maize were harvested by the farmers under the supervision of an agronomist and technicians at maturity in a net plot (10 and 6 rows respectively for bean and maize crops in each plot), and the fresh weight of both grains was taken. The bean and maize grains were then air-dried and the dry weight taken.

4.2.3. Statistical analyses

Data analysis started using descriptive statistics in Excel (Microsoft Office, 2013). Statistical significances between fertilizer treatment, variety type and their interactions were tested with the Student *t* test with $P < 0.05$. The effects of various factors and their interactions were compared by computing the standard error of difference. The variation in fertilizer and variety effects between farms were also carried out and expressed in a cumulative frequency distribution curve.

Regression tree analysis using the *"rpart"* package (Therneau et al., 2015) was used as a way of making quantitative predictions (for soil covariates and delay in planting) and was fitted to each node to give the predicted values of the dependent variable (fertilizer/variety effects). Tree models are computationally intensive techniques for recursively partitioning response variables into subsets based on their relationship to one or more (usually many) predictor variables. Recursive partitioning is a fundamental tool in data mining. It helps us explore the structure of a set of data, while developing easy to visualize decision rules for predicting a categorical (classification tree) or continuous (regression tree) outcome. All tree-based techniques produce one or more tree objects that represent a series of splits from the 'root' or top of the tree. Each split is based on finding the one predictor variable (and a given threshold of that variable) that results in the greatest change in explained deviance. The soil covariates were pH, Olsen P, total N, total C and soil texture. The delay in planting was defined as the number of days that passed since the first farmer planted. These predictors were then plotted in regression trees for both variety and fertilizer effects. As the datasets were rather small (62 fields for beans and 39 fields for maize), two levels were retained for each tree for fertilizer and variety effects while only one level was retained in the regression tree for profitability of improved bean and maize varieties in order to maximize their probability. These trees were based on a modelled distribution of yield effects.

4.2.4. Economic analysis

A simple financial analysis was performed to assess the profitability of the treatments. The total cost (TC) of the operations included the costs for land preparation, seeds, application of DAP fertilizer input, staking for climbing bean, weeding, harvesting and post-harvest handling. Staking one hectare of climbing bean requires around 25,000 stakes, with a cost estimated at $ 350; corresponding to that used by Ruraduma et al. (2012). In this study, one stake was used for 4 plants (2 hills) and gave the highest yield (Ruraduma et al., 2012). Labor was valued at a wage of $ 0.17

per hour. One bag of 50 kg of fertilizer costed \$ 40 and \$ 26.67 for DAP and urea, respectively. Bean and maize grains were sold at 0.67 and 0.4 \$ kg^{-1}, respectively. This analysis was done for individual crops (bean and maize) and for crop type (bush or climbing bean) by using the farm gate prices of the inputs and outputs. Original prices were recorded in Burundese Francs (BIF) and converted to US dollars (U\$). One U\$ was about 1500 BIF in February 2012.

Net benefits (NB), expressed in \$ ha^{-1}, were calculated as the production value (PV) minus the total costs (TC). To assess profitability of fertilizer use, the value cost ratio (VCR, \$ $\$^{-1}$) and marginal rate of return (MRR, \$ $\$^{-1}$) of fertilizer use were calculated as the ratio of the difference in PV between the treatment with fertilizer and the control, over the difference in TC, and the ratio of the difference in NB between the treatment with fertilizer and the control, over the difference in TC, respectively. To calculate the profitability for the crop type, PV, TC and NB were summed for the bean and subsequent maize crop, and then the VCR and MRR were calculated. The VCR of an alternative practice should preferably be 2 minimally (CIMMYT, 1988) before considered to be profitable to farmers.

Regression tree analysis was then performed to indicate those covariates that explain the most profitable VCR values for bean and maize crop type. Covariates include the soil parameters (pH, Olsen P, total C, total N, clay, sand and silt) and delay in planting (renamed as delayPBeans and delayPMaize).

4.3. Results

4.3.1. Production of bean and maize crops under different practices

4.3.1.1. Means and variation in distributions of varieties and fertilizer effects

a) Climbing beans

Yields for local climbing bean variety (LCB) are on average 1733 kg ha^{-1} in the non-fertilized plots and 2225 kg ha^{-1} in the fertilized plots. Hence the yield increase due to fertilizer addition is on average 28 % (492 kg ha^{-1}). For the improved climbing bean variety (ICB), the yields are on average 2293 kg ha^{-1} in the non-fertilized plots and 3060 kg ha^{-1} in the fertilized plots. The yield increase is then on average 33 % (766 kg ha^{-1}). Large and significant ($P \leq 0.05$) differences in average yields between the local and improved climbing bean varieties were obtained in the control (32 %) and fertilized (37 %) plots, respectively (Table 4.2).

Table 4.2. Mean grain yields (kg ha^{-1}) of local and improved climbing bean varieties for both control and fertilized plots of the individual fields (n = 62)

Treatment	**LCB**	**ICB**
	….Overall mean grain yields (kg ha^{-1})…….	
Control	1733.44 (±101.88)	2293.24 (±113.42)
DAP	2225.37 (±109.52)	3059.62 (±100.78)
SED	150	152
SED Fertilizer	100***	
SED Bean type	152***	
SED FxBT	173**	

LCB: local climbing bean variety; ICB: improved climbing bean variety; SED: standard error of difference (only presented when significant at $P \leq 0.05$); *** significant at $P \leq 0.001$; ** significant at $P \leq 0.01$.

It is clear that an improved bean variety is more responsive to applied fertilizer than the local bean variety and also produces a larger yield in the non-fertilized plots than the local variety ($P \leq 0.05$).

The differences between the mean grain yields of the two bean varieties, fertilizer treatments and their interaction are clearly largely significant ($P \leq 0.01$).

Effects of a change in climbing bean variety (improved instead of local climbing bean) were positive for about 81 and 90 % of the farmers in the control and fertilized plots, respectively, while fertilizer effects were positive for about 95 % and 98 % of the farmers for the local and improved climbing bean variety (Figure. 4.2). Variance in bean varieties' effects was relatively smaller than variance in fertilizer effect.

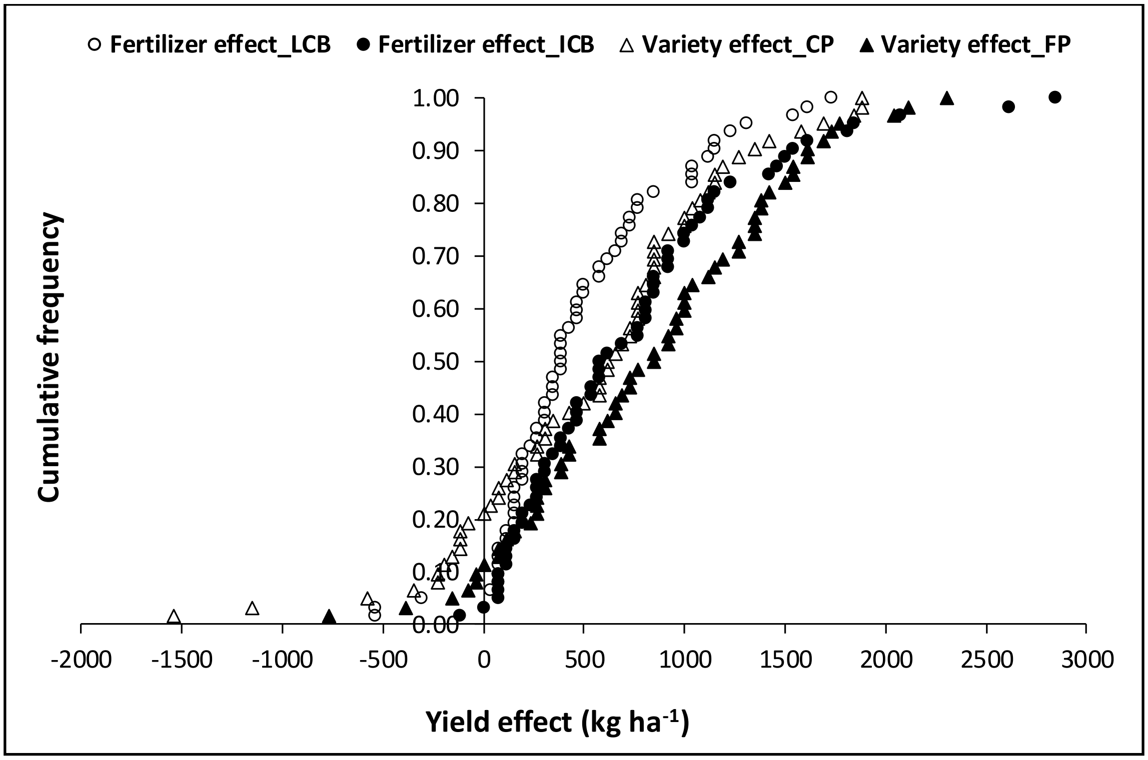

Figure 4.1. Cumulative distribution of the variety effect (ICB yield-LCB yield for both control and fertilized plots) and the fertilizer effect (yield with fertilizer minus yield without fertilizer). CP: Control plots, FP: Fertilized plots

b) Maize

Yields of the local maize variety (LM) are on average 1737 kg ha^{-1} in the non-fertilized plots and increase up to 3055 kg ha^{-1} in the fertilized plots. Hence, a yield increase of 76 % (1318 kg ha^{-1}) is derived from fertilizer addition. For the improved maize variety (IM), the yields are on average 3979 kg ha^{-1} in the non-fertilized plots and 5230 kg ha^{-1} in the fertilized plots. The yield increase is then 31% (1251 kg ha^{-1}). Differences in average yield between the two maize varieties were significant and large ($P \leq 0.01$). Large significant differences between the means were also found between all treatments (Table 4.3).

Table 4.3. Mean grain yields (kg ha^{-1}) of local and improved maize varieties for both control and fertilized plots of the individual fields (n = 39)

Treatment	**LM**	**IM**
Control	1737.32 (±37.22)	3979.37 (±202.66)
DAP	3055.16 (±90.18)	5230 (±199.57)
SED	98	284
$\text{SED}_{\text{Fertilizer}}$	222***	
$\text{SED}_{\text{maize type}}$	206***	
SED_{FxBT}	ns	

LM: local maize variety; IM: improved maize variety; SED: standard error of difference (only presented when significant at $P \leq 0.05$); *** Significant at $P \leq 0.001$; ns: not significant.

The production of local and improved maize varieties with use of DAP fertilizer is summarized in Figure 4.2. With use of local maize variety, the average grain yields are 1737 kg ha^{-1} in the control plots and 3055 kg ha^{-1} in the fertilized plots. This is a fertilizer-induced yield increase of 76 % (1318 kg ha^{-1}). For the improved maize variety, the grain yields are on average 3979 kg ha^{-1} in the control plots and 5230 kg ha^{-1} in the fertilized plots. The fertilizer-derived yield increase hence is on average 41 % (1251 kg ha^{-1}). The grain yields were significantly different between the two maize varieties ($P < 0.05$) irrespective the treatments.

Both the improved and local variety respond to fertilizer in the same way; they are equally responsive to fertilizer.

The variation in yield effect between the different farmers is smaller for fertilizer effects (DAP vs Control), than for maize varieties effects (IM vs LM). For about 99 % of the farmers, fertilizer and variety effects are positive and significantly larger with the improved variety ($P < 0.05$) (Figure 4.2).

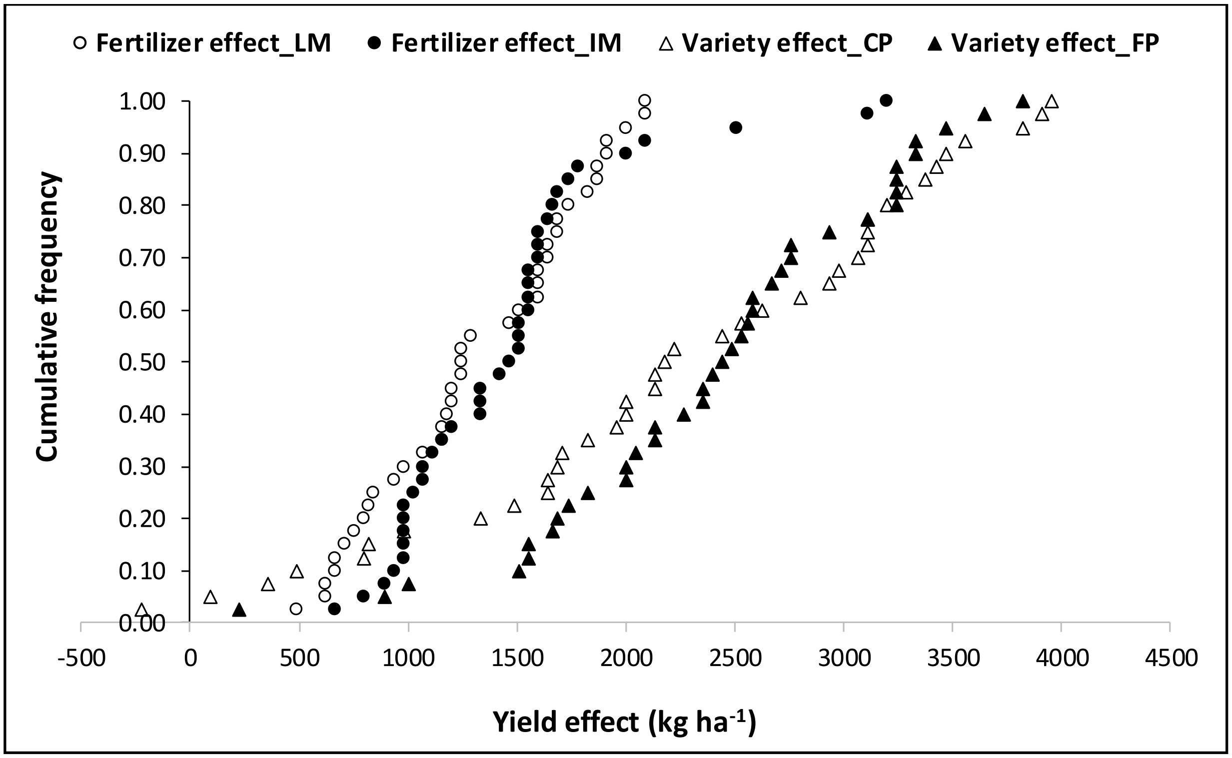

Figure 4.2. Cumulative distribution of the fertilizer effect (yield with fertilizer minus yield without fertilizer) (right) and the variety effect (IM yield-LM yield) (left) for maize. These differences are plotted in the X-axis as the yield effect in kg ha^{-1}. LM: Local maize; IM: Improved maize; CP: Control plot; FP: Fertilized plot

4.3.1.2. Varieties and fertilizer effects as affected by soil covariates and crop management

The relationships between variety and fertilizer effects were first tested with soil covariates (pH, Olsen P, total C, total N, clay, sand and silt) and they were found to be weak. Next we added the "delay in planting" as part of the crop management, to the soil covariates to check for significant predictors. We did not include other data related to crop management (weeding, cropping cycle, etc.) in the analysis because they were standardized and hence cannot explain variation.

