USE OF MINJINGU PHOSPHATE ROCK WITH *TITHONIA DIVERSIFOLIA* IN MAIZE-BEAN INTERCROP FOR IMPROVED MAIZE YIELDS IN TWO SOIL TYPES IN KENYA

Filbert Leone Ahmat
(MSc. Agronomy)

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DECLARATION

I, **Filbert Leone Ahmat** declare that this thesis is my original work and has not been presented for the award of a degree in any other university or any other award.

Date: 13/05/2015

Filbert Leone Ahmat
Reg. No.: A99F/24650/2011

Supervisors:

We confirm that the work reported in this thesis was carried out by the candidate under our supervision and has been submitted with our approval as university supervisors.

Date: 14/05/2015

Dr. Joseph Onyango Gweyi
Department of Agricultural Science and Technology, Kenyatta University

Date: 14/05/15

Dr. Jayne Njeri Mugwe
Department of Agricultural Resource Management, Kenyatta University

Date: 17 May 2015

Dr. Stephen Kimani
Principal Scientist of Land and Water Management, Kenya Agricultural and Livestock Research Organization (KALRO)

DEDICATION

To my loving parents: Mrs. Hellen Fatna and Mr. Leone Ahmed; and beloved relatives: Mrs. Ernesta Sitna, Mr. Fabiano Kangira, Late Gabriel Dua-tuka Wagi and Late Easterina Mohengata.

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ABBREVIATIONS AND ACRONYMS

Al:	Aluminum
ANOVA:	Analysis of Variance
B:	Boron
BNF:	Biological Nitrogen Fixation
C:	Carbon
Ca:	Calcium
CA:	Citric Acid
Cu:	Copper
FA:	Formic Acid
FAO:	Food and Agriculture Organization of the United Nations
Fe :	Iron
FURP	Fertilizer Use Recommendation Project
FYM:	Farmyard Manure
H^+ :	Hydrogen ion
ha:	Hectare(s)
IFDC	International Fertilizer Development Centre
IFPRI:	International Food Policy Research Institute
K:	Potassium
KARI:	Kenya Agricultural Research Institute
Kg:	Kilogram(s) per year
LMWOA :	Low Molecular Weight Organic Acid(s)
Mg:	Magnesium
mg:	Milligrams(s)
Mn :	Manganese
Mo:	Molybdenum
Mol:	Mole
MPR:	Minjingu Phosphate Rock
N:	Nitrogen

NAC:	Neutral Ammonium Citrate
NAR	Net Assimilation Rate
NH_4^+ :	Ammonium
NO_3^-:	Nitrate
NPK:	Nitrogen-Phosphorus-Potassium
O:	Oxygen
OC	Organic Carbon
OH^-:	Hydroxyl ion
OM	Organic Matter
P:	Phosphorous
P_2O_5:	Phosphate Pentoxide
RAE:	Relative Agronomic Efficiency
RGR	Relative Growth Rate
PR:	Phosphate Rock
S:	Sulphur
SAS:	Statistical Analysis Software
SED:	Standard Error of Differences
SSA:	Sub-Sahara Africa
SSP:	Single Super Phosphate
t/ha:	Tone(s) per hectare
TSP:	Triple Super Phosphate
UNDESA	United Nations Department of Economic and Social Affairs
UNEF	United Nations Emergence Force
UNIDO	United Nations Industrial Development Organization
USDA:	United States Department of Agriculture
WAP	Weeks after planting
yr:	Year
Zn:	Zinc

ABSTRACT

Phosphorus deficiency and aluminium phytotoxicity are major factors limiting crop production in acid soils. Use of mineral fertilizers, especially by small scale farmers, to alleviate deficiencies of nutrients, such as P, is mainly hindered by their high costs and frequent unavailability. This has made the low input approach using locally available resources such as *Tithonia diversifolia* and Minjingu Rock Phosphate (MPR) gain a substantial research attention. However, less is known on the response of maize to integrated application of *Tithonia* and MPR. Therefore, four experiments were conducted to generate this information. Experiment one aimed to examine the relationship between mineral N and available P of surface soils and *Tithonia* biomass quality (N and P); whereas experiment two was to determine the effect of *Tithonia* and MPR on soil nutrients, pH and exchangeable Al. The third and forth experiments investigated the influence of the acid synthesized and secreted into the rhizosphere by beans on MPR solubilization and the agronomic responses of maize to *Tithonia* and MPR application under maize-bean intercrop. In experiment one soil and leafy samples were collected from five areas and analysed for N and P. The second experiment was an incubation experiment with five treatments while the third experiment was a greenhouse pot experiment with two factors consisting of sole maize and maize-bean intercrop as main factor treatments; and use of different fertilizing input sources plus one combination as sub factor treatments. The fourth was a field trial conducted for two consecutive planting seasons at Kavutiri in Embu County and Muguga in Kiambu County. The experiment was laid in a split plot organized in a Completely Randomized Block Design with two factors: sole maize and maize-bean intercrop as the main factor treatments; and sub factor treatments consisting of: Control; T alone (5t/ha dry weight); MPR alone (60 Kg P/ha); TSP alone (60 Kg P/ha); T (5t/ha) combined with MPR (50 Kg P/ha); and T (5t/ha) combined with TSP (50 Kg P/ha). Analysis of Variance (ANOVA) was done using the General Linear Model (GLM) procedure of the Statistical Analyses Software (SAS), version 9.3. Results showed that the concentration levels of mineral N and available P of the top soils weakly correlated ($- .22 \leq r \leq + .62$) with their respective levels in the biomass while in the biomass, N concentration, however, increased with the rising concentration of P ($r = +. 95$). Integrated application of *Tithonia* biomass with MPR not only resulted in significant rise, above the control, of available soil N (30.2%), P (182.3%), K (27.6%) and Ca (70.8%) but also in a significant decrease of the concentration of soluble Al; MPR solubilization was further enhanced by 68.7% for MPR applied alone and 223.6% for MPR combined with the biomass under maize-bean intercrop as compared to sole maize. Effects of the applied *Tithonia* biomass and MPR on agronomic parameters of maize differed under the two cropping systems. In conclusion, this study reveals that integrated use of the low fertilizing inputs (*Tithonia* biomass and MPR) under maize-bean intercrop improves maize yield on a P-deficient acid soil that is highly saturated with soluble Al more than mineral P fertilizers. Dissemination to farmers of this newly established low input technology by appropriate institutions, such as the ministry of Agriculture, is highly recommended.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Soil fertility depletion on smallholder farms is the major biophysical root-cause of the declining per capita food production in Sub Sahara Africa (Sanchez et al., 1997). The depletion is caused by negative balance resulting from losses of nutrients exceeding inputs, especially the amount removed from the soil in harvests. In Kenya, the annual net nutrient mining from the soil averages 42 kg N/ha; 3 kg P/ha and; 29 kg K/ha (Smaling, 1993). The trend clearly indicates that there is an urgent need to increase use of external fertilizing inputs in order to reverse the prevailing negative nutrient balance if food production is to be increased. Nutrient replenishment may be achieved through use of either mineral fertilizers, organic inputs, or a combination of both, depending on the availability of those inputs in the area, level of nutrient deficiency in the soil, and the economic capacity of farmers to afford the quantity required.