In the bean season, variety effects were larger in soils that have larger total N (TN > 1.5 g kg^{-1}) and total C (TC > 16 g kg^{-1}) contents. Fertilizer effects were larger when planted early (DelayP < 10 days). Larger fertilizer effects were likewise found in soils with a pH below 5 (Figure. 4.3).

For the maize season, variety effects were large when planted early (DelayP < 4.5 days), in soils with large clay (clay > 38 %) content. Fertilizer effects were large in soils with clay content less than 40 % and high total C (TC ≥ 19 g kg^{-1}) content (Figure 4.3).

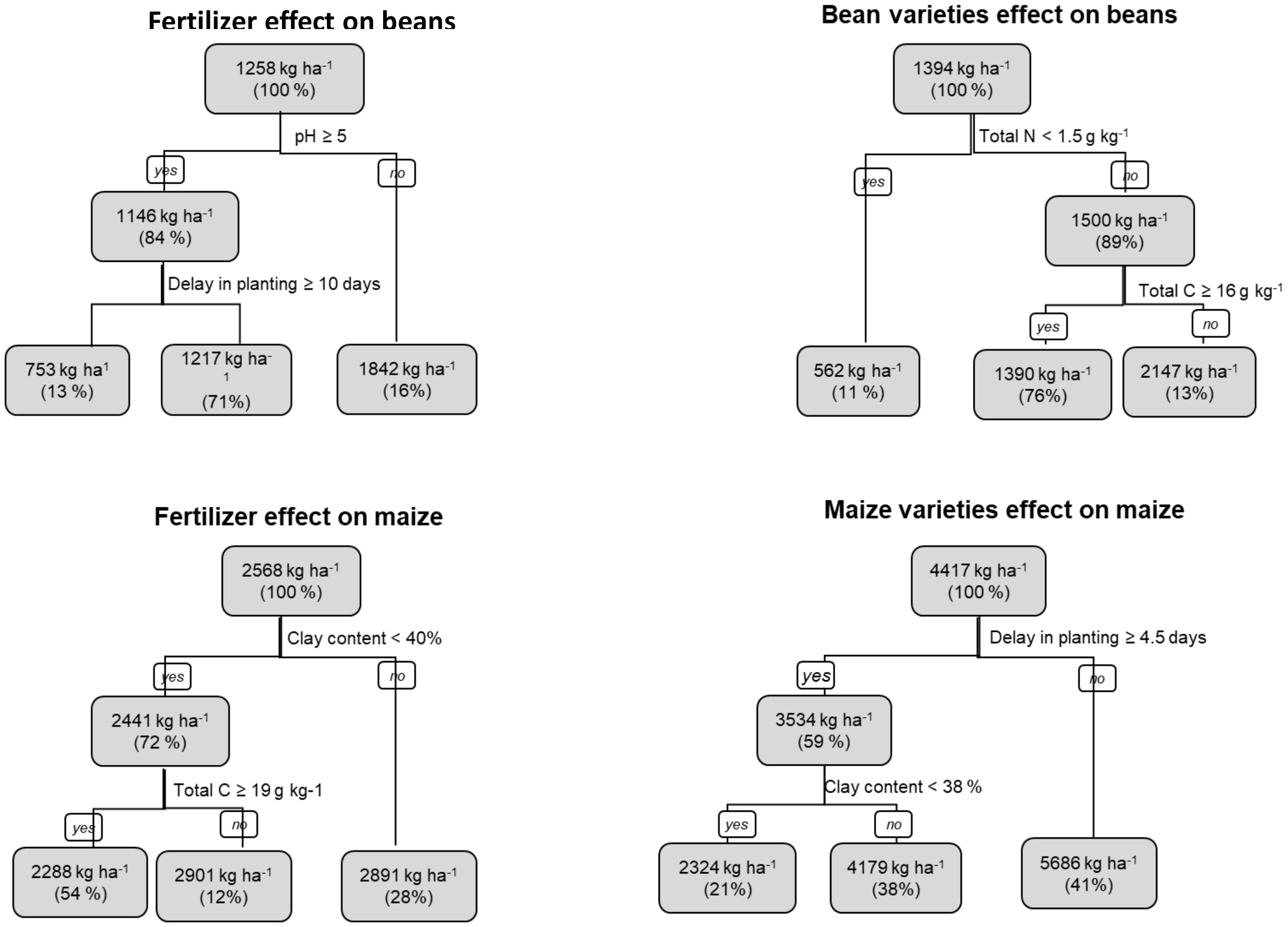

Figure 4.3. Regression trees analysis results for the individual 62 and 39 beans and maize fields, respectively, restricted to two branching depths in the study, for BLUPs for climbing bean varieties or fertilizer effects as explained by soil parameters and delay in planting. The average grain yield effects and proportion of observations (%) are also shown at each node

4.3.2. Economic analysis

The economic returns from the application of DAP fertilizer to climbing bean and maize crops were positive, thus producing a positive net benefit for both traditional and improved varieties. The net benefits were on average, twice as large for ICB (\$ 1279 ha^{-1}) than for LCB (\$ 683 ha^{-1}) in the control treatment. In the corresponding fertilized treatment, the trend was also the same for the net benefits ($P < 0.05$) between the two bean varieties. The differences in net benefits were due to the differences in the unit price for seed and grain between LCB and ICB. Fertilizer use increased total costs (TC), slightly increased NB (on average) but significantly ($P < 0.05$) when applied to LCB, and significantly increased very much ($P < 0.001$) when applied to ICB. Moreover, the Value Cost Ratio for ICB was on average larger than that of LCB (4.79 versus 3.19 respectively) (Table 4.4). Referring to the marginal rate of return, for every $ 1.00 invested in bean cropping, a farmer can expect to gain $ 2.19 with LCB while obtaining an additional $ 3.79 with ICB. In general, the marginal rate of return is considered as profitable when it is larger than one (CIMMYT, 1988) and this has been achieved respectively by 61 % (n = 38) of farmers using LCB and 63 % (n = 39) for those growing ICB (Table 4.4). DAP fertilizer induced large differences in net benefits between LCB and ICB. The Value cost ratio and marginal rate of return were also larger for ICB than for LCB ($P < 0.001$).

The net benefits for IM were on average 3 times larger ($ 1349 ha^{-1}) than for LM ($ 346 ha^{-1}) in the control treatment and being twice as large in the corresponding fertilized treatment (Table 4.4). The value cost ratio for IM was on average larger than that of LM (7.33 versus 5.43 respectively). Moreover, the marginal rate of return followed the same trend as for value cost ratio. For $1.00 invested in maize cropping, farmer could expect to gain $ 4.43 for LM; recover the $1.00 and obtain an additional $ 6.33 for IM. The value cost ratio has also increased on average being larger than 2 across all cropped fields (Table 4.4). From this study, the use of DAP fertilizer to improved varieties was found profitable for both bean and maize crops and for all farmers within the study area.

Table 4.4. Financial analysis, including total costs (TC), net benefits (NB), value cost ratio (VCR), and marginal rate of return (MRR) from the application of DAP fertilizer to local, improved climbing bean (n = 62) and maize (n = 39) varieties in Buraza district

Crop type	**TC**		**NB**		**VCR**	**MRR**
	Control	DAP	Control	DAP		
	……………………….. $ ha^{-1}………………………				………. $ $$^{-1}$…………..	
First season (LR2011)						
LCB	224	304	683	859	3.19	2.19
ICB	242	322	1279	1582	4.49	3.79
Second season (SR2012)						
LM	209	289	346	700	5.43	4.43
IM	224	304	1349	1856	7.33	6.33

LCB: local climbing bean; ICB: improved climbing bean. LM: local maize; IM: improved maize; SED: standard error of difference; TC: total cost ($ ha^{-1}); NB: net benefit ($ ha^{-1}); VCR: value cost ratio ($$$^{-1}$); MRR: marginal rate of return ($$$^{-1}$); #SED: standard error of Difference (only presented when significant at $P < 0.05$); ns: not significant

In the fertilizer response treatment, the application of DAP to improved maize increased the net benefits and the value cost ratio to a larger extent than with local maize. Yet, the use of DAP fertilizer was cost-effective, despite the high price.

Figure. 4.4 shows cumulative distribution of the value cost ratio (VCR) for fertilizer cumulated over the local and improved climbing bean and maize varieties, respectively plotted for the individual 62 and 39 fields in the study. The VCR of improved climbing bean was profitable for 65 % of the farmers, while only profitable for 63 % of the farmers with the local climbing bean. For maize cropping season, the VCR was profitable for all farmers with larger net returns with improved maize.

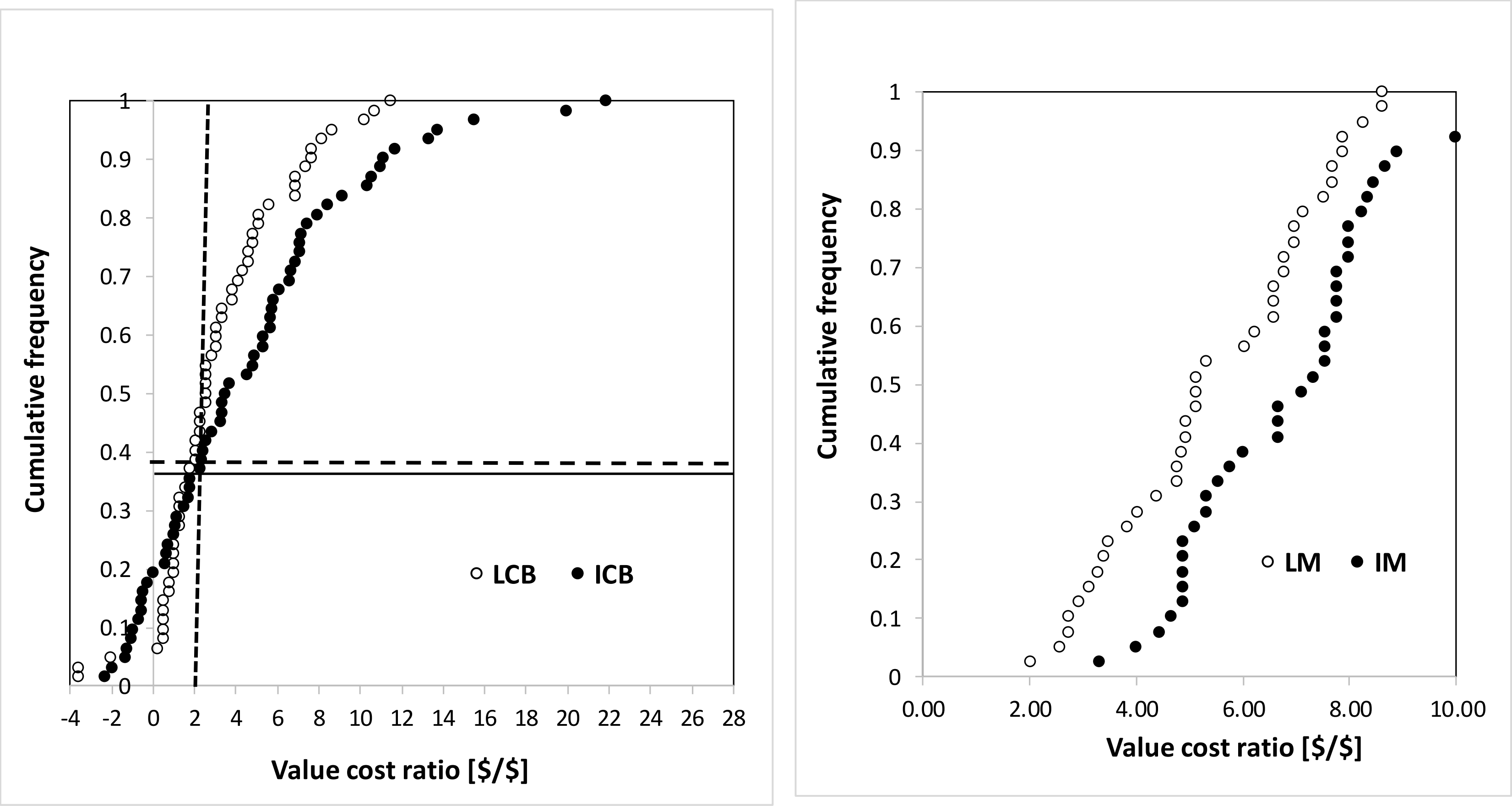

Figure 4.4. The cumulative distribution of the value cost ratio (VCR) for fertilizer cumulated over the local and improved climbing bean and maize varieties, respectively plotted for the individual 62 and 39 fields in the study. The cumulative probability (Y-axis) reflects the likelihood for obtaining a value larger than a given VCR (X-axis). In the left figure, vertical line denotes VCR = 2, and the dash and continuous bold horizontal lines which intersect with the cumulative distribution curves of VCR for local and improved climbing beans varieties, respectively, show the proportion of farmers who had a VCR > 2. All VCR values for fertilizer over the local and improved maize varieties are equal or larger than 2 in the right figure

The covariates that predict the high profitability for the improved climbing bean was soil total C below 2.5 g kg^{-1}. This denotes that fields with low profitability for beans in a soil with high total C content were probably fertile fields with high control yields. For improved maize, it was predicted by available P larger than 44 mg kg^{-1} (Figure.4.5).

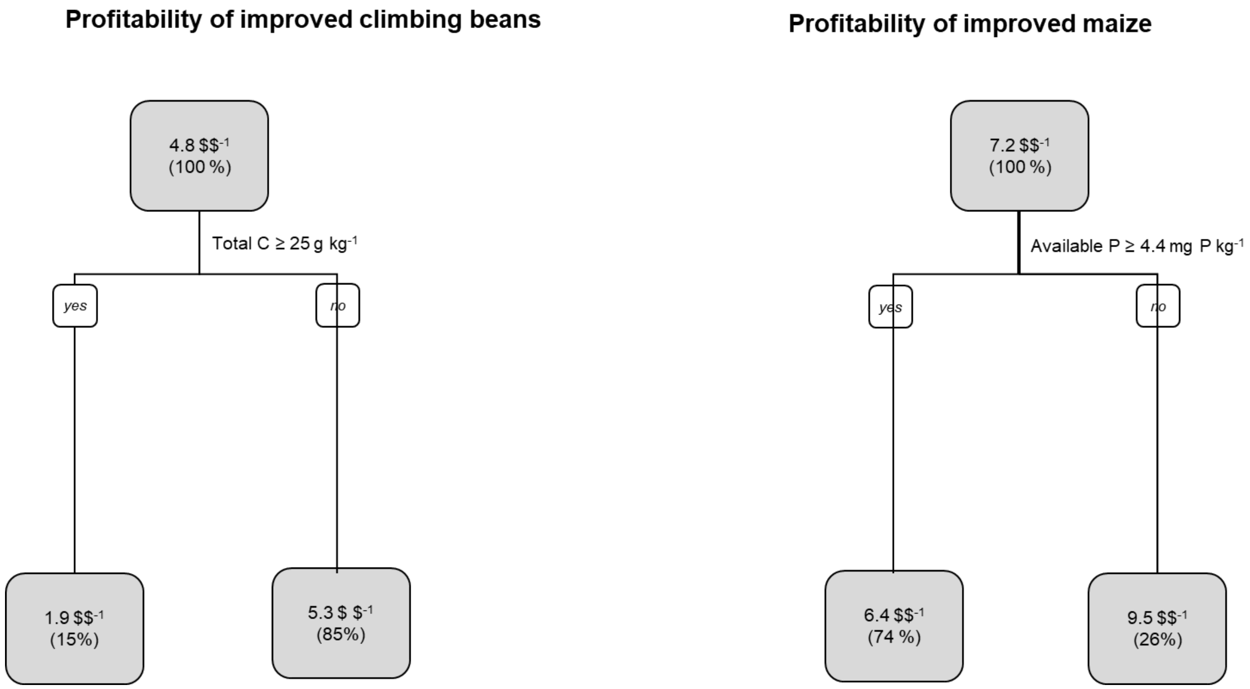

Figure 4.5. Regression tree analysis results, restricted to one branching depth, for profitability of improved climbing bean and maize as explained by soil covariates and delay in planting (for beans and maize). This one tree level is sufficient to distinguish the fields with low and high profitability for bean and maize varieties. The value cost ratio values and proportion of observations (%) are shown at each node

4.4. Discussion

4.4.1. The production of maize-based systems under different practices

The soils under study in Buraza district are acidic (Table 4.1) and need to be replenished with nutrients for a better crop production. In such depleted soils, strategic fertilizer application with incorporation of crop residues over several seasons would be necessary to increase yields over time. Alternative organic nutrient resources, such as compost and animal manures, may also play an important role in replenishing soil fertility, but available quantities are limited and the quality is often poor.

The first cropping season was exclusively under bean production. The improved climbing bean variety was shown as particularly more productive than local climbing bean variety (Kalyebara et al., 2008). The high productivity of the improved climbing bean may be explained by genetic characteristics with larger biomass accumulation and resistance to pest and diseases compared to the local variety (Blair et al., 2004; Mazina et al., 2014). This biomass may provide ground cover, control weeds and contribute to soil organic matter when not all the leaves are harvested (Ramaekers et al., 2013).

In our case study, an improved climbing bean variety "G13607" known for its high yielding potential; in combination with improved management practices can produce up to 4 metric tons per hectare (CIAT, 2005), while a local climbing bean variety "AMAKUTSA" produces less than one ton per hectare (Kelvin, 2016). G13607 is also recognized as an efficient land user, tolerant to environmental stresses and a major source of proteins, energy and micronutrients (e.g. Fe and Zn) especially for smallholder farmers (Ntukamazina, 2008).

An improved maize variety "ZM605-24C" known for its high yielding potential can produce up to 8 metric tons per hectare when subject to improved management practices (Baramburiye et al., 2013), while a local maize variety "ISEGA" produces between 2 and 3 tons per hectare (ISABU, 2008).

The use of DAP fertilizer (100 kg ha^{-1}) to the improved climbing bean variety induced a larger yield effect than the local climbing bean variety.

The improved climbing beans are often preferred by smallholder farmers as a solution to decreasing yield, resistance to pests and diseases, adaptation to climate change. However, farmers are constrained by the poor availability of improved seeds (Grisley, 1991; David and Sperling, 1999; David et al., 2002) at the local market due to very high market prices, competition from farmer-saved seed, strong region specific varietal preferences and low adaptation of improved seeds to regional biotic and abiotic stresses (Almekinders et al., 1994; David, 2004), poor availability and cost of stakes, and lack of knowledge on the best staking methods (Mazina et al., 2014).

Soil total N and C were the most important soil characteristics determining the yield differences between the two bean varieties (Figure 4.5). The higher the total N and C, the larger the bean yield differences. However, the effects of these two soil characteristics were more frequently observed on improved climbing bean compared to the local climbing bean variety. In spite of these characteristics having relatively high values, they were still below the critical values generally accepted for fertilizer response. Especially for N, the value of 1.5 g kg^{-1} is below the critical value of 2.5 g N kg^{-1} required for N response (Salvagiotti et al., 2008).

Application of DAP fertilizer to the two bean varieties resulted in large yield differences when beans when planted on time (DelayP < 10 days). Planting date is one variable in tropical cropping systems which is under direct control of the farmer. Planting dates may significantly affect bean yield (Bhardwaj et al., 2002).

In the second cropping season, where maize was planted, the variety effects were large when maize was planted on time in soils with moderate clay (clay > 38 %) content while large fertilizer effects were obtained in soils with clay content below 40 % and high total C (TC $\geq$ 19 g kg^{-1}) content. These effects were mostly realized with the improved maize variety compared to the local maize variety. Such response was expected since the initial soil analysis indicated that the soils in which maize was cropped, were of low fertility, acidic, with small values for total N, total C and available P (Table 4.1). Acidic soils may render N and P unavailable, the latter through P adsorption and the former by slowing down nitrification (Stevenson and Cole, 1986).

The use of DAP to the improved climbing bean/maize variety can be associated with the good management practices provided by technicians which resulted in larger grain yields compared to that of local climbing bean/maize variety.

4.4.2. Economic analysis

Low grain yields obtained from the control under local climbing beans resulted in small net benefits. This was not the case for its corresponding fertilized treatment where yields and net benefits were increased by 28 and 26 %, respectively. On the other side, improved climbing beans had high yields and large net benefits despite the quite expensive seed price (Table 4.4).

Large fertilizer and improved variety effects consequently resulted in large value cost ratios. For improved climbing beans, VCR values on average were 4.49 \$ $\$^{-1}$ which is more than the average of 3.19 \$ $\$^{-1}$ obtained from local climbing beans. The same trend was also observed for maize, where the value cost ratio for the improved maize on average, was almost twice the one of local maize (Table 4.4).

The application of DAP was highly profitable (VCR ≥ 2) for the improved climbing bean and maize varieties (Table 4.4). Such profitability was realized by 63 % and 65 % farmers for local and improved climbing beans, respectively while it was 100 % profitable for farmers growing local and improved maize.

The net benefits were significant and largely different between the control and DAP fertilizer treatments ($P < 0.001$) across all cropped fields for both climbing bean and maize varieties (Table 4.4). The use of DAP fertilizer for the improved climbing bean and maize varieties resulted in larger grain yields, larger net benefits, larger value cost ratios and larger marginal rates of return than for local climbing bean and maize varieties. Variety effects seem to exceed fertilizer effects in both bean and maize. The use of good improved varieties therefore seem to be larger constraint than the soil fertility issues on relative importance of yield-limiting factors. Fertilizer effects seem to be largely independent of the germoplasm used through, and overall positive profitable increases are observed. This outcome confirms the importance of STEP 2 (figure 1.13, pge 27) of the Integrated Soil Fertility management' staircase by providing more positive profitability on the good use of fertilizer and good improved germoplasm compared to STEP 1 where fertilizer was applied on local germoplasm following farmers' practices and consequently provides very small positive profitability (Table 2.10, pge 50). It is essential to achieve durable yield improvements, but intensification can only proceed if farmers have access to markets to buy improved seeds, commercialize their produce and purchase inputs at a reasonable price. Farmers are encouraged to adopt this practice to improve soil fertility and be assured of net returns to investments (Kimani et al., 2004). Therefore, it is paramount to account for economic net return of introduced practices. Profitability is the main driver for adoption by farmers, but risk and uncertainty also influence farmers 'decision-making (Chianu et al., 2002 cited by Pypers et al. (2012)).

4.5. Conclusion

Results from this study revealed that the use of DAP fertilizer to an improved climbing bean/ maize is a promising alternative to the local smallholder farmers' practices. This may lead to a more sustainable bean and maize production in Buraza district of Central Burundi. The improved climbing bean/maize variety planted on soils enriched with DAP fertilizer was more profitable compared to that of local climbing bean/maize variety.

The results are here in line with the “staircase concept” of the Integrated Soil Fertility Management framework in a way that a combination of judicious fertilizer use and use of good improved germoplasm (climbing bean/maize) provides more economic returns of bean and maize production compared to the profitability of DAP supplied in the survey in chapter 2.

Chapter 5

[1]Profitability of DAP use in bush and climbing bean-maize rotations in smallholder farms of Central Burundi

5.1. Introduction

Burundi is facing food insecurity due to a decrease in soil fertility and a high population density, with more than 90 % of the population being traditional farmers. Burundi's population is currently growing at 3 % per year, which is expected to continue (CIA, 2015). This leads to enormous land pressure resulting in continuous (intensive) cultivation and depletion of soil nutrients. In such conditions, soil fertility decline is a major factor limiting per capita crop production in the area. The smallholder farmers are not able to buy and apply adequate quantities of mineral fertilizers and/or organic sources of nutrients, precluding soil fertility replenishment.

Agriculture is considered as the backbone of Burundi's economy and is the second most important contributor to the gross domestic product (GDP) after the service industry. However, agricultural productivity is low and constrained by certain agro-ecological and socio-economic factors, like soil degradation and lack of market access (World Bank, 2014). Especially the decline in soil fertility as a result of soil nutrient mining and erosion, is threatening a secure food supply.

Crop rotations with annual grain legumes have been reported to improve soil physical, chemical and biological conditions in the long run (Bagayoko et al., 1996; Chan and Heenan, 1996; Bagayoko et al., 2000; Giller, 2001; Yusuf et al., 2009), thereby enhancing soil nutrient availability (Loewy, 1987). Not only the annual grain legumes are expected to increase soil N through the BNF, but they can also improve the N use efficiency and prompts changes in various N sources, affecting their availability to the plant (López-Bellido and López-Bellido, 2001). However, most annual grain legumes grown under smallholder farming conditions in sub-Saharan Africa (SSA), cannot supply alone all the N requirements by the non-legume component of the maize-based cropping system. The current practice of exporting all aboveground biomass of the legume at harvest often

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[1] An adapted version is published as: Niyuhire, M.-C., Pypers, P., Vanlauwe, B., Nziguheba, G., Roobroeck, D., Merckx, R., 2017. Profitability of diammonium phosphate use in bush and climbing bean-maize rotations in smallholder farms of Central Burundi. *Field Crops Research*, 212, 52 - 60.

contributes to negative soil N balance (Sanginga et al., 2002). Supplementary N fertilizer would therefore be necessary to increase the yield of the subsequent maize crop.

Sustainable agricultural intensification is urgent and may be implemented through the integrated soil fertility management (ISFM) framework (Figure 1.13), recognized for boosting crop productivity (Vanlauwe et al., 2010). In this, improving fertilizer use efficiency is considered a key factor. One of the appropriate ways of addressing soil fertility depletion and increasing fertilizer use efficiency is the combined application of organic and mineral fertilizers. This has been shown to be especially relevant in low-external input systems, typical for SSA including Burundi and forms an integral part of ISFM (Vanlauwe et al., 2010).

Legume-cereal rotation is reported by Rayar (2000) cited by Ndayisaba (2013) as one of the well-established agronomic practices for successful ISFM. Its advantages are (i) addition of organic matter through incorporation of crop residues, (ii) improved soil moisture management, (iii) addition of nitrogen (N) through the inclusion of legume in the rotation, (iv) effective control of insects and diseases, (v) effective weed control, (vi) assured income to the farmers, and (vii) an increased agronomic efficiency of mineral fertilizer. The sum of these effects explains why maize yields are consistently reported to be improved when grown following a legume in rotation. The size of the rotational yield effect varies with the legume varieties. From the literature, it was shown that climbing bean is of greater importance compared to bush bean for nitrogen fixation under different agronomic conditions (Graham and Rosas, 1977; Graham and Temple, 1984; Kipe-Nolt and Giller, 1993). Climbing bean is by far the bean type with high biomass production and probably high N fixation capacity; therefore, considerable rotational benefits are expected, and its integration in the production system can improve and sustain crop productivity (Lunze and Ngongo, 2011). The capacity to fix N can go up to 125 kg N ha^{-1} for climbing bean while 35 kg N ha^{-1} for bush bean (Guerena, 2016). However, a positive effect on soil-N depends on the harvest index of the beans, which may still imply a zero negative budget (Vanlauwe and Giller, 2006). In fact, Van Schoonhoven and Pastor-Corrales (1994) reported by Lunze and Ngongo (2011) found that climbing bean develops extensive nodulation three times more than bush bean, which is an indication of higher capacity for N fixation. The evidence of benefit of climbing bean cultivation may exist, either as rotational effects or as improved nitrogen nutrition. There is a necessity of rational use of this potential to develop farming practices that are economically viable. Although climbing bean is being extensively promoted in the potential regions to intensify productivity, the soil fertility benefits of climbing bean versus bush bean have been very little studied and exploited. It is, however, assumed that climbing bean promotion is the appropriate strategy for higher productivity and sustainability for smallholder farmers.

In the current study, the application of mineral fertilizers was tested with improved bean varieties, in rotation with a subsequent improved maize variety. Rotational effects of a bush and climbing bean variety were compared, and the profitability of diammonium phosphate (DAP, 18-46-0) fertilizer assessed in bean-maize rotations in smallholder farms of Mutaho district, Gitega Province in Central Burundi.