Use of manufactured mineral fertilizers by smallholder farmers in Sub Sahara Africa (SSA), including Kenya, is however constrained by several socio-economic factors, such as high prices, their timely availability to farmers, high transport costs, and lack of credit facilities (Jama and Van Straaten, 2006). For this reason, use of locally available organic inputs to increase crop yields and food production by these financially-unable farmers is increasingly becoming an alternative to the expensive mineral fertilizers (Ikerra *et al.,* 2007). However, due to their extremely low P concentration, ranging from 0.15 to 1%, organic materials do not provide enough P for the growth of annual crops on soils which are deficient in P. As a result, soil amendment with organic materials may therefore not be an effective option to increase the yields of annual crops on P deficient soils located in the densely populated humid and sub humid regions of East Africa (Weil *et al.*, 1991; Jama *et al.*, 1997; Palm *et al.*, 1997).

Although P deficiency is widespread in East Africa, it is most severe in many areas of Kenya, where responses of maize to P application were shown to be significant even at rates as low as 10 kg P/ha (Jama *et al.*, 1997). Some soils in the country are so deficient in P such that without additional P, the impact of other agricultural technologies is limited (Sanchez *et al.*, 1997). Several studies indicate that about 80% of the smallholder land used for maize production in Kenya is deficient in soil available P. Therefore, amendment of these soils with only organic materials may not be sufficient to achieve better maize yields. In Western Kenya, better maize yields were achieved on the soils when organic materials were used in combination with P sources, such as rock phosphate (PR) or mineral P fertilizers (Gachengo *et al.*, 1999; Nziguheba *et al;* 2002; Opala *et al.*, 2010). With the prevailing global economic crisis which has negatively affected the purchasing capacities of smallholder farmers, many workers today consider use of PR, which is a water-insoluble but acid-soluble indigenous P source, to be more relevant for these resource limited farmers in comparison to the prohibitively expensive mineral P sources.

Results from trials conducted in Kenya (Gachengo *et al.*, 1999) and Tanzania (Ikerra *et al.*, 2007) both showed that significantly higher maize yields were obtained when prunings from *Tithonia diversifolia*, as compared to other potentially available organic resources, were applied in integration with Minjingu Rock Phosphate (MPR) on

P deficient acid soils. The effectiveness of this combination of inputs in increasing maize yields was reported to be relatively lower in comparison to mineral P fertilizers but with longer and better residual effects.

In Kenya, as elsewhere in Sub Sahara Africa (SSA), maize, which was the test crop in the study, is frequently grown in intercrop with beans in small scale farming systems (Woomer *et al*., 1997; Giller, 2001; Mucheru-Muna *et al*., 2010). This maize-bean system has the advantage of reducing household risks during poor growing seasons and producing modest surpluses during favourable seasons. The system thus displays risk avoidance features. These risk avoidance features are considered sound in that bean leaves and green pods may be consumed early in the growing season; and dry beans mature rapidly. On the other hand, the system allows a maximum utilization of land and labour as well as the attainment of larger crop yields (Mucheru-Muna *et al.,* 2010). Maize and beans are the main staple food not only in Kenya but also in the whole of East Africa and SSA. At national level, maize is ranked first among the locally grown cereals and other food crops. It is grown on two out of every three farms and is majorly produced under rain-fed conditions (Wokabi, 2000). The key maize growing areas of the country are located in ecological zones that allow the crop to grow irrespective of limiting temperature and rainfall environments. The crop is grown in a wide range of soils in the country which include Andosols, Vertisols, Phaeozems, Cambisols, Luvisols, Nitsols, Acrisols and Ferralsols (Muchena *et al.,* 1988). The total land area under maize production in both monocrop and intercrop systems is estimated at 1.5 million hectares, which is equivalent to 55.5% of the land area under cereal production (2,701,226 ha), 28.3% of the arable land (5,300,000 ha), and 0.1% of the agricultural land (272,500,000 ha) (World Bank, 2012). Without use of manufactured mineral fertilizers or manures, maize grain yields usually range from 1.1 to 2.5 t/ha on small holder farms against an estimate of 4 to 5 t/ha with fertilization. In areas with a bimodal annual rainfall pattern, in the central highlands of Kenya for example, maize is grown twice a year, during both the long and short rains.

Botanically, beans belong to the group of grain legumes which, by definition, are pod and grain producing plants; and have the capacities of fixing and utilizing to their own need nitrogen from the atmosphere through a process known as 'Biologically Nitrogen Fixation' (BNF). This process is made possible by the presence of some bacteria of the group of *Rhizobia*, located in root nodules of the host plant. The process of biologically fixing nitrogen in grain legumes is characterized by a series of biochemical reactions that result in the secretion of hydrogen protons (H^+) by the plant roots into the rhizosphere or root environment, thus inducing the acidification of the rhizosphere (Israel and Jackson, 1982; Raven *et al.*, 1991; Horst, 1995; Perez *et al.*, 2006).

1.2 Statement of the Problem

Intercropping maize with beans (cereals-legumes) is a well known farming practice to agronomists and many other agricultural scientists in the world (Willey, 1979; Fujita *et al.,* 1992; Giller, 2001; Woomer *et al.,* 2004; Fan *et al.,* 2006; Mucheru-Muna *et al.,* 2010;). This type of intercropping is widespread among small scale farmers in Sub Sahara Africa (SSA), in general, and in East Africa (EA), in particular, where both maize and beans are the main staple food of the population. Poor yield prevalence of maize crop, caused by severe P-deficiency, is a common phenomenon on acid soils. A cheaper alternative to use of mineral P fertilizers could have been offered by direct application of a reactive phosphate rock, Minjingu phosphate rock (MPR) for instance, with the biomass of *Tithonia diversifolia*. Unfortunately, this option was reported to be ineffective in the season of application under sole maize due to low solubility of the water-insoluble but acid soluble rock (Msolla *et al.,* 2007; Opala *et al.,* 2010). Thus, the presence of beans in maize system is postulated to play a crucial role in the further enhancement of MPR solubilization, P availability to maize, and P uptake and utilization by maize which may ultimately result in the achievement of improved maize grain yields. Bean crop, *Phaseolus vulgaris* in this case, is potentially expected to affect MPR dissolution through its rhizosphere acidification which occurs during the process of biological nitrogen fixation (BNF) (Nyatsanga and Pierre, 1973; Van Beusichem, 1981; Unkovich *et al.*, 2008). In this study, rhizosphere acidification by beans is hypothesized to reinforce the initial level of soil acidity and consequently contribute to further solubilization of MPR. Less attention, however, has been paid to research on the widely-practiced maize-bean intercropping in relation to maize monocropping. As a result, there is scanty documented information on the level of responses of maize to use of MPR with *Tithonia* leafy biomass under maize bean intercrop on P deficient acid soils. This study was therefore intended to evaluate the effect of bean rhizosphere acidification on the dissolution of MPR applied with *Tithonia* leafy biomass under maize-bean intercrop and the agronomic responses of maize to such a low input integration in two soil types in Kenya.

1.3 Research Questions

1. What is the relationship between mineral N and available P of the surface soils (0-20 cm deep) and the N and P contents of *Tithonia* leafy biomass?
2. What is the effect of *Tithonia* leafy biomass and MPR applications on soil nutrients, pH, exchangeable acidity and soluble Al?
3. What is the influence of the bean (*Phaseolus vulgaris*) rhizosphere acidification on MPR solubilization?
4. What is the agronomic response of maize to a combined application of *Tithonia* leafy biomass and MPR under maize-bean intercrop in relation to sole maize?

1.4 Objectives of the Study

1.4.1 General Objective

To investigate the processes by which *Tithonia* leafy biomass and MPR contribute to improved maize yields in maize-bean intercrop on P-deficient acid soils in Kenya.

1.4.2 Specific Objectives

i. To investigate the relationship between mineral N and available P of the surface soils and N and P contents of *Tithonia* leafy biomass in different areas;

ii. To determine the effect of *Tithonia* biomass and MPR applications on soil nutrients, pH, exchangeable acidity and soluble Al;

iii. To assess the influence of bean (*Phaseolus vulgaris*) rhizosphere acidification on MPR solubilization, and;

iv. To evaluate the agronomic response of maize to a combined application of *Tithonia* leafy biomass with MPR under maize-bean intercrop as compared to sole maize.

1.4.3 Hypotheses of the Study

a. The amount of N and P in *Tithonia* leafy biomass is directly related to N and P in the top soil;

b. A combined application of *Tithonia* leafy biomass with MPR significantly increases soil nutrients, pH, exchangeable acidity and soluble Al;

c. Bean rhizosphere acidification significantly increases P availability from MPR applied with *Tithonia* leafy biomass under maize-bean intercrop and subsequently improves maize dry matter yields, and;

d. A combination of *Tithonia* leafy biomass with MPR under maize-bean intercrop significantly increases the agronomic response of maize as compared to sole maize.

1.5 Justification

In order to further increase crop yields and improve payback of the activity while lowering to the minimum the cost of production, there is need to focus on low input approaches. It is, however, important to ensure that any new technology being developed complies with farmers' practices for ease adoption. Integrated use of *Tithonia* leafy biomass with MPR under maize-bean intercrop, particularly on P deficient acid soils of the tropics and sub tropics, has the potential of raising maize yields to a level equal to, or even above, the one achieved by mineral fertilization. Other advantages associated with the low input strategy include its significant role in building up soil microbial biomass population, soil nutrient capital, soil structure and texture, improving soil water holding capacity, regulating soil temperature and conferring to soil the ability to resist erosion. Most of these roles are unachievable by mineral fertilizers but contribute tremendously to the sustainability of agriculture.

Due to the exorbitant costs of mineral fertilizers, many peasant farmers hardly afford the quantities of fertilizers required for their farms. As a result, farmers resort to either applying insufficient amount of mineral fertilizers or growing crops without fertilizers. These aspects have contributed to poor yields on small holder farms.

One important aspect of the low input strategy used in this study is its adoptability to farmers' practices. This aspect is considered to be a pre-requisite to its successful dissemination in the region. Farmers are always reluctant to totally abandon their life-long practices for new practices. In Sub Sahara Africa, including Kenya, maize is rarely grown in monocrop on small holder farms. It is traditionally cultivated in intercrop with grain legumes, such as common bean, cowpea and soybean.

1.6 Significance

The information generated in this study will be useful to farmers, agricultural researchers, agriculture-promoting institutions and Non-Governmental Organizations such as the World Bank and Food and Agriculture Organization of the United Nations (UNFAO), agricultural policy makers (including the ministry in charge of agriculture), extension officers and farmers, especially those in Sub Sahara Africa (SSA). The information will be of great use in the design of new policies and strategies to increase food production particularly that of annual crops, on acid soils that have been shown to be deficient in P and highly saturated with soluble Al. It will mainly be utilize to the benefit of smallholder farmers, especially those in SSA who have very limited purchasing power and therefore are unable to afford acquiring the amount of mineral fertilizers required for their farms due to the high costs of these fertilizers. In SSA, smallholder farmers constitute the overwhelming majority of the population.

1.7 Conceptual framework of the study

In this study, the research uses the low input model schematized in Figure 1.1. The model involves the integration of Minjingu Phosphate Rock (MPR) with *Tithonia* leafy biomass under maize-bean intercrop in order to achieve improved maize yields on P deficient acid soils. It was a modification of the common model based on maize monocrop, used by previous workers (Savini *et al.,* 2006; Ikerra *et al.,* 2007). In the current model, maize monocrop was substituted by a bean based maize system, the maize-bean intercrop.

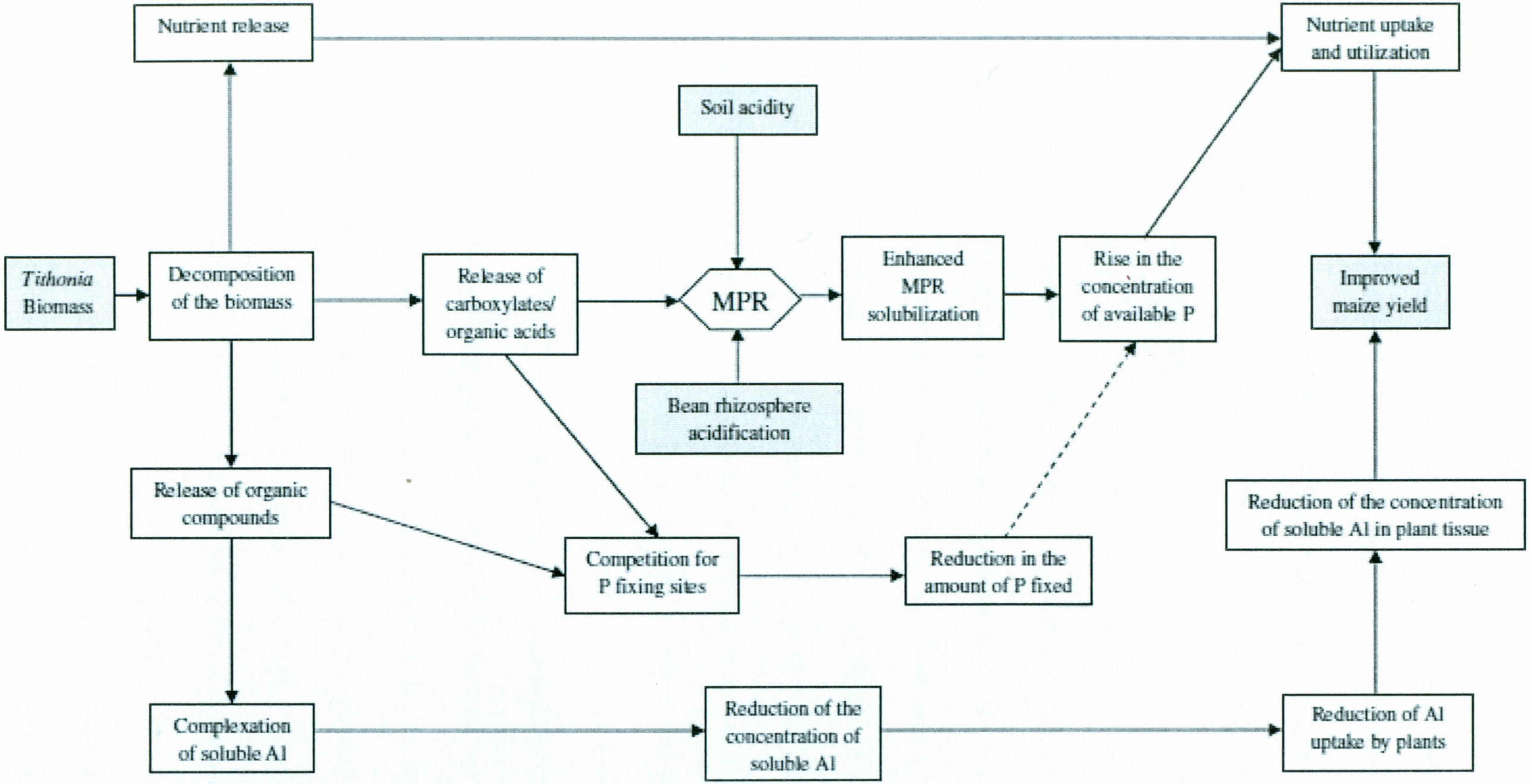

Figure 1.1: Schematized Conceptual Framework showing the low input approach used by the research study

Presence of the bean (*Phaseolus vulgaris* L.) in the model was postulated to change the dimension of the output (i.e. maize grain yield) by significantly increasing the yield level of maize as compared to that of maize monocrop. The change was expected to arise from the well-known acidifying effect of the roots of beans in soil (Roberts, 1997; Sanchez et al., 1997; FAO, 2004). Proton (H^+) excretion into the bean rhizosphere is driven by the process of biological nitrogen fixation (BNF). Bean rhizosphere acidification adds up to the initial soil acidity and jointly contributes to a further solubilization of the reactive rock phosphate, the Minjingu Phosphate rock (MPR) which would result to the release of more P for uptake and utilization by maize therefore leading to improved maize yields.