5.2. Material and Methods

5.2.1. Study area

The study was conducted in Mutaho district, Gitega Province in Central Burundi. The climate is humid-tropical. The district is characterized by a bimodal rainfall pattern with long rains (LR) between February and June and short rains (SR) between October and January. The mean annual temperature varies between 15 and 20 °C (ISTEEBU, 2014). Rainfall during the first season (beans, LR 2012) was 569 mm, and during the subsequent season (maize, SR 2013) was 321mm, while averages during the past 20 years were 520 mm and 369 mm for the LR and SR, respectively. The available rainfall data are estimates from the Tropical Rainfall Measuring Mission (TRMM) by National Aeronautics and Space Administration (NASA), with a resolution of 0.25 x 0.25 degrees. The dominant soil groups in the region are Ferralsols (WRB, 2015).

Table 5.1. Main characteristics of the study area (n = 59)

Parameters measured	Unit	Mean	Range
Soil properties			
pH$_{water}$		5.8	4.9-8.5
Olsen P	mg kg^{-1}	8.2	2.7-27.1
TC	g kg^{-1}	23.7	11.3-34.5
TN	g kg^{-1}	1.8	1.0-2.8
Clay	%	36.9	32.4-45.3
Sand	%	41.0.	37.2-45.1
Silt	%	17.0	13.9-21.8
Biophysical characteristics			
Altitude (meters above sea level)	m	1559	1499-1618
Annual mean temperature**	^{0}C		15-20
Topography			
Dominant soil group (WRB,2015)			Ferralsols
Slope	%	2.04	0.25-6.78
Socio-economic indicators			
Average farm size*	ha	0.5	0.4-0.8
Population density**	#km^{-2}	432	
Family size*	#	6	
Distance to main market**	km	42	

*Source: Author, * Ouma et al. (2010) and ** ISTEEBU(2014)*

Bean-maize rotation is one of the most important cropping systems, practiced by all rural households (CIALCA, 2015). We therefore implemented this type of rotation in a field experiment conducted over two seasons, comparing an improved bush and climbing bean variety planted in LR 2012 (February to June 2012), and a subsequent maize crop planted during SR 2013 (October 2012 to January 2013). Trials were set up in 59 farmer's fields in Mutaho district (29˚ 51' E, 3˚ 09' S), within a 5 km diameter area (average distance between fields of 1.8 km) to cover variation in local soil fertility while minimizing variation in rainfall conditions. Only fields with less than 10% of slope and having enough space for the experiment were selected. The selection of fields, trial establishment and soil analysis were conducted as in previous chapters. Fields next to the scrubland, recently cleared and/or isolated fields were avoided.

The trial establishment was performed at the onset of the season by the farmers and supervised by a team of an agronomist and technicians. All field operations during crop growth were performed by farmers, while observations during growth and at the harvest were taken by an agronomist and technicians. In each field, four plots were demarcated to accommodate two improved bean varieties each receiving two treatments, a control without fertilizer, and a treatment with DAP applied at one bag (50 kg) per hectare (9 kg N ha^{-1} and 10 kg P ha^{-1}). The experimental design was a latin-square (species randomized in the x-direction and fertilizer application in the y-direction).

All plots received a basal application of manure at a rate of 2500 kg ha^{-1} before planting. Manure was applied in the rows and mixed with DAP fertilizer where necessary at the soil surface. This mixture was then covered by soil to avoid volatilization of DAP or burning the plants. Manure was supplied by the Burundi Agricultural Research Center of Murongwe located in Mutaho district. The application of manure to crops is common in the area. The C/N ratio of the manure applied was 15.8, and nutrient contents were 20 g N kg^{-1}, 1.5 g P kg^{-1}, 21.6 g K kg^{-1}, 6.4 g Ca kg^{-1}, and 13.7 g Mg kg^{-1} on a dry matter basis.

The plot size was measuring 36 m^{2} (6 m x 6 m). Improved varieties of bush bean and climbing bean, "MLB 122-94B" and "G13607", respectively, were planted at a spacing of 50 cm between planting lines and 40 cm between plants within lines, and two bean seeds planted per hill.

Maize *(Zea mays)* was planted in the SR season (SR 2012) following the harvest of beans (*Phaseolus vulgaris* L.) on the same plots. An improved "ZM605-24C", an open pollinated maize variety from CIMMYT Zimbabwe, was planted at a spacing of 75 cm and 50 cm inter-and intrarow, respectively and two maize seeds were planted per hill. The control and fertilized treatments were laid out as for beans but with a different rate for DAP (two bags of 50 kg per hectare, or 18 kg N ha^{-1} and 20 kg P ha^{-1}). The DAP was applied as a single dose just before planting. In addition, 100 kg urea ha^{-1} (46 kg N ha^{-1}) was applied 45 days after planting as a blanket treatment to all plots of maize.

At maturity, bean and maize crops were harvested in a net plot (10 and 6 rows respectively for bean and maize crops in each plot) and the fresh weight of both grains was taken. The aboveground biomass was not measured and left to farmers. The bean and maize grains were then air-dried and the dry weight taken.

5.2.3. Statistical analyses

A Linear Mixed-Effect Model based approach was used to test the effects of fertilizer and bean variety yield, using the ‘lmer’ package (Bates et al., 2014) of the R statistical analysis software (Team, 2016).The model includes fixed effects for variety and fertilizer (and their interaction), and two random intercepts for farmer (or field), calculated separately for each level of variety and fertilizer, respectively. Maximum likelihood tests were carried out to ascertain contribution of the random effects to overall explained variance. The fixed effects assess whether there are differences between the means of the effects of the two bean varieties, fertilizer treatments and their interaction. Least square means with confidence intervals, and standard errors of difference (SED) were calculated to evaluate the significance of variety and fertilizer effects and their interaction at $P \leq 0.1$, $P \leq 0.05$, $P \leq 0.01$ and $P \leq 0.001$. The random part assesses whether there are differences in the distribution (variance) of yields in individual fields between bean varieties, or fertilizer treatments, and the variance associated with a change in bean variety or to fertilizer application were calculated based on the estimated variance and covariance components.

Thereafter, best linear unbiased prediction (BLUP) was used for the estimation of random effects of variety and fertilizer. By convention, BLUPs are referred to as predictions, calculated from the estimated mean and variance, and the data. Fertilizer and variety BLUPs were then tested for correlation with soil covariates (pH, Olsen P, total C, total N, clay, sand and silt) and delay in planting. The delay in planting was defined as the number of days that passed since the first farmer planted. Rainfall was not included as a covariate, as trials were close to one another (within a 5 km diameter area) and therefore experienced little difference in rainfall.

Regression tree analysis was used as a way of making quantitative predictions (for soil covariates and delay in planting) and was fitted to each node to give the predicted values of the dependent variable (fertilizer/variety effects). The predictors were then plotted in regression trees using the "*rpart"* package (Therneau et al., 2015) and cross-validated for both variety and fertilizer effects. As the dataset is rather small (n = 59), only two levels were retained for each tree in order to maximize their probability.

5.2.4. Economic analysis

A simple financial analysis was performed to assess the profitability of the treatments. The total cost (TC) of the operations included the costs for land preparation, seeds, application of manure and/or DAP fertilizer inputs, staking for climbing bean, weeding, harvesting and post-harvest handling. Staking one hectare of climbing bean requires around 25,000 stakes, with a cost estimated at \$ 350 corresponding to that used by Ruraduma et al. (2012). In this study, one stake was used for 4 plants (2 hills) and gave the highest yield (Ruraduma et al., 2012). Labor was valued at a wage of \$ 0.17 per hour. One bag of 50 kg of fertilizer costed \$ 40 and \$ 26.67 for DAP and urea, respectively. Bean and maize grains were sold at 0.67 and 0.4 \$ kg^{-1}, respectively. Opportunity cost for land were not included, as land was available in the area. This analysis was done for individual crops (bean and maize) and for the rotational cycle by using the farm gate prices of the inputs and outputs. Original prices were recorded in Burundi Francs (BIF) and converted to United States dollar (\$). One \$ was about 1500 BIF, February 2012.

To assess profitability of fertilizer use, net benefits (NB), expressed in \$ ha^{-1}, value cost ratio (VCR, \$ \$$^{-1}$) and marginal rate of return (MRR, \$ \$$^{-1}$) were calculated, respectively, as described in chapters 2 and 4. To calculate the profitability for the rotational cycle, PV, TC and NB were summed for the bean and subsequent maize crop, and then the VCR and MRR were calculated. The VCR should have a minimum of 2 (CIMMYT, 1988) for alternative practices to be profitable to farmers.

Regression tree analysis was then performed to predict which covariates among the soil parameters (pH, Olsen P, total C, total N, clay, sand and silt) and delay in planting (renamed as delayPBeans and delayPMaize, as these are two different things when evaluating VCR of the system for beans and maize) that would explain the most profitable bean-maize rotation system.

5.3. Results

5.3.1. Production of bean-maize systems under different practices

5.3.1.1 Means and variation in distributions of varieties/systems and fertilizer effects

The production of different bean varieties and DAP fertilizer for the first season is summarized in Table 5.2. The average grain yield for bush beans is 1000 kg ha^{-1} in the control plots and 1138 kg ha^{-1} in the fertilized plots showing a fertilizer-induced yield increase of 14 % (138 kg ha^{-1}). For the climbing beans, the grain yield is on average 1550 kg ha^{-1} in the control plots and 1871 kg ha^{-1} in the fertilized plots. The fertilizer-derived yield increase is 21 % (321 kg ha^{-1}). The response to DAP fertilizer was significantly ($P < 0.001$) larger in climbing beans than in bush beans (Table 5.2).

In the second season, the production of maize following the different bean varieties and as affected by DAP fertilizer is also summarized in Table 5.2. For maize following bush beans (BB-M), the average grain yield was 4008 kg ha^{-1} in the control and 4342 kg ha^{-1} with fertilizer applied. The fertilizer-induced yield increase is on average 8 % (334 kg ha^{-1}). For maize following climbing beans (CB-M), the grain yields were on average 4053 kg ha^{-1} in the control plots and 4929 kg ha^{-1} in the fertilized plots. The yield increase due to fertilizer application hence is on average 22 % (876 kg ha^{-1}). Maize grain yields were not significantly ($P < 0.05$) different in the control treatments, but the response to fertilizer was significantly ($P < 0.001$) higher following climbing beans than following bush beans (Table 5.2).

Table 5.2. Mean grain yields (kg ha^{-1}) of bush beans, climbing beans and maize (following bush beans/climbing beans) for both control and fertilized plots of the individual 59 fields in the study

Treatment	**First season**		**Second season**	
	Bush beans	Climbing beans	BB-M	CB-M
	……...............Overall mean grain yield (kg ha^{-1})...................			
Control	1000.33	1550.26	4008.06	4052.88
DAP	1138.07	1871.38	4342.45	4929.19
SED	95	128	370	400
SED fertilizer (F)	38***		200***	
SED bean species (S)	98***		253***	
SED F x S	144***		381***	

BB-M: Maize following bush beans; CB-M: Maize following climbing beans; SED: Standard error of difference (only presented when significant at $P \leq 0.05$); *** Significant at $P \leq 0.001$.

Based on the variance and covariance components associated with farmer, the distribution of the effect of a change in bean variety (climbing beans instead of bush beans), and the effect of fertilizer application were calculated and plotted (Figure 5.1). The effect of changing bush beans for climbing beans resulted in a yield increase for about 80 % of the farmers. The effect of fertilizer application was positive for about two thirds of the farmers. Variance in the effect of a change in bean variety was larger than variance in fertilizer effect.

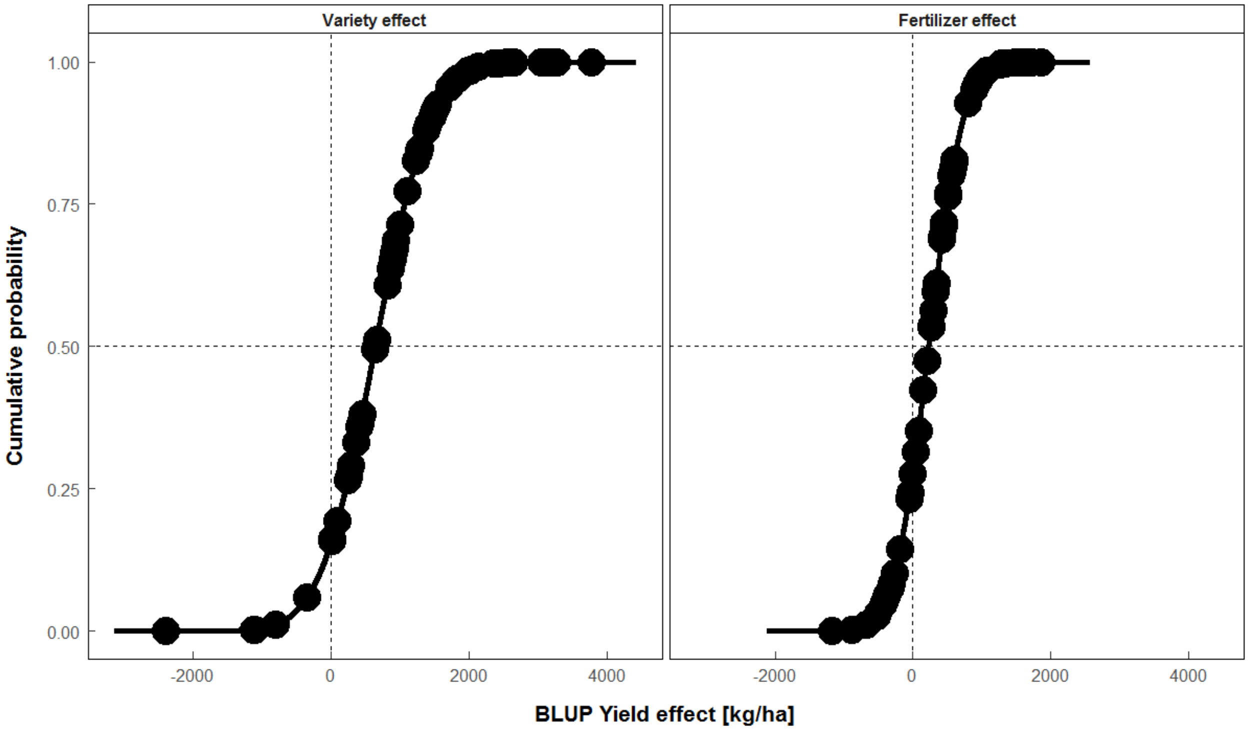

Figure 5.1. Modeled variation in bean variety effect (climbing bean yield minus bush bean yield) (left) and the fertilizer effect (yield with fertilizer minus control yield) (right). 'BLUPs (Best Linear Unbiased Prediction)' are plotted for the individual 59 fields in the study. The cumulative probability (Y-axis) reflects the likelihood for obtaining an effect larger than a given yield effect (X-axis)

Similarly, in the subsequent season, the distribution in effects on maize yield of the preceding bean varieties, and the effect of fertilizer were calculated and plotted (Figure 5.2). The variation between the different farmers was larger for fertilizer effects (yield in the treatment with DAP minus control yield), than for cropping system effects (yield of maize following climbing beans minus yield following bush beans). For about 60 % of the farmers, fertilizer effects were positive. Maize grain yields of the CB-M system were larger than those for the BB-M system for about 48 % of the farmers ($P < 0.05$).

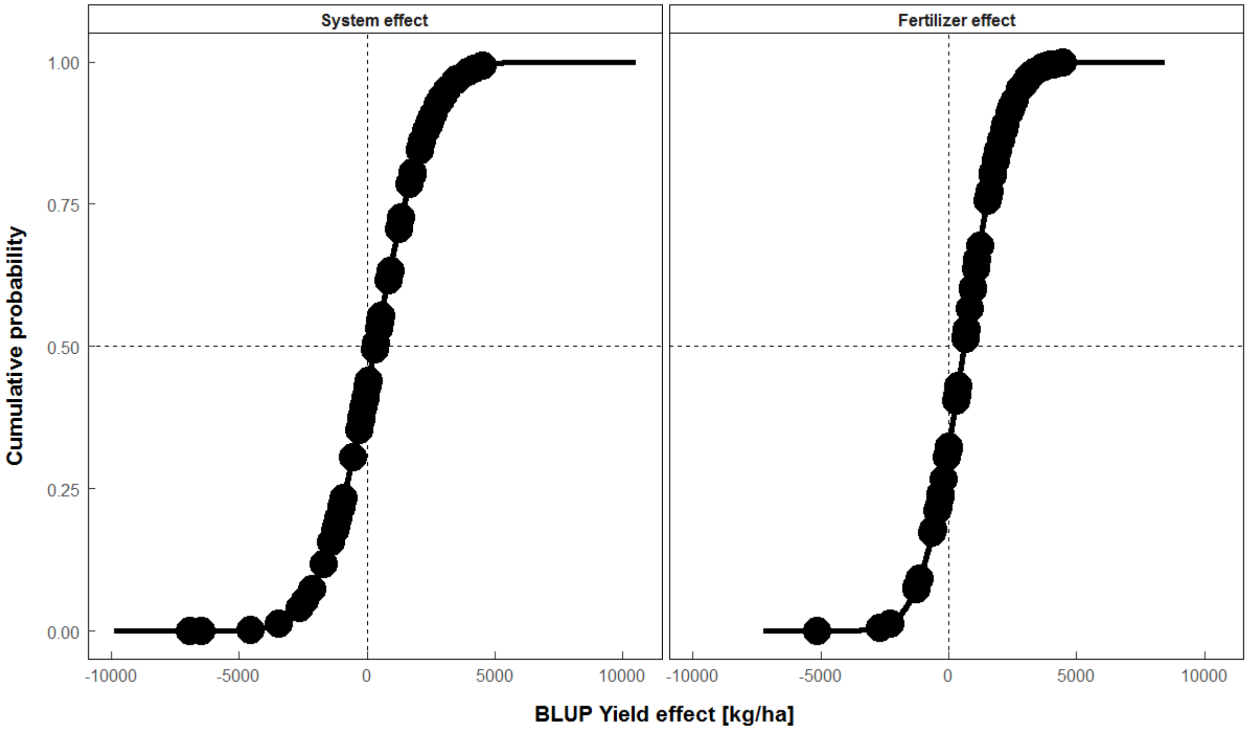

Figure 5.2. Modeled variation in effect of preceding beans varieties (maize yield following climbing beans minus yield following bush beans) (left) and the fertilizer effect (yield with fertilizer minus control yield) (right). 'BLUPs (Best Linear Unbiased Prediction)' are plotted for the individual 59 fields in the study. The cumulative probability (Y-axis) reflects the likelihood for obtaining an effect larger than a given yield effect (X-axis)

5.3.1.2. Varieties/systems and fertilizer effects as affected by soil covariates and crop management

Regression tree analysis was performed to evaluate whether BLUPs for bean varieties effects or fertilizer effects can be related to soil parameters (pH, Olsen P, total C, total N, clay, sand and silt). We included as well "delay in planting" as a parameter, but no other parameters related to crop management (weeding, cropping cycle, etc.) because they were standardized and cannot explain variation, or rainfall data trials were near to one another (within 5 km diameter area) and did not experience much difference in rainfall.

In the first season, bean effects were larger in soils that have high total N (TN > 1.8 g kg^{-1}) and Olsen P (P > 4.9 mg kg^{-1}) contents. Fertilizer effects were larger when planted early (less than 3.5 days delay), and in soils with high total C content (TC > 25 g kg^{-1}) (Figure 5.3). For the second season, effects of the preceding bean varieties were larger when planted early (less than 6.5 days delay) in soils with moderate pH (pH ≥ 5.8), or in soils with low clay content (less than 38 % clay). Fertilizer effects on the subsequent maize were larger when planted early (less than 8.5 days delay) in soils with moderate clay (34 - 38 %) content (Figure 5.3).

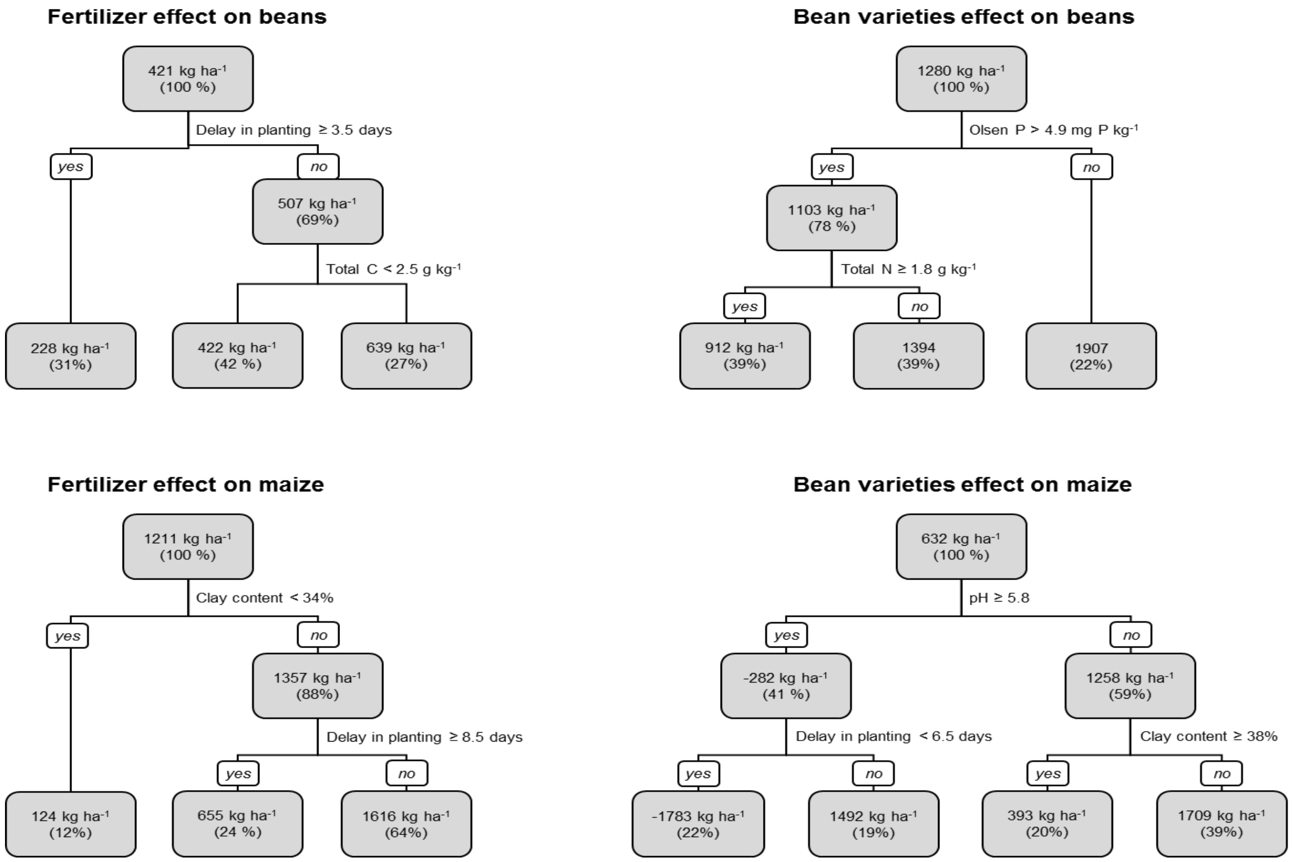

Figure 5.3. Regression trees analysis results for the individual 59 fields in the study, restricted to two branching depths, for BLUPs for bean varieties or fertilizer effects as explained by soil parameters and delay in planting. The average grain yield effects and proportion of observations (%) are also shown at each node

5.3.2. Economic analysis

In the first season, farmers growing bush beans without fertilizer had on average higher net benefits (NB) than when growing climbing beans, as the benefits from the higher yield did not compensate for the cost of staking (Table 5.3). Fertilizer use increased total costs (TC), slightly increased NB (on average) but significantly ($P < 0.05$) when applied to bush beans, and significantly large increased ($P < 0.001$) when applied to climbing beans. The value cost ratio (VCR) was more than doubled (4.25 \$ $\$^{-1}$) compared with the bush bean (1.83 \$ $\$^{-1}$). Generally, a value of 2 \$ $\$^{-1}$ is considered as cut-off point to consider an investment profitable (CIMMYT, 1988). For the subsequent maize crop, similarly, the application of DAP increased NB more following climbing beans than following bush beans, and the VCR values were profitable (on average, 3.61 \$ $\$^{-1}$). As yields of maize were higher following climbing beans, NB and profitability was also higher. Summed over both crops, net benefits were highest in the climbing bean-maize rotation with fertilizer applied with VCR values again profitable (on average, 3.83 \$ $\$^{-1}$).

Table 5.3. Financial analysis, including total costs (TC), net benefits (NB), value cost ratio (VCR), and marginal rate of return (MRR) from the application of combined manure and DAP fertilizer to improved bush, climbing bean varieties cropped in rotation with maize crop at the end of their crop cycles for the individual 59 fields in the study.

System	**TC**		**NB**		**VCR**	**MRR**
	Control	DAP	Control	DAP		
	……………………………$ ha^{-1}…………………………………..…..				…$ $^{-1}$……..	
Bush bean-maize rotation						
BB	296.79	336.79	236.92	270.08	1.83	0.83
BBM	278.37	358.37	1057.95	1088.11	1.38	0.38
Total	575.16	695.16	1294.87	1358.19	1.53	0.53
Climbing bean-maize rotation						
CB	746.89	786.89	79.99	210.18	4.25	3.25
CB-M	278.37	358.37	1075.89	1284.89	3.61	2.61
Total	1025.26	1145.26	1155.88	1495.07	3.83	2.83
SED#	ns	ns	134.78	161.47	0.61	

BB-M: Maize following bush beans; CB-M: Maize rotated to climbing beans. SED: standard error of difference. TC: Total cost (\$ ha^{-1}); NB: Net benefit (\$ ha^{-1}); VCR: Value cost ratio (\$ $\$^{-1}$); MRR: Marginal rate of return (\$ $\$^{-1}$); #SED: standard error of difference (only presented when significant at $P < 0.05$); ns: not significant.

Figure 5.4 shows modeled variation in value cost ratio (VCR) for fertilizer cumulated over the first bean crop and subsequent maize crop. The VCR in climbing bean-maize rotation was profitable for 67 % of the farmers, while only profitable for 45 % of the farmers in the bush bean-maize rotation.