The decomposition of *Tithonia* leafy biomass following its incorporation into soil is expected to result in the release of nutrients, carboxylates and Low Molecular Weight Organic Acids (LWMOA) in addition to other organic compounds. Part of the nutrients released would be taken up by the crops after mineralization, the other part is fixed in the soil, while the carboxylates/organic acids and the organic compounds are postulated to play other roles indirectly favouring the achievement of an optimum crop production on the P deficient acid soils that are highly saturated with soluble Al. Ikerra *et al.* (2011) observed that the LMWOAs released by *Tithonia* biomass during decomposition has a limiting effect on P sorption activities in the soil, thus indirectly contributing to the improvement of the concentration of P in soil solution. The organic acids compete with P for the fixing sites and were said to always overcome P in this competition. Furthermore, the organic compounds released were expected to chelate soluble Al therefore reducing its concentration and negative effect on crop growth.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview

The need to feed a fast growing world population, expected to reach 8,000 million by 2020 and 9,400 million by 2050 (Lal, 2000), is a constant pressure on crop production, as is coping with an increasingly degraded environment and uncertainties resulting from climate change and the need to adapt farming systems to these scenarios. Approximately 50% of potentially arable land is currently under annual and permanent crops. A further 2 billion hectares (ha) has been degraded and land degradation continues through a wide range of processes, mainly related to mismanagement by mankind (Oldeman, 1994; FAO, 1999b; UNEF, 2000).

Agriculture is critical for both human welfare and economic growth in Africa. In Sub-Sahara Africa (SSA), roughly two-third of the population live in rural areas and are dependent on agriculture for their livelihood; nearly a half live in extreme poverty, earning less than $ 1/day and one-third are undernourished. In the poorest countries such as Malawi, more than 90% of the population depends on small-scale farming for their survival (FAOSTAT, 2000). Agriculture currently contributes 30 - 50% of national incomes in SSA and can generate considerably greater income and stimulate economic growth (FAOSTAT, 2000). The low performance of agriculture in Africa is at the heart of its food insecurity and slow economic growth. Ghana today is among the leading fastest developing countries in Africa and the economy of the country is dominated by agriculture which accounts for more than 30% of the total Gross Domestic Product

(GDP) (Breisinger *et al.,* 2008). Thirty percent (30%) is the highest contribution. Sixty percent (60%) of the population live in rural areas employed by agricultural sector.

Use of mineral fertilizers to increase crop yields by African farmers is widely reported to be an expensive, ambiguous venture because of the high costs of these fertilizers, whenever they are available on the market, and the unreliability of their supply due to poor infrastructure (Woomer *et al.,* 1998). Low crop yields are a widespread phenomenon among the predominant smallholder farmers in the continent. For example, cereal yields in Africa are only a quarter of global average (Figure 2.1).

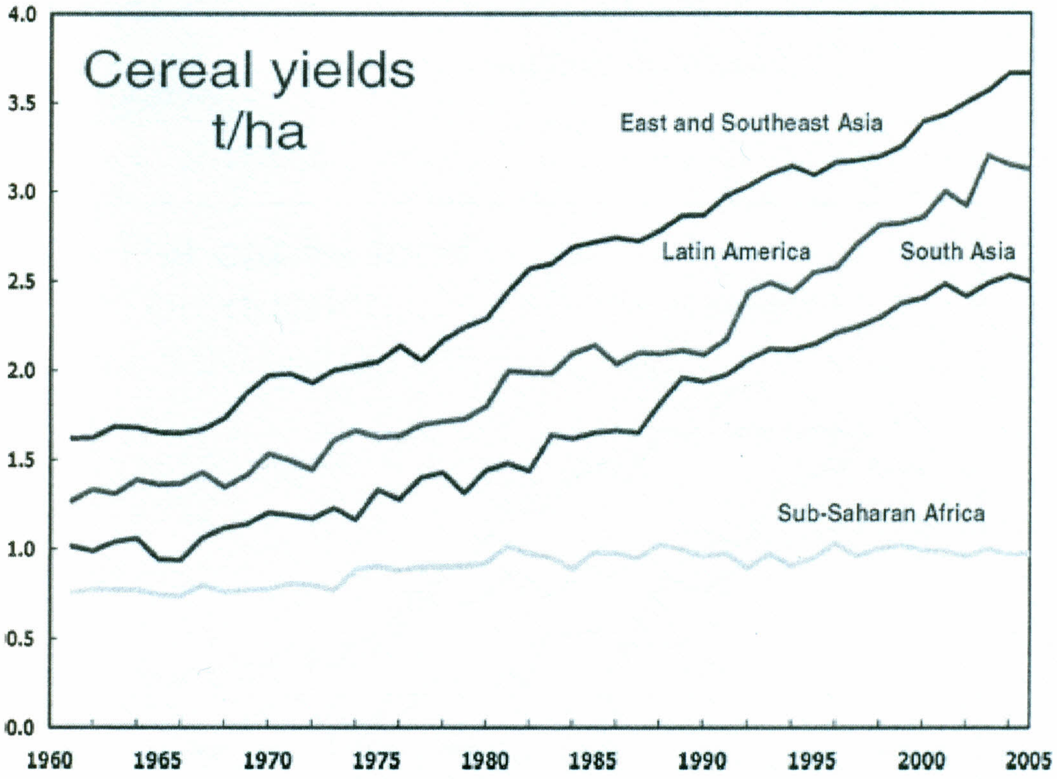

Figure 2.1: Trend of cereal yields in SSA and other parts of the world in the past decades (Toenniessen et al., 2008).

In Kenya, where maize is the major food crop with a per capita consumption of 103 kg yr^{-1} (Pingali, 2001), an average maize yield of 0.5 to 1.5 t/ha was reported by Ouma *et al.* (2000) on smallholder farms in the central highlands. This finding concurs well with the indication of Figure 2.1. The poor crop yield prevailing in this region was essentially accused to low fertility of the soil.

Africa has vainly tried to keep up with its growing population's demand for more food by significantly expanding the area under crop production and by reducing fallow periods, thus contributing to a serious deforestation and land degradation, respectively. More than three-quarter of the farmland in SSA has been depleted of basic plant nutrients, and farmers increasingly face severe soil fertility depletion problem which has resulted in reducing per capita food production (Figure 2.2).