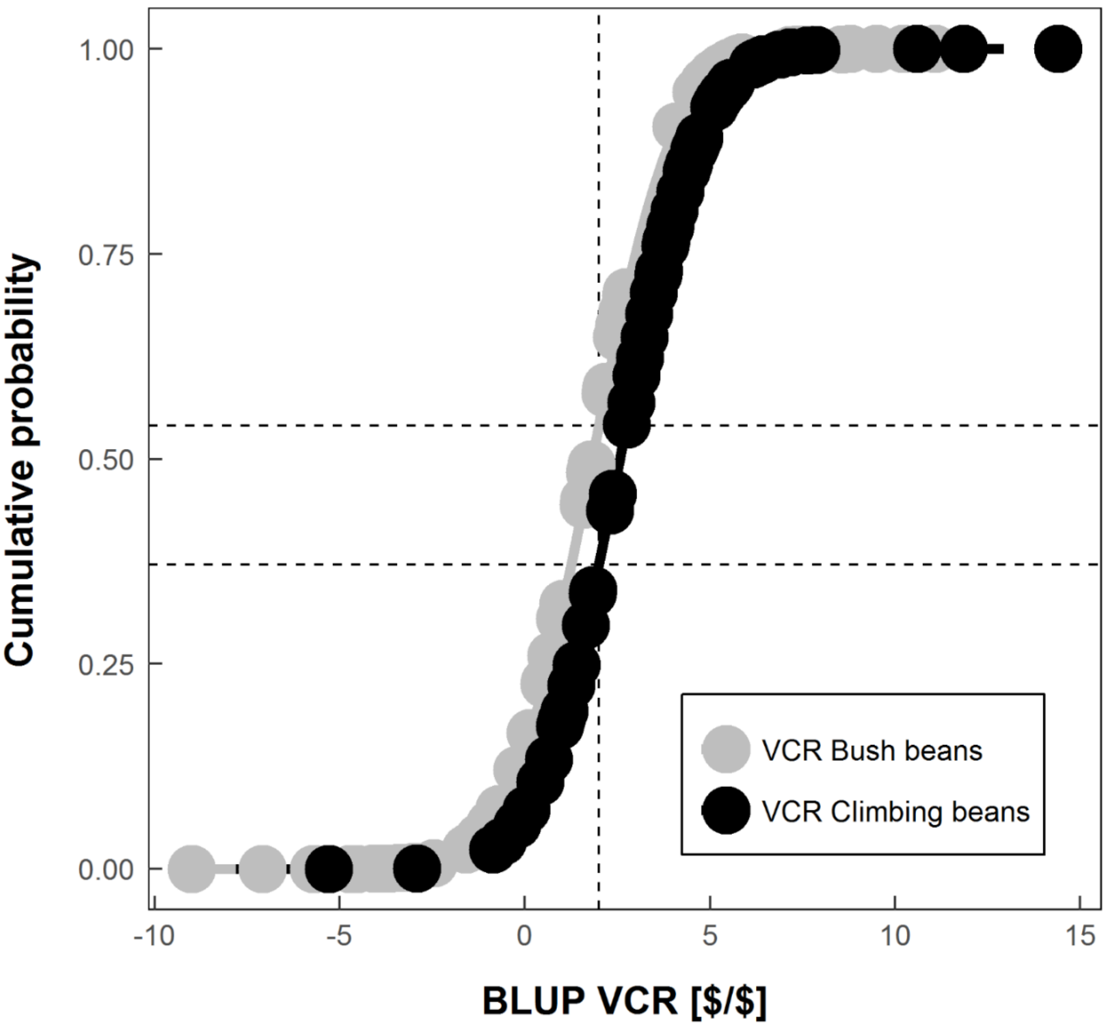

Figure 5.4. Modeled variation in value cost ratio (VCR) for fertilizer cumulated over the first bean crop and subsequent maize crop, and 'BLUPs (Best Linear Unbiased Prediction)' plotted for the individual 59 fields in the study. The cumulative probability (Y-axis) reflects the likelihood for obtaining a value larger than a given VCR (X-axis). Vertical line denotes VCR = 2, and horizontal lines intersect with the cumulative distribution curves for bush beans and climbing beans as first crop

The covariates that predict the high profitability in the climbing bean-maize rotation were soil total C larger than 23 g kg^{-1}, soil total N lesser than 2 g kg^{-1} and more than 37 % of clay content (Figure 5.5).

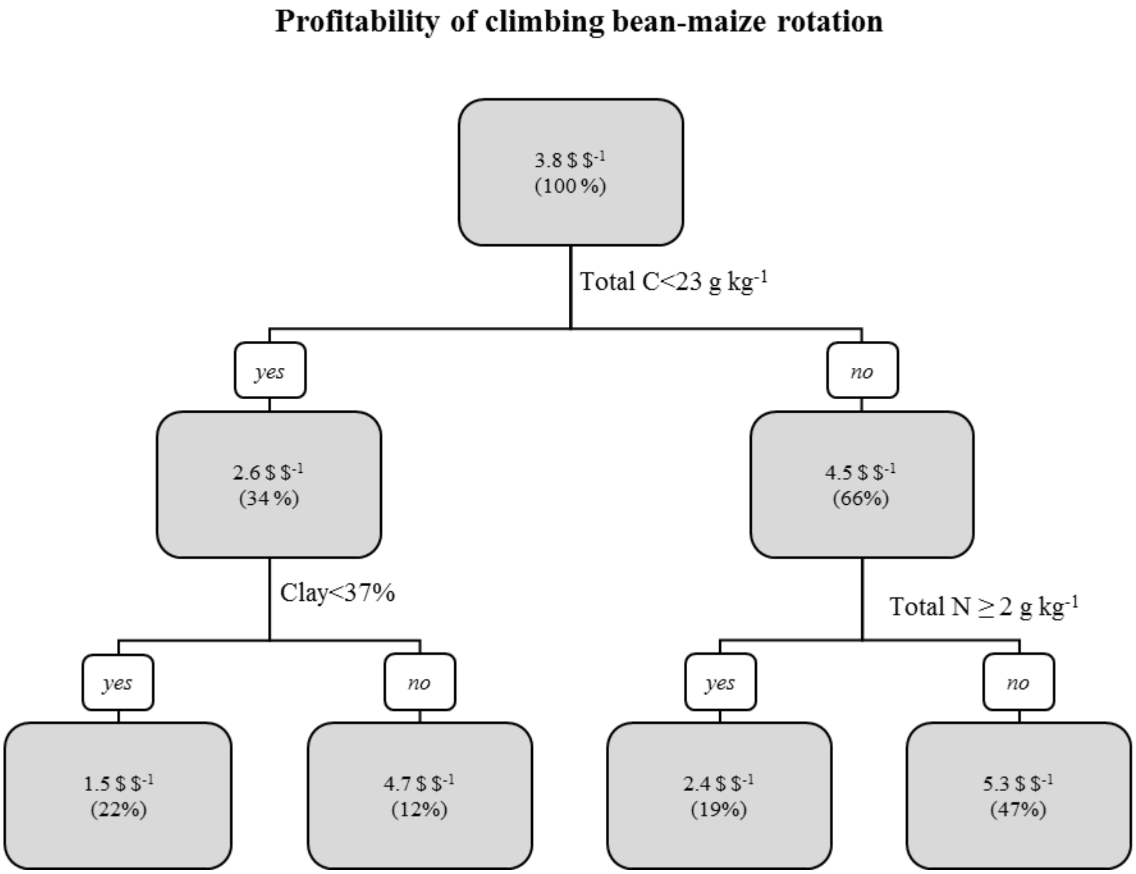
Profitability of climbing bean-maize rotation

Figure 5.5. Regression tree analysis results (n = 59), restricted to two branching depths, for profitability of climbing bean-maize rotation as explained by soil covariates and delay in planting (for beans and maize). The value cost ratio values and proportion of observations (%) are shown at each node

5.4. Discussion

5.4.1. The production of maize-based systems under different practices

The first cropping season was exclusively under bean production. Genetic characteristics of both climbing beans and bush beans could explain the yield differences observed between the two bean varieties (Marandu et al., 2013). The climbing beans are particularly more productive, efficient land users by producing two or three times more than bush bean types (Mazina et al., 2014). They were also more tolerant to environmental stresses including both abiotic (rainfall irregularity/drought, nitrogen and phosphorus deficiencies and acidic soils) and biotic (fungal, bacterial and viral diseases; insects pests) constraints (Beebe et al., 2012).

The high productivity of climbing beans is also due to their longer growth cycles and larger biomass accumulation (Blair et al., 2004). This biomass may provide ground cover, control weeds and contribute to soil organic matter when not all the leaves are harvested (Ramaekers et al., 2013). In our case study, the length of growing cycle ranged from 110 to 120 days for climbing beans (“G13607”) and from 80 to 90 days for bush beans (“MLB 122 – 94 B”) varieties, respectively. MLB 122 - 94 B also called “MUSENGO” was selected for its high yield (600 - 800 kg ha^{-1}), size (medium) and color of the seeds (white streaked brown); and tolerance to pests and diseases (ISABU, 2012). G13607 locally called “TWUNGURUMURYANGO” was also selected for its high yield (750 - 1000 kg ha^{-1}) under farmer practices (Ntukamazina et al., 2009). The use of DAP fertilizer (50 kg ha^{-1}) increased on average grain yields up to 1000 kg ha^{-1} for bush beans and 1800 kg ha^{-1} for climbing beans, respectively.

With improved management practices, climbing beans can produce up to 4000 kg ha^{-1} while bush beans can produce between 1000 and 2000 kg ha^{-1} , as reported by CIAT (2005) cited by Mazina et al. (2014). The climbing beans are often preferred by smallholder farmers as a solution to decreasing land sizes as the same yield can be obtained on a smaller piece of land compared to bush beans (Ramaekers et al., 2013). However, farmers are constrained by the poor availability of improved seeds (Kalyebara and Buruchara, 2008; Ibrahim, 2013) at the local market. This may be explained by the poor adaptation of new varieties to most farmers’ conditions; lack of incentives to motivate extension agents, extension services, poor farmers’ ability to access improved seeds from the markets due to low incomes and lack of credit facilities, poor seed delivery system and inadequate seed security stocks and lack of a clear seed strategy (Ibrahim, 2013). Moreover, competition from farmer local seeds, strong regional preference specific varieties are some of the local market dynamics (Almekinders et al., 1994; David, 2004). At farm level, biotic and abiotic stresses, poor availability and cost of stakes, and lack of knowledge stresses on the best staking methods (Mazina et al., 2014).

Soil N and P were the most important soil characteristics determining the yield differences between the two bean varieties (Figure 5.3). The higher the N and P the larger the bean yield differences. However, the effects of these two nutrients were more observed on climbing beans compared to the bush beans. In spite of these nutrients being relatively high, they were still below the critical values of fertilizer response. Especially for N, the value of 1.8 g kg^{-1} is below the critical value of

2.5 g N kg^{-1} presumed for N response as reported by Okalebo et al. (2002) cited by Koskey et al.(2017). Therefore, the climbing beans still fix N and this had contributed to high yields obtained from this legume (Beebe et al., 2012). In addition, the relatively high P may have enhanced more N fixation by the climbing beans compared to the bush beans (Beebe et al., 2012).

Application of DAP fertilizer to the two bean varieties resulted in large yield differences when planted on time and on soils with a total C below 2.5 %. Such response was expected since the initial soil analysis indicated that the soils in which beans were cropped, were of low fertility, acidic, with small amounts of total N, total C and Olsen P (Table 5.1). Acidic soils may render N and P unavailable, the latter through P adsorption and the former by slowing down nitrification (Stevenson and Cole, 1986). Micro-organisms that are important in mineralization of organic N and P compounds, are also inhibited in acidic soils (Stevenson and Cole, 1986).

In the second season, where maize was rotated with beans, the variety and fertilizer effects were large when maize was planted on time in soils with moderate clay (34 - 38 %) content and a pH of about 5.8. These effects were mostly realized from the climbing bean-maize system compared to the bush bean-maize system. The effects may be attributed to a larger residual soil N from the former system compared to the latter (Bagayoko et al., 1996). These effects obviously derive from the larger amounts of above- and belowground biomass/residues returned to the plots after harvesting the beans and perhaps also because of changes in microbial activities after legumes (Shipton, 1977; Turco et al., 1990). The same effect is sometimes referred to as allowing subsequent crops to access more P (Johnson et al., 1992; Bainville et al., 2005). Combing manure with DAP gave larger grain yield compared to the application of manure alone. This underlines the importance combined use of inorganic and organic fertilizer resources for improved crop performance and the more so for these acidic soils (Vanlauwe et al., 2001).

Maize yields obtained from control plots were high due to the fact that those plots benefited from application of manure. Next to the application of manure to an improved maize variety, the good management practices provided by technicians of the research center of Murongwe also contributed to the high yields obtained in the control plots. All inputs were provided by the same research center and therefore of certified quality. In addition, the residual effect of bean biomass left to the fields may have also contributed to the high yields observed from the control plots, but its fate was not carefully monitored. The farmers may have used it for livestock, if any, or heaped it to compost.

Famers have variable access to sources of organic matter. They resort to leaving crop residues on the field, use compost and in rare cases green manures (Giller et al., 1997). In general, the amounts so recycled are small and of low quality. Sometimes when they have money they can buy livestock that will produce some manure, but often also of poor quality. Manure of good quality is mainly provided from farmers' organizations or cooperatives and agricultural research stations. Only few farmers are able to access such manure due to their general low income. The same applies for access to improved seeds. These can be available at the beginning of the season in agricultural research stations or farmers' cooperatives but at prices too high compared to the price of non-improved seeds which are always available at the local market. In general, Burundi is still facing inadequate seed security stocks and lacks a clear seed strategy (Ibrahim, 2013).

Manure can influence nutrient availability through (i) the total nutrients added, (ii) the control of net mineralization-immobilization patterns, (iii) serving as a source of C and energy to soil microbes, (iv) serving as precursors of soil organic matter resulting in more favorable soil physical and chemical properties (De Ridder and Van Keulen, 1990), and (v) through interactions with the mineral soil in complexing toxic cations and reducing the P sorption capacity of the soil (Palm et al., 1997). An application of 2500 kg ha^{-1} of manure supplied the following amounts of nutrients per hectare: 50 kg N, 37.5 kg P, 54 kg K, 16 kg Ca and 34 kg Mg respectively for both bean and maize crops. These values are close to those reported by Lupwayi et al. (2000) while evaluating plant nutrient contents of cattle manure from small-scale farms and experimental stations in the Ethiopian highlands. They applied 3000 kg ha^{-1} of manure from which supplied nutrients were on average per hectare: 35 - 82 kg N, 7 - 21 kg P, 32 - 163 kg K, 30 - 74 kg Ca, 10 - 37 kg Mg, 11 - 67 kg Fe, 0.8 - 5.7 kg Mn, 0.02 - 0.26 kg Cu and 0.15 - 0.65 kg Zn. The differences in nutrient contents are due to the animal type and diet and the way manure was stored. Under African conditions, however, where animal diets are often very poor, the composition of macronutrients may be lower than the values indicated above that are derived from a research station (Bayu et al., 2005). The positive effect of these nutrients on maize yields was realized for about 60 % of the farmers. With the use of the same nutrients, maize following climbing beans outyielded maize following bush beans for about 48 % of the farmers (Figure 5.2).

5.4.2. Economic analysis

Low grain yields obtained from the control under bush beans resulted in small net benefits. This was not the case for its corresponding fertilized treatment where yields and net benefits were increased by 14 % respectively. On the other side, climbing beans had high yields and large net benefits although the staking was quite expensive (Table 5.3).

Large fertilizer and bean variety effects consequently resulted in large value cost ratio. For climbing beans, VCR values on average, 4.25 $ $^{-1}$ more than doubled the average of 1.83 $ $^{-1}$ obtained from bush beans. The same trend was also observed for maize planted after beans, where the control maize plots on average yielded 4000 kg ha^{-1}. The value cost ratio was on average two times larger when maize followed climbing beans than when it followed the bush beans (Table 5.3).

The application of DAP was highly profitable (VCR ≥ 2) for the climbing bean-maize rotation (Figure 5.4). Such profitability was realized when maize yields had ranges between 1067 and 4622 kg ha^{-1}. This yields were obtained from fields with high total C (TC > 23 g kg^{-1}), low total N (TN < 2 g kg^{-1}) and high clay content (more than 37 % clay) (Figure 5.5). However, the delay in planting failed to predict the profitability for the climbing bean-maize rotation since high delays in beans did not coincide with high delays in maize. In fact, all farmers who planted their beans late planted their maize on time, and vice versa. This explains why there is only a negligible predictive value in the delay parameters.