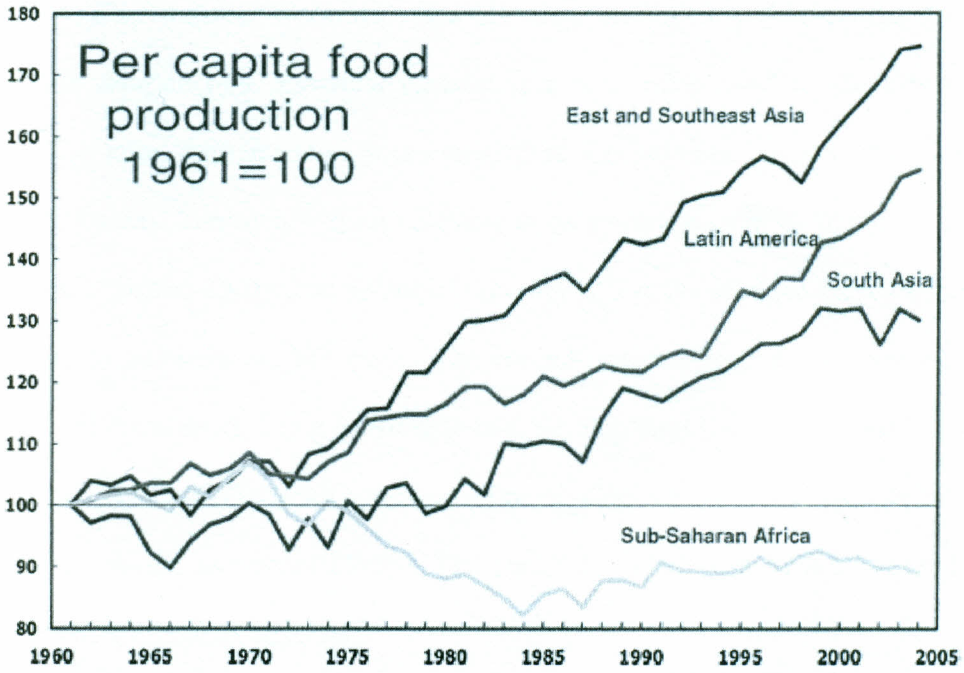

Figure 2.2: Trend of per capita food production in SSA and other parts of the world within the past decades (Toenniessen et al., 2008).

The challenge is serious because Africa's population has already exceeded the productive capacity of the continent's current food production system, and population growth rates remain high. The International Food Policy Research Institute (IFPRI, 2007) predicts that Africa will probably continue to be the "troubled region" in terms of imbalance between food demand and supply. Their projections suggest that Africa is the only region that will experience major food shortages and where malnutrition is projected to rise over the next 20 years. Because of poor performance in its agricultural sector, Africa's annual food imports are projected to rise from \$ 6.5 billion in 2007 to \$ 11 billion by 2020, with the economic, social, and political costs of relying on imported food being high (Pimentel *et al.,* 1997).

2.2 Plant nutrients and growth

A plant *nutrient* is defined as a chemical element that is essential for plant growth and reproduction. *Essential element* is a term often used to identify a plant nutrient. The term 'nutrient' implies essentiality; so it is redundant to call these elements essential elements. Commonly, for an element to be a nutrient, it must fit certain criteria (Baker and Pilbeam, 2007). The principal criterion is that the element must be required for a plant to complete its life cycle. The second criterion is that no other elements substitute for the element being considered as a nutrient. And last but not least, all plants require the element. The term essential mineral element (or mineral nutrient) was proposed by Arnon and Stout (1939). The concluded three criteria must meet for an element to be considered essential.

These criteria are:

i. A plant must be unable to complete its life cycle in the absence of the mineral element.

ii. The function of the element must not be replaceable by another mineral element.

iii. The element must be directly involved in plant metabolism.

These criteria are important guidelines for plant nutrition but exclude the beneficial elements. Beneficial elements are those that can compensate for toxic effects of other elements or may replace mineral nutrients in some other less specific functions such as the maintenance of osmotic pressure. But knowing the nutrients required to grow plants is only one aspect of successful crop production. To achieve optimum yields requires knowing the rate to apply, the method and time of application, the source of nutrients to use, and how the elements are influenced by soil and climatic conditions (Tucker, 1999).

For a plant to grow well, nutrients should occur in soil in a sufficiency range (McCauley *et al.,* 2009). A plant's sufficiency range is defined as the range of nutrient necessary to meet the plant's nutritional needs and maximize growth (Figure 2.3). The width of this range will depend upon individual plant species and the particular nutrient. Nutrient levels outside of a plant's sufficiency range will cause a deficiency or toxicity. Nutrient deficiency occurs when an essential nutrient is not available in sufficient quantity to meet the requirements of a growing plant. On the other hand, toxicity occurs when a nutrient is in excess of plant needs and therefore decreases plant growth or quality.

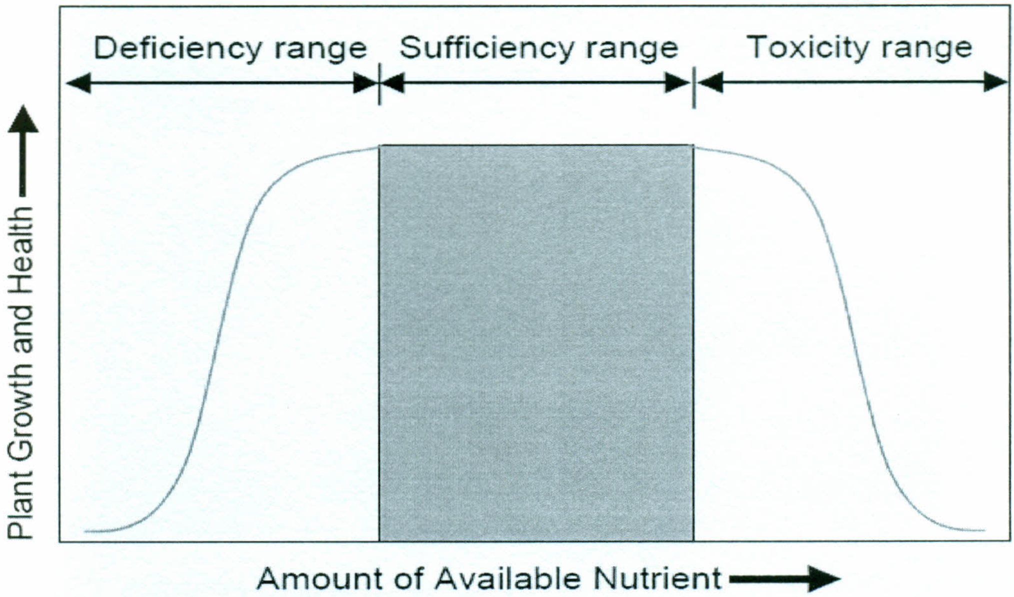

Figure 2.3: Relationship between plant growth and health and the amount of nutrient available (Brady and Aweil, 1999).

A first step in diagnosing nutrient deficiencies/toxicities is to describe what the symptoms look like. Each symptom must be related to some function of the nutrient in the plant (Havlin *et al.,* 1999). Symptoms caused by nutrient deficiency are generally grouped into five categories, namely: stunted growth; chlorosis; inter-veinal chlorosis; purplish-red colouring, and; necrosis. In maize, for example, P deficiency is usually visual in young plants with leaves turning purple (Plate 2.1); while K deficiency in the young plants provokes chlorotic and necrotic spotting along leaves with abrupt boundaries between dead and live tissue (Plate 2.2). However, much attention needs to be paid while making visual diagnoses in the field as some symptoms seem to look alike.

Plate 2.1: P deficiency in maize. Leaves are purplish (dark areas in the photo) and tips are brown and necrotic (McCauley *et al.*, 2009).

Plate 2.2: K deficiency in maize. Older leaves are chlorotic and leaf edges are burned, but the midrib remains green (Bennette, 1993).

There are presently 16 plant nutrients (Appendix I) known to be essential for the growth and reproduction of higher plants. Of the 16 nutrients, 3 are basically supplied by the atmospheric carbon and water. These are Carbon (C), Hydrogen (H) and Oxygen (O). Nitrogen (N) is added to the list when considering N_2-fxing legumes. The 3 basic, atmosphere and water supplied nutrients represent 90-96% of the dry matter of all plants. The remaining of 4-10% is obtained from the soil and/or fertilizer inputs. Concerning the other 13 nutrients, they are taken up from the soil and are usually grouped as primary nutrients, secondary nutrients and, micronutrients.