The total costs and the net benefits were significant and largely different between the control and DAP fertilizer treatments ($P < 0.001$) across all cropped fields (n = 59) and for both bean-maize systems (Table 5 3). The use of manure in combination with DAP fertilizer for the climbing bean-maize system resulted in larger grain yields, larger net benefits, larger value cost ratio and marginal rate of return than in the bush bean-maize system. It is essential to achieve durable yield improvements, but intensification can only proceed if farmers have access to markets to buy seeds, commercialize their produce at a reasonable price and purchase inputs at a subsidized price. Farmers are encouraged to adopt this practice to improve soil fertility and be assured of net returns to investments (Kimani et al., 2004). Therefore, it is paramount to account for economic net return of introduced practices. Profitability is the main driver for adoption by farmers, but risk and uncertainty also influence farmers ‘decision-making (Chianu et al., 2002 cited by Pypers (2012)).

5.5. Conclusion

Results from this study revealed that an improved climbing bean preceding an improved maize on soils enriched with manure in combination with DAP fertilizer is a promising alternative to the local smallholder farmers' practices. This may lead to a more sustainable maize production in Mutaho District of Central Burundi. The climbing bean-maize rotation was more profitable compared to the bush bean-maize rotation.

For the system to be profitable, there is a need for integrated soil fertility management, and that a combination of judicious fertilizer use, an improved grain legume (climbing bean) and adjustment to local conditions (targeting to responsive soils) maximizes economic returns of legume-cereal rotation systems. Profitability of the rotation system seems to highest in high C-low N soils. This seems very logical and corroborates the integrated soil fertility management principles that interventions should be targeted to responsive conditions.

CONCLUSIONS

Chapter 6

General conclusions and research perspectives

The soil fertility status in Gitega Province, Central Burundi is low due to its low inherent fertility and its continuous use for agriculture without replenishment of nutrients removed. Soil acidity and low N and P supply capacities are common problems over large areas of agricultural land. These problems are aggravated by the lack of improved and resilient germplasm of the major crops in the region, including maize and beans. In this area, the use of small rates of fertilizers from different sources is prevalent. To increase productivity, farmers use various management strategies, among them the inclusion of legumes into crop rotations and sourcing of nutrients from various resources available to them. Thus the main constraint is in optimizing the economic benefits of these resources without depletion of soil nutrients and related possible nutritional disorders.

The Institut des Sciences Agronomiques du Burundi (ISABU), the Consortium for Improving Agriculture-based Livelihoods in Central Africa (CIALCA; www.cialca.org) and other development partners, aim at reversing above trends and restoring soil productivity through adoption of Integrated Soil Fertility Management (ISFM) options.

Our field studies attempted to evaluate three first ISFM options (Figure 1.14, page 28) for bean-maize-based farming systems in Gitega Province, with a specific focus on assessing the profitability of mineral and organic inputs used as affected by their management, the target crops and soil conditions. This information will be summarized in a decision support framework for site-specific recommendations within these farming systems. The results and conclusions respond to a real need in the Sub-Sahara-African-context where sites specific fertilizer recommendations have been shown repeatedly to be inadequate and beyond farmers' reach. They clearly show the diversity of farming systems and acknowledge the need for a specific management for each region. We found that the combination of the various ISFM components always enhanced the productivity and the economic returns of the system. Differences in agricultural systems were also significant and the required soil fertility approaches would vary depending on the system's specificities. This work documents the knowledge of local farmers towards use of fertilizers, demonstrates the importance of site specific recommendations and assesses the profitability of diammonium phosphate (DAP, 18-46-0) and manure for each system. The studied sites in this work: Buraza, Makebuko (chapters

2, 3 and 4 for Buraza only), and Mutaho (chapter 5) have different soil types and would therefore be good representatives of the humid tropical regions of East and Central Africa (ECA). The general conclusions and research perspectives for this work are drawn below based on the hypotheses and objectives presented in Chapter 1.

Objective 1. To document the current practices of the smallholder farmers on the fertilizer use in bean and maize production

This objective was addressed in chapter 2. As a starting point, you may notice that the current fertilizer effect is small due to poor varietal characteristics, poor management, and lack of appropriate accompanying measures. We then aimed at investigating local farmers' knowledge on fertilizer use in Buraza and Makebuko districts of Gitega province, Central Highlands of Burundi. Knowledge of the local smallholder farmers on the use of fertilizer is limited to the types of the fertilizers available to the local markets. Similarly, farmers are still limited by various environmental, social and economic factors. As such, we found a large variability in rates of DAP applied by farmers within a same area and crop (beans or maize). This illustrates how farmers have different attitudes towards fertilizer use. Moreover, beans are rather produced for family subsistence while maize plays a vital role in ensuring food security, especially in highland areas where it is stored and consumed throughout the year. Maize is consumed in various forms – grilled or whole, as a cake, or as porridge – especially in urban centres. Over 70 % of the maize is consumed as food, and about 10 % is used as animal feeds (USAID, 2010). There is also increasing demand for value-added products (maize flour, poultry feeds, etc.).

Assessing and considering the knowledge held by farmers allows the development of more appropriate technologies as well as favoring communication between farmers and other interventionists (Desbiez et al., 2004). It enables farmers to confidently seek new options while facilitating the process of filling the "knowledge gap" that exists between local and scientific traditions (Bwambale, 2015). The increment in bean and maize grain yields was on average increasing with the application of DAP but profitability of fertilizer use under farmers' practices remain very low. This denotes good soil responsiveness to DAP fertilizer while most soils are of poor fertility status in way that nutrient removed from soils are not replaced and the conditions which support soil fertility are not well maintained. We recommend site specific trainings on fertilizer use and strong collaboration taking into consideration the complex nature of smallholder farming system between farmers, extension workers, researchers and decision makers to improve crop intensification of family farms by using appropriate integrated soil fertility approaches suitable to transform subsistence farms into market oriented farms in Burundi.

Objective 2. To diagnose nutrient deficiencies if any in maize in low input systems using the Compositional Nutrient Diagnosis (CND) in Central highlands of Burundi

The application of small rates of fertilizers from different sources due to environmental, social and economic factors is widespread in ECA. Such rates lead to nutrient mining and consequently to imbalance in crops. However, they could be attractive if well formulated. In Burundi, there is little use of agricultural lime and micronutrient fertilizers. Available fertilizer resources include mostly N, P and K nutrients. Thus the question of possible nutritional disorders at low nutrient application rates arise. Soil and biomass analyses, establishment of critical nutrient indices and sufficient ranges are tools that are used in our study to diagnose nutrient deficiencies. Most fertilizer recommendations are based on these tools. Unfortunately, these have disadvantages of being strongly dependent on the crops for which they are established (Delstanche, 2011). CND has been adopted as a robust mathematical tool in nutrient deficiency diagnosis. To improve on fertilizer use efficiency, establishment of CND norms for different crops of the ECA region is a prerequisite that needs attention in applied research. A part from assessing the applicability of CND approach under smallholder farming practices, diagnosing the nutrient deficiencies in maize cropping is also essential in evaluating the frequency of nutrient deficiencies. This is shown in our experiment in Chapter 3. In this chapter, the application of the CND approach to our dataset revealed the most obvious nutrient deficiencies in maize: zinc and manganese for Buraza district; Nitrogen and Phosphorus for Makebuko district. A clear difference between the districts emerged, where in Buraza district Zn-deficiency was the most prominent issue while totally not an issue in Makebuko district. In the latter district, Nitrogen and Phosphorus were the most important limiting nutrients, Phosphorus ranked first in the control plots while the same ranking for Nitrogen in the fertilized plots. Given the worthiness of the CND approach, there is a dire need to add micronutrients in the nutrient response trials to allow a fair assessment of their nutrient norms, which can be referred to while conducting CND analysis in a way of optimizing fertilizer use and sustain crop productivity in Burundi.

Objective 3. To evaluate the profitability of DAP use on local and improved varieties of climbing bean and maize in smallholder farms of Buraza district in Gitega province, Central highlands of Burundi

Low purchasing power, large cost and restricted availability of fertilizers and distance to where input sources can be purchased in the countryside are some of the majors constraints that contribute to low crop productivity and hence to food insecurity. The small amount of fertilizer available is used mostly on cash crops (Wodon et al., 2008). Moreover, farmers prefer using improved seeds, but most of the times do not use the recommended quantity of seeds as they are often out of reach in terms of cost and market availability. This was observed in Chapter 4 where we assess the advantage of using DAP fertilizer on improved germplasm in terms of economic net returns compared to local ones.

Results from this study confirmed that the use of DAP fertilizer to an improved climbing bean/ maize is a promising alternative to the local smallholder farmers' practices. This may lead to a more sustainable bean and maize production in the Central highlands of Burundi. The improved climbing bean/maize variety planted on soils enriched with DAP fertilizer was more profitable compared to that of local climbing bean/maize variety. The use of DAP fertilizer to the improved climbing bean and maize varieties resulted in larger grain yields when planted on time, larger net benefits, larger value cost ratios and larger marginal rates of return than for local climbing bean and maize varieties. Fertilizer effects were large independent of the improved germoplasm used through, and overall positive profitability increases are observed and are large compared to the profitability of fertilizer use on the local germoplasm obtained under farmers' practices in chapter 2. There is a need to achieve durable yield improvements, but intensification can only proceed if farmers have access to markets to buy improved seeds, purchase inputs and commercialize their produce and at a reasonable price.

The results are here in line with the staircase concept of the Integrated Soil Fertility Management framework in a way that a combination of judicious use of fertilizer and good improved variety (climbing bean/maize) maximizes economic returns of bean and maize production.

Objective 4. To evaluate effects of addition of organic inputs (manure and/or biomass generated by the use of improved bean varieties) on the profitability of DAP fertilizer in bean-maize systems

Soil fertility depletion and high population density are the fundamental roots for food insecurity, limiting per capita crop production in the area. The smallholder farmers are not able to buy and apply adequate quantities of mineral fertilizers and/or organic sources of nutrients, precluding soil fertility replenishment that faces our country. Few rotation studies have attempted to include grain legumes as one of the well-established agronomic practices for successful ISFM. Grain legumes play a dual role in improving soil fertility as well as providing grains that would provide some cash to the farmers as well as enrich nutritional diet. For the few that have worked on this, their studies have been under controlled conditions which are unlikely to give a true picture of the field conditions. Our study in Chapter 5 was able to do this and results obtained strongly suggested that soil fertility rehabilitation and economic returns drawn can be obtained with careful selection of the grain legume variety to be incorporated into a rotation. The application of DAP fertilizer was tested with improved bean varieties, in rotation with a subsequent improved maize variety. Rotational effects of a bush and climbing bean variety were compared, and the profitability of DAP fertilizer assessed in bean-maize rotations in smallholder farms of Mutaho district, Gitega Province in Central Burundi. Results from this study revealed that the use of DAP fertilizer for climbing bean-maize system resulted in larger grain yields, larger net benefits, larger value cost ratio and marginal rate of return than in the bush bean-maize system. Targeting fertilizer use to soils with higher C and clay content, and ensuring timely planting are the predominant factors to ensure fertilizer response and profitable returns. From our economic assessment, we concluded that not all rotation effects would provide benefits. Profitability of the rotation system seems to highest in high soil total C-low soil total N and this is corroborates the ISFM principles that interventions could be targeted to responsive conditions. It also depends on the ability of the legume to yield, both in terms of biomass and grains. There is a need for Integrated Soil Fertility Management, in which a combination of judicious use of fertilizer and an improved grain legume (climbing bean) provide large economic returns of legume-cereal rotation systems. This way, legume grain yields are assured and consequent net returns of the rotation system achieved.

General outlook and recommendations for future research

In Burundi, food insecurity is being aggravated by low soil fertility, continuous cultivation without replenishment of nutrients removed (pH < 5), soil acidity, low N and P supply capacities, lack of improved and resilient germplasm of crops that led to low crop yields, poverty and leaving many farm families disappointed. Joint efforts are being deployed by the Government and its development partners to break the vicious cycle of underlying rural poverty. These are expected to pursue different agricultural policies and strategies to enhance agricultural production to ensure food security through increased food production capacities, one of the major action point for the country's Poverty Reduction Strategies framework II. Integrated Soil Fertility Management (ISFM) was targeted as one of the most important approaches to sustain the intensification of agriculture that will enable to feed the fast growing population having small cropping areas. To better value the ISFM approach, we aimed at investigating local farmer's knowledge on the fertilizer use which is a precondition for the establishment of profitable and sustainable nutrient management systems. This resulted in a database displaying a huge variability in plot sizes, plant densities, mineral DAP fertilizer rates on beans and maize production in Buraza and Makebuko where soil types were Acrisols and nitisols, respectively; illustrating how farmers have different attitudes towards the use of fertilizer. The increment in crop yield was on average increasing with the application of DAP for beans and was always larger in Makebuko (Nitisols) than in Buraza (Acrisols) district (Tables 2.4.a, chapter 2). This may be explained by differences in soil types (Table 2.1, chapter 2) and properties (i.e. lower total N in Makebuko compared to Buraza district), disproportionality between fields with large DAP rates (i.e. large proportion of farmers (> 50 %) applied smaller DAP rates in Makebuko compared to Buraza district (Figure 2.1.a, chapter 2). We may not rule out the proximity of Makebuko district to the extension services located in Gitega Town (Table 2.1, chapter 2) which may help farmers to obtain easy access to improved technologies. This was not the case for maize production. No significate predictors were found for DAP effect on maize. The latter may be explained by other factors such as management issues, soil acidity, etc. although they were not measured cannot be ruled out. Based on this information, researchers, extension services and development partners can develop appropriate integrated soil fertility approaches suitable to transform subsistence farms into market oriented farms in Burundi. In the same way, we saw that local farmers' knowledge on the application of DAP to replenish nutrient exports is still limited. In addition, the lack of up-to-date and site-specific fertilizer recommendations limits their efficiency for crop production. Since 1 kg of DAP was given to farmers to be used following their local practices and on variable plot sizes, the rates of N and P applied were also different among farmers and districts. The occurrence of nutrient deficiencies showed that 1 kg of DAP resulted in some removal of N and P deficiencies especially in Buraza district. However, N and P remained the main limiting nutrients for maize productivity in both control and fertilized plots in Makebuko district while Zn and Mn were the most important limiting nutrients in both control and fertilized plots of Buraza district. Zn and Mn-deficiencies are expected to limit yields. We indeed observed in this study that in Buraza district, the DAP fertilizer induced a smaller yield increase on average (29 %) compared to the one in Makebuko district (46 %) where these two nutrients are not limiting (Table 3.7, chapter 3). Demonstrations on best management of DAP fertilizer use to improved varieties and its profitability were conducted in Buraza district for beans and maize production (Chapter 4). The use of DAP to the improved climbing bean/maize variety resulted in larger grain yields (Figure 4.1 & 4.2, chapter 4), larger net benefits, larger value cost ratio and larger marginal rate of returns (Table 4.4, chapter 4) than for local climbing bean and maize varieties when planted on time in a soil with high total C ($TC \geq 1.9$ g kg^{-1} , figure 4.5, chapter 4) and moderate clay content (38 - 40 %, figure 4.5, chapter 4). These results are in line with the staircase concept of the Integrated Soil Fertility Management framework in a way they contribute to a promising alternative to the local smallholders' farmers' practices and may lead to a more sustainable bean and maize production in Central Burundi. We also worked on the profitability of DAP use in bush and climbing bean-maize rotations in smallholder farms in Central Burundi. We saw that the use of DAP fertilizer for climbing bean-maize system resulted in larger grain yields (Table 5.2, chapter 5), larger net benefits, larger value cost ratios and larger marginal rates of return in a soil with high total C ($TC > 23$ g kg^{-1}), low total N ($TN < 2$ g kg^{-1}) and high clay content (more than 37 % clay) (Figure 5.5, chapter 5) than in the bush bean-maize system.