The *primary nutrients*—nitrogen (N), phosphorus (P) and potassium (K)—are commonly found in blended fertilizers. Primary nutrients are utilized in the largest amounts by crops, and therefore, are applied at higher rates than secondary nutrients and micronutrients (Appendix II).

The *secondary nutrients*—calcium (Ca), magnesium (Mg) and sulphur (S)—are required in smaller amounts than the primary nutrients. The major source for supplementing the soil with calcium and magnesium is dolomitic lime (aglime), although these nutrients are also available from a variety of fertilizer sources. Sulphur is available in fertilizers such as potassium and magnesium sulphate, gypsum (calcium sulphate) and elemental sulphur.

Micronutrients—iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B) and molybdenum (Mo)—are required in even smaller amounts than secondary nutrients (Appendix iii). They are available in manganese, zinc and copper sulphates, oxides, oxy-sulphates and chelates, as well as in boric acid and ammonium molybdate.

2.3 Major constraints to crop production on tropical and subtropical acid soils

2.3.1 Phosphorus (P) deficiency in soil

Of all the macronutrients in soils, P has by far the smallest quantities in solution or in readily soluble forms for plant uptake in mineral soils. Thus, soil P deficiency is one of the most limiting factors affecting plant growth on a worldwide basis (Fairhurst *et al.*, 1999). About 5.7 million hectares (ha) of soils in the world do not contain sufficient available P for optimum crop production (Sanchez and Salinas, 1981; World Bank, 1994; Batjes, 1997). According to Von Uexkill and Mutert (1995), 95% of the acid soils located in tropical Africa, America, Asia and the Pacific, and Australia are P deficient. In many of these soils the extent of P deficiency is so high that plant growth ceases once the P stored in the seed has been exhausted.

Although P deficiency is also widespread in East Africa, it is, however, most severe in the densely populated highlands of Kenya. Responses of maize to P fertilizers application were shown to be significant even at rates as low as 10 kg P /ha (Jama *et al.*, 1997). This therefore clearly shows the importance of adding P to crops in order to raise their productivity in this region which has a relatively good rainfall. Several studies indicate that about 80% of the smallholder land used for maize production in the region is deficient in available soil P. But when P deficiency is overcome through P inputs, N limits maize growth in nearly all cases. After P and N deficiencies are overcome, K therefore becomes the limiting nutrient for maize growth in about 25% of the land (Jama and Van Straaten, 2006).

Generally, P deficiency in soil has a dual effect on the environment. It drastically hampers crop productivity on the land whereas on the other hand it occasions land degradation through soil erosion as a result of inadequate soil cover due to poor development of the native vegetation (Sanchez *et al.,* 1997).

The phosphorus problem in soil fertility is three-fold (Brady and Weil, 2008):

i. The total P content of soils is relatively low, ranging from 200 to 2000 kg P in the upper 15 cm of one hectare of soil;

ii. The P compounds commonly found in soils are mostly unavailable for plant uptake, often because they are highly insoluble, and;

iii. When soluble sources of P, such as those in fertilizers and manures, are added to soils, they are fixed (changed to unavailable forms) and with time form highly insoluble compounds.

Added to the above is the practice of continuous cultivation of the land with the use of only insufficient, or even of no, fertilizing inputs. Unfortunately, this is a widely practiced system among farmers of the Sub Sahara Africa (SSA), who, in most cases, lack an adequate financial resource to afford the imported prohibitive mineral fertilizers. Consequently, soil fertility in this region is reported to have decreased considerably over the past 30 years due to the continued removal of nutrients in crop harvest without adequate compensation (Gachengo *et al.,* 1999). Nutrients removed by harvest in this case are usually greater than the amount returned to soil as fertilizers. The deficit thus created in the soil fertility management system is therefore referred to as a ‘negative nutrient balance’, also called ‘nutrient imbalance’. Smaling (1993), for example, estimates the average annual net mining of nutrients from soils in Kenya at 42 kg N/ha, 3 kg P/ha and 29 kg K/ha. After number of years, this may have an adverse impact on the environment, rendering the land barren for crop production and prone to degradation.

2.3.2 Aluminium (Al) phytotoxicity

Acid soils comprise large areas of the world's lands, particularly in the tropics and subtropics (Foy *et al.,* 1978; Foy, 1984). About 40% of the world's cultivated land area has acid soil constraints (Foy *et al.,* 1978; Kochian, 1995; De la Fuente-Martinez and Herrera-Estrella, 1999). Thus, it is a factor limiting food production in many developing countries, most of which are situated in Africa. Aluminium (Al) toxicity is one of the main factors limiting crop productivity in acid soils around the world. In cereals, this problem can effect between 30 and 40% of crop yields. Al toxicity is exacerbated by use of ammonium fertilizers and acid rains (Von Uexkull and Murtert, 1995). It is important to note that Al is the most abundant metal and third most common element in the earth's crust, next to oxygen and silicon in acid soils. The earth's crust is comprised of about 8% Al by weight (Marschner, 1995, Havlin *et al.,* 1999).

The main soil Al molecular forms exist in five major species of hydroxy-aluminium that their concentrations in soils depend on the pH (Figure 2.4). These species are: $Al(H_2O)_6^{3+}$; $Al(OH)^{2+}$; $Al(OH)_2^{+}$; $Al(OH)_3$; and $Al(OH)_4^{-}$. All of them fall under the general group of monomeric Al. In acid soil of a pH value less than 5.0, $Al(H_2O)_6^{3+}$, octahedral hexahydrate, which by conversion is usually called Al^{3+}, is the dominant species. Based on the findings of several studies (Foy, 1988; Kochian, 1995), Al^{3+} is the most toxic species to plants (phytotoxic species). However, two other species $Al(OH)^{2+}$ and $Al(OH)_2^{+}$ become dominant when the soil pH range is from 5.0 to 6.0. In general, these two species are not as toxic to plants as Al^{3+} (Kinraide, 1990; Kinraide, 1991; Kinraide, 1997; Kochian, 1995). These two species ($Al(OH)^{2+}$ and $Al(OH)_2^{+}$) were, however, suggested by Kochian (1995) to relatively be much toxic to dicots than monocots. At neutral soil pH, $Al(OH)_3$ (gibbsite) forms, which is relatively insoluble and limits the solubility of other Al monomers. This is a non-phytotoxic species of Al. As the pH is increased further (pH = 8.0), another phytotoxic species of hydroxyl Al called Aluminates, $Al(OH)_4^-$, becomes dominant.

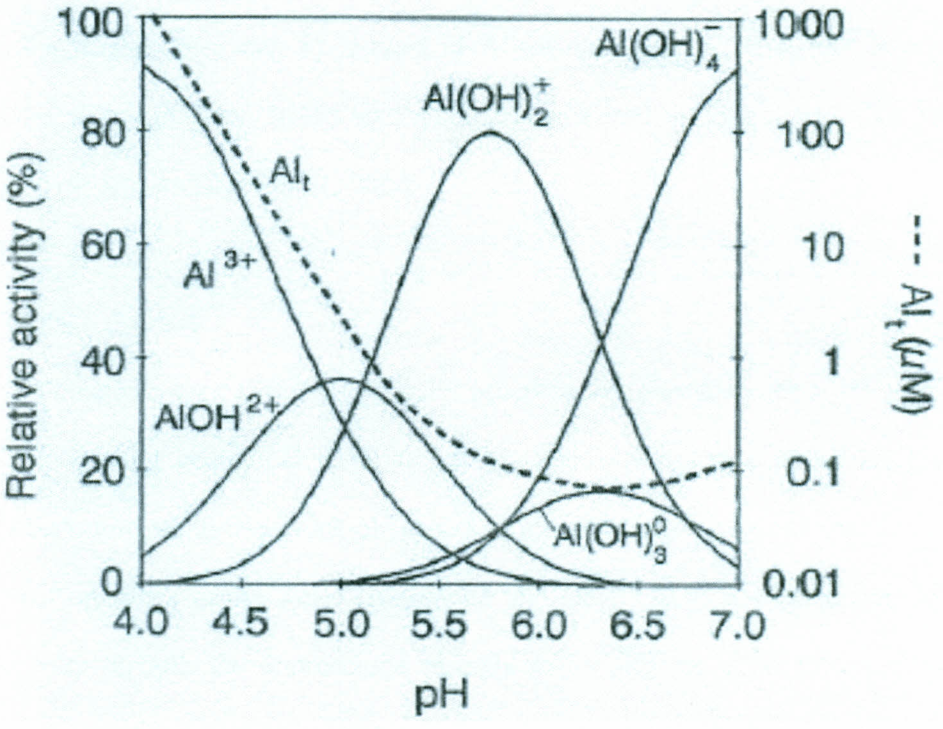

Figure 2.4: Variation in the concentrations of monomeric Al species in the soil as affected by the soil pH (Kinraide, 1991)

Critical values of Al saturation in soil for field crops differ with crop types. For instance, the critical Al saturation value for maize (*Zea mays*) of 30% is far above the one for common bean (*P. vulgaris*) which is 20% (Fageria, 1984).

The main symptom of Al toxicity is a rapid inhibition of root growth which occurs immediately after exposure of the plant to phytotoxic Al species. Reduction in root growth reduces the absorption of nutrients and water, vigour, and consequently crop yields (Rengel, 1992; Kochian *et al.,* 2005; Yang *et al.,* 2006). Plants have different mechanisms to resist or tolerate the toxic effect of Al in response to stress. These resistance mechanisms in plant have been classified as: a) external or exclusion through the exudation of organic acids from the radical apexes and subsequent chelation of the root in the rhizosphere, and; b) internal or Al-tolerant since Al chelation is produced inside the cell and later stored and compartmentalized in organelles like vacuole (Kochian, 1995; Ramgareeb *et al.,* 2004).

2.4 Phosphate rock

Phosphate rock (PR) is a globally accepted but imprecise term describing any naturally occurring geological material that contains one or more phosphate minerals suitable for commercial use. Rock phosphate is the trade name of about 300 phosphates of different qualities in the world (Hammond and Day, 1992). Several authors use the term to refer to both the unprocessed phosphate ore and the concentrated phosphate products (Notholt and Highley, 1986).

The phosphate minerals present in PR are of diverse origins and therefore have different chemical and physical properties. The phosphorus content or grade of phosphate rocks is commonly reported as phosphorus Pentoxide (P_2O_5). The principal phosphate minerals in PR are Ca-P (Calcium-Phosphate), mainly apatite. Pure fluor-apatite contains 42% P_2O_5, whereas francolite, the carbonate-substituted form of apatite, may contain 34% P_2O_5.

Five major types of phosphate resources are currently being mined in the world. These are:

- Marine phosphate deposits;
- Igneous phosphate deposits;
- Metamorphic deposits;
- Biogenic deposits, and;
- Phosphate deposits as a result of weathering.

In general, PR sources differ widely in their mineralogy and chemistry. The chemical reactivity or solubility of phosphate rocks is the measure of the PR's ability to release P for plant uptake. Rajan *et al* (1996) defines reactivity as 'the combination of PR properties that determine the rate of dissolution of the PR in a given soil under given field conditions'. The reactivity of sedimentary phosphate rocks is relatively high compared to those of igneous and metamorphic origins. The fundamental difference lies in the crystal chemistry of apatite, specifically the degree of isomorphous substitution of phosphate by carbonate. It has been shown that the solubility of carbonate substituted phosphate rocks is higher than the solubility of pure fluor-apatite with little or no carbonate-substitution (Chien and Hammond, 1978). Increasing carbonate substitution in the phosphate rocks increases the easy breakdown of the structure of the apatite thereby releasing P to the soil solution under acidic conditions. The chemical and mineralogical features are key factors in determining the reactivity and subsequent agronomic effectiveness of a given phosphate rock.

Phosphate Rock (PR) sources with high relative reactivity are best suited for direct application as fertilizers to acid soils with low Ca and P concentrations. Examples of high to medium reactive PR resources from Africa that do not need any further modification, apart from fine grinding, are those of Mali (Tilemsi PR), Tanzania (Minjingu PR), Nigeria (Sokoto PR) and Niger (Tahoua PR). With time, those ones from Cabinda in Angola and Holle in the Republic of Congo are likely to be added to this list if they are confirmed.

Phosphate Rock sources are generally less soluble in water but much soluble in acid compounds. The solubility of PR sources in acids and consequently in acid soils, in particular of apatite which is the P bearing mineral constituent of PR, is illustrated by the following chemical equation:

$$Ca_{10}(PO_4)_6F_2 + 12\,H^+ \leftrightarrow 10Ca^{2+} + 6H_2PO_4^- + 2F^-$$

The equation is a clear indication of the reason why phosphate rock is significantly effective in increasing crop yields only on acid soils deficient in Ca and P. The effectiveness of PR sources in enhancing crop yields on these soils is therefore explicitly explained by the soils' relatively higher concentration of hydrogen ion as compared to that of alkaline soils (Bolland and Gilkes, 1989; Roberts, 1997; FAO, 2004).

2.4.1 Phosphate Rock Solubility Tests

The solubility or reactivity of a PR resource closely depends on the solubility level of the constituent apatite mineral(s) of the resource. To measure the solubility/reactivity of PR resources one of the following three different solutions is used:

1. Neutral ammonium citrate (NAC);
2. 2% citric acid, and;
3. 2% formic acid.

Each of the three differs by the laboratory procedures, the length and extreme values of each of the three class intervals for classifying the solubility potentials of PR resources. Regardless of the laboratory analytical procedures, PR solubilities are always measured in per cent phosphorus pentoxide (% P_2O_5). Although there is no widely accepted system for classifying and grading PR sources for direct application based on their solubility measurements, however, Diamond (1979) proposes the below (Table 2.1) threshold classification system according to NAC, 2% citric acid (CA) and 2% formic acid (FA) solubilities.

Table 2.1: Proposed classification of PR for direct application by solubility and expected initial response

Potential	Solubility (% P_2O_5)		
	NAC	2% CA	2% FA
High	> 5.4	> 9.4	> 13.0
Medium	3.2 – 4.5	6.7 – 8.4	7.0 – 10.8
Low	< 2.7	< 6.0	< 5.8

(Source: Diamond, 1979)

Hammond and Leon (1983), who worked much on PRs from South American, suggest a ranking system which slightly differs from the above by the total number of classes considered (four instead of three), the extreme values for each class, and the interval length of classes. In the method, the solubility of PR sources was measured only in NAC and the results grouped into four distinct classes (Table 2.2), instead of the initial three above, with each class associated with a corresponding estimated Relative.