Generally, maize grain yields have stagnated at an average of 1.2 ton ha^{-1} at farm level (Worldbank, 2014) against a potential of 6 - 8 tons ha^{-1} produced in research stations (Manirakiza, 2004) and /or field experiments with adequate management. In our study, we attained on average 4 tons ha^{-1} in one cropping season for both treatments through the use of DAP fertilizer to improved germplasm (chapter 4) and to bush and climbing bean-maize rotation systems (chapter 5). Our results corroborate the idea that the yield gaps can be closed by using appropriate soil fertility management practices in accordance with the local conditions in which they are applied. This points out the importance of farmers' awareness. Our farmers continue to farm in their traditional ways, or sometimes apply blanket fertilizer recommended rates of N, P and K fertilizer irrespective of their different local conditions. Efforts to increase the farmer's awareness and to encourage them to take advantage of the best set of ISFM practices demonstrated in this thesis should be a priority in a policy to manage soil fertility in the region.

Finally, the contribution of this work was to provide information about existing gaps in the context of ISFM and possible promising ways to bridge the gaps. Findings of this work can be useful for decision makers, research, extension services, and development partners working on rehabilitating depleted soils of Burundi. More further research are needed to predict nutrient deficiencies in the remaining locations within Burundi for results validation, establish site specific nutrient recommendations and translate these results into practical guidelines for farmers.

Profile description up to 150 cm (WRB, 2012)

A.1. Mr. Karenzo Venant's farm

I. Site information

-Profile number: Buraza

-Authors: Joram Sinzinkayo; Marie-Chantal Niyuhire

-Date of description: 07/02/2013

-Location (coordonnées):

- Agroecological zone : Kirimiro
- Province : Gitega
- District : Buraza
- Division : Mugano
- Location : Cunguza
- **GPS :**
- Latitude : 03.75 672°N
- Longitude : 029 86877° E
- Altitude :1829 m asl;

-Physiography: upper part of slope, slope is between 16 and 30 % with a convex side

-Occupation of soil: maize, cassava and grevillea

II. General information on the soil

- Geological Substrate: Basic Intrusion Schist

-Parental material: Schistobasic

-Drainage: Good

-Permeability: Low permeability

-State water status: Fresh

-Erosion: Superficial

-Presence of salts: none

III. Classification:

➲ WRB, 2012: Acrisols

IV. Description of horizons

Thickness/depth (cm)	0-20	20-47	47-95	95-133	133-150
Color	5YR3/3	2.5YR3/3	2.5YR3/4	2.5YR3/6	2.5YR4/6
Texture	Ò	Ò heavy clay	Ò	Ò	Ò
Structure	elementary	Sub angular strongly developed	Sub angular strongly developed	Sub angular strongly developed	-
Consistence	Fresh	Fresh	Fresh	Fresh, very firm	Fresh, very firm
Roots	Many fine and medium	Few, fines	few	Very few, fine and medium	inexistent
Occupation of soil	maize	cassava	Grevillea		
Horizon	Ap	A/B	B2c	B/C	C
FAO Description	Fine clay	Fine clay	Fine clay	Heavy clay	Fine clay

Plate A.1. Buraza profile

A.2. NAHIMANA Ferdinand's farm

I. Site information

-Profile number: Makebuko

-Authors(s): Joram Nsinzinkayo and Marie- Chantal Niyuhire

-Date of description : 06/02/2013

-Localisation (coordinates) :

. Agro ecological zone: Kirimiro
. Province: Gitega
. District: Makebuko
. Division: Bungere
. Location: Bungere
. GPS:
. Latitude: 03.14541°
. Longitude: 029.88743°
. Altitude: 1715 m

- Physiography: plat (2%),

-Occupation of sol: Eragrostis and surrounding crops: maize and banana plantation;

II. General information on the soil

- Geological Substrate: Schist

-Parental material: schist-sandstone

-Drainage: Good

-Permeability: Good

-Water moisture level: Fresh

-Nature of the charge: gr

-Erosion: none

-Presence of salts: none

III. Classification:

➲ WRB, 2012: Nitisols

IV. Description of horizons

Depth (cm)	0-24	24-65	65-108	108-150	
Color	5YR 4/5	2.5YR 4/6	5YR 4.5/6	3.75 Y 4/6	
Texture	I. very fine sand	I.0 fine sand	I.0 fine sand	0	
Structure	elementary	Granular moderately developed	Granular weakly developed		

Roots	Many and fines	Many and fines	Many and fines	moderate and very fines	
Occupation of soil	fallow	maize	cassava	eucalyptus	
Horizon	Ap	B21l	B22 l	C	
FAO Description	Silty loam	Silty loam	Silty.loam	Silty.loam	

Plate A.2. Makebuko soil profile

A.3. MPFAYOKURERA Josephine’s farm

I. Site information

-Profile number: MUTAHO

-Author(s): Joram Nsinzinkayo and Marie-Chantal Niyuhire

-Date of description: 05/02/2013

-Location (coordinates):

- Agroecological zone: Kirimiro
. Province: Gitega
. District: Mutaho
. Division: Mutaho
. Location: Mutaho
. GPS:
. Latitude: 03.14537^0
. Longitude: 029.86740◦
. Altitude: 1731 m

- Physiography: sloppy (16-30 %)

-Slope at the profile location: 3 %

-Occupation of soil: maize, cassava, grevillea, avocado and banana plantation

II. General information of the soil

-Substrate geological: Shale

-Parental material: Schist (gritty shale resting on shale)

-Drainage: Good

-Permeability: Good

-Water moisture level: Fresh

-Depth of the water table:

-Deep gley / pseudogley depth:

-Erosion: surface '(superficial and illuvial)

-Human activity (crop system, rotation, etc ...): Crop rotation

III. Classification:

➲ WRB, 2012: Ferralsols (typical Hygroxeroferrarisol)

IV. Description of horizons

Depth (cm)	0-26	26-70	70-98	98-150
Color	3.75YR4/3	7.5YR3/4	3.75YR3/6	2.5YR3.5/6
Texture			isf	
Structure	elementary	Sub angular strongly developed	Sub angular moderately developed	
Consistence	Fresh strongly developed	Fresh, firm	Fresh, firm	Fresh, firm
Roots	Many, thin	Many, medium and thin	Moderate, thin	Roots of avocado
Occupation du sol	maize			
Horizon	Ap B21C	B22C	C	
FAO Description	Sandy	Sandy 3.759R3/4	Clayer	

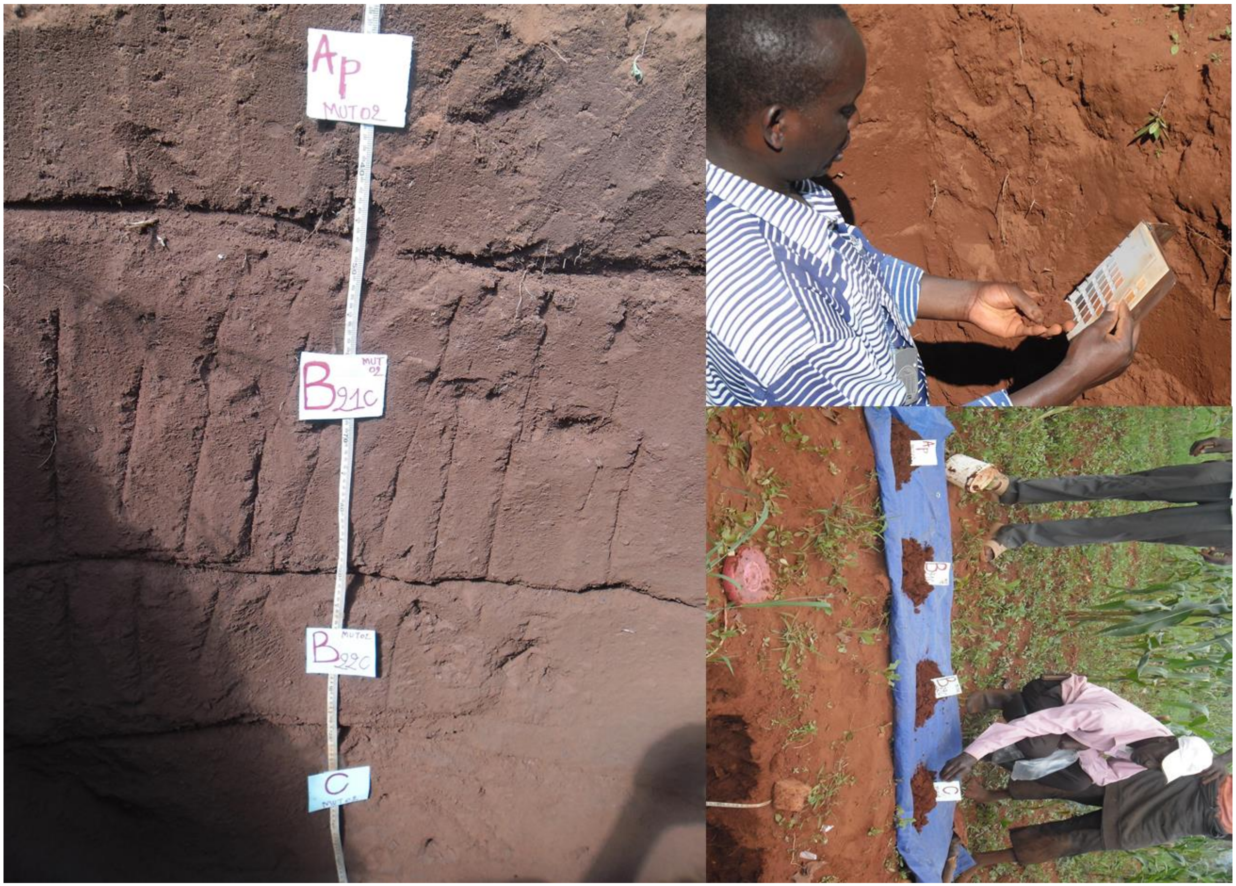

Plate A.3. Mutaho soil profile

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List of publications

A. Published in International peer-reviewed Journals

Niyuhire, M.C., Pypers, P., Vanlauwe, B., Nziguheba, G., Roobroeck, D. and Merckx, R., **(2017)**. Profitability of diammonium phosphate use in bush and climbing bean-maize rotations in smallholder farms of Central Burundi. *Field Crops Research, 212,* pp.52-60.

B. Book chapter (peer-reviewed)

Ochieng, J., **Niyuhire, M.C**., Ruraduma, C., Birachi, E. and Ouma, E**., (2014)**. Bean utilization and commercialization in Great Lakes region of Central Africa: The case of smallholder farmers in Burundi. In: Vanlauwe, Bernard; Van Asten, Piet; Blomme, Guy; (ed.). (**2014**). *Challenges and Opportunities for Agricultural Intensification of the Humid Highland Systems of Sub-Saharan Africa* (pp. 295-306). Springer, Cham.

C. Conference presentations

1. **Niyuhire, M.C**., Roobroeck, D., Nziguheba, G., Vanlauwe, B., and Merckx, R. **(2015)**. Compositional nutrient diagnosis to determine nutrient deficiencies in maize cropping under farmer practices in the central highlands of Burundi. Poster presented at the International Congress "Africa in Profile 2015"-Launch of the French version of the Soil Atlas of Africa at KU Leuven, Heverlee, Belgium, 4th December 2015.
2. **Niyuhire, M.C**., Pypers, P., Vanlauwe, B., and Merckx, R. **(2013)**. Evaluation of fertilizer agronomic efficiency and value cost ratio under farmer practices in Central Burundi. Poster presented at 6th International Nitrogen Conference under the theme: *Just enough N: Perspectives on how to get there for "too much" and "too little"*, Kampala, Uganda, 18th-22nd November 2013.
3. **Niyuhire, M.C**., Pypers, P., Vanlauwe, B., and Merckx, R. **(2012)**. Maize response to mineral N, P and K, and manure and lime amendments in acid soils in the highlands of Central Burundi. Poster presented at the Conference "Integrated Soil Fertility Management in Africa: from microbes to markets (ISFM Africa 2012). Nairobi, Kenya, 22nd-26th October 2012.

4. **Niyuhire, M**.C., Ndimurirwo, L., and Ouma, E. **(2011).** Adoption and dissemination of improved bean varieties in Burundi. Presented at CIALCA International Conference under the theme "Drivers for adoption" of the "Challenges and opportunities for agriculture intensification of the humid-highland system", Kigali, Rwanda, 23rd-29th October 2011.

D. Factsheet

Léa Vicky Magne Domgho, Ferdinand Nganyirinda, **Marie-Chantal Niyuhire**, Gert-Jan Stads., **(2017).** Burundi: Fiche d'information sur les indicateurs de la R&D agricole. ASTI-ISABU country factsheet. https://www.ifpri.org/node/1163.