Table 2.2: Relative Agronomic Effectiveness (RAE) calculated in relation to Triple Super Phosphate (TSP)

Soluble P_2O_5 in NAC (% P_2O_5)	RAE (%)	Solubility ranking
> 5.9	> 90	High
3.4 – 5.9	90 – 70	Medium
1.1 – 3.4	70 – 30	Low
< 1.1	< 30	Very low

(Source: Hammond and Leon, 1983)

No matter the type of classification considered, PR sources of high solubilities are considered to be reactive whereas all the others are of unreactive status. Most sedimentary deposits contain the carbonate-fluorapatites collectively known under the name of 'francolite' (McConnell, 1938). Francolites with high carbonate for phosphate substitution are the most highly reactive phosphates and therefore the most suitable for direct application to crops as fertilizers.

2.4.2 Uses of Phosphate Rock

Rock phosphate is used both in industry as a raw material for manufacturing P fertilizers and some other chemicals, and in agriculture for direct application to crops on acid soils as an indigenous P fertilizer source or soil amendment. In fertilizer industries, PRs and sulphuric acid are the raw materials used in the production of Single Super Phosphate (SSP) and phosphoric acid. Phosphoric acid is an important immediate by-product that is used to make Triple Super Phosphate (TSP) and ammonium phosphate (Van Straaten, 2002). Highly concentrated, compound NPK formulations now form the mainstay of the world fertilizer industry (Engelstad and Hellums, 1993; UNIDO and IFDC, 1998).

Use of PR sources for direct application as a native P fertilizer source to increase crop yields on acid soils low in available P and Ca has reportedly been shown to be an attractive alternative to use of manufactured water-soluble P fertilizers that are always sold very expensive on the local markets and frequently reported to be unavailable (Mutuo *et al.*, 1999; Tian and Kolawole, 2004; Msolla *et al.,* 2007). Because of their extremely variable and complex chemical composition, PRs have the advantage over manufactured P fertilizers of being sources of several nutrients other than P. They are usually applied to replenish the soil P status, but upon dissolution they also provide other nutrients that are included in their chemical composition (FAO, 2004, Msolla *et al.*, 2007). Application of medium and highly reactive PRs to highly weathered tropical acid soils has a potential trigger effect on plant growth and crop yields as a result not only of P release but also of their effects on increasing exchangeable Ca and reducing Al saturation in addition to their liming effect in the soil (Chien, 1978a; Mnkeni *et al.*, 1991; Ahn, 1993). The resulting harvest products and residues have a better nutritional quality, mainly due to their higher P content in relation to unfertilized plants. The incorporation of such organic residues enhances biological activity and soil carbon (C) accumulation, leading to improved soil physical and chemical properties. Thus, PRs have an important role in contributing to improving soil fertility and soil degradation control, in particular nutrient mining.

Crop yield responses to direct application of reactive PR sources on P deficient acid soils are usually significantly above the one from the control but below that from the water-soluble P fertilizer treated plots, resulting in the relative agronomic efficiency (RAE) being generally less than 100%. The yield responses are however much enhanced when a PR source is applied in combination with an organic resource, such as farmyard manures (FYM), composts, crop residues, and leafy biomass transfer. The yield improvement that occurs with the combined application of the two input sources is attributed not to any improvement in PR solubilization but to the beneficial effects of the products of decomposition of the added organic resource. However, it is worth noting that the residual effect resulting from sole PR application is much higher than the one from water-soluble P fertilizers.

2.4.3 World Phosphate Reserves

Phosphate Rock reserves are widely distributed throughout the world. According to the data adopted from Mew (2000) and republished in 2004 by FAO (Food and Agriculture Organization), in North America, the USA (United States of America) dominates, possessing 84% of the reserves whereas in South America, Brazil and Peru lead with 97% of the total reserve. In Europe, the former Soviet Union (FSU) countries possess 99% of the total reserves. Within Africa, Morocco, South Africa, Algeria, Senegal and Tunisia possess 98% of the reserves. In Asia, 88% of the reserves occur in Iraq, Israel, Jordan and China. In the Oceania, 87% of the reserves are found in Australia.

In the last twenty years, about 80 - 90% of the world production is provided by sedimentary deposits while the remaining 10 – 20% comes from non-sedimentary ones. These latter are exploited in the Russian Federation, Canada, South Africa, Brazil, Finland and Zimbabwe but also occur in Uganda, Malawi, Sri Lanka and several other locations. They usually contain varieties of fluorapatite that are relatively unreactive and are therefore the least suitable for direct application to crop.

Among the current leading four PR producing countries in the world, Morocco is in the most advantageous position and may possess over half of the world's phosphate reserves. Some countries nevertheless have increased their phosphate production in the last two decades. Within this period of time, China is reported to have approximately doubled her phosphate production while Tunisia's production increased by around two million tons.

2.5 Tithonia diversifolia [Hemsley] A. Gray

2.5.1 Botanic Classification

According to the United States' Department of Agriculture (2010), *Tithonia diversifolia* (Appendix V) is classified under the following taxonomic ranks:

- Kingdom: plantae
- Division: Magnoliophyta
- Class: Magnoliopsida
- Order: Asteraceae
- Genus: *Tithonia*
- Species: *diversifolia*

2.5.2 Physiognomy

Tithonia diversifolia, commonly known as 'wild sunflower' or the 'Mexican sunflower', is a succulent and soft shrub that grows up to the height of about 3 meters. The plant bears large leaves that are alternatively positioned along the stem. Each leaf has 3 to 5 lobes with toothed margins, pointed apex and a long petiole (ICRAF, 1997). The leaf veins are parallel. The flower disc is about 3 cm in diameter and has yellow petals of 3 – 4 cm long. Mature stem may bear several flowers at the top of the branches. The plant usually flowers and produces seeds almost throughout the year. The lightweight seeds are easily dispersed by winds, water and animals (ICRAF, 1997).

2.5.3 Origin and geographical distribution

The plant originated from Mexico and is now widely distributed throughout the humid and sub-humid tropics in Central and South America, Asia and Africa (Sonke, 1997). Presumably, it was introduced in Africa as an ornamental plant. At present the plant has been reported present in many African countries including Kenya (Niang et al, 1996), Uganda (Jama *et al*, 2000), Tanzania (Ikerra *et* al, 2007), Rwanda (Drechsel and Reck, 1998), Zambia (Jama *et al*, 2000), Malawi (Ganunga *et al*, 1998), Zimbabwe (Jiri and Waddignton, 1998), Nigeria (Ayeni *et al*, 1997), Cameroon (Jama *et al*, 2000) and Ghana.

In Kenya, the plant is found in Western and Central regions as well as in Coastal regions and parts of the Rift Valley, where it grows in hedges, along roadsides and on wasteland (ICRAF, 1997). In the different parts of the country, the plant is known under different native names that vary from one dialect to another, but all referring, however, to the bitter taste of the plant. Some of these native names are: *Maruru* (Kikuyu), *Maua makech* (Luo) *Maua malulu* (Luhya), and *Amaua amororo* (Kigusii).

2.5.4 Propagation and biomass production

The plant can be propagated either sexually using the seeds or asexually (vegetatively) from stem and branch cuttings (ICRAF, 1997). But frequently, seeds disseminated in the surrounding of the plant by wind, water or animals germinate naturally and grow into mature plants. This always results in the establishment of big population of the plant, covering a vast area of land, just from one leg of plant. Seed germination in the field can be poor if the seeds are sown deep into the soil or covered with thick layer of clayey soil. Seedlings are transplantable and can therefore be easily transported from one place to another.

2.5.5 Uses of the Plant and Quality of the Organic Material

The plant has several uses including fodder (Anette, 1996; Rootheart and Patterson, 1997), poultry feed (Odunsi *et al*, 1996), fuelwood (Ng'inja *et al,* 1998), compost (Drechsel and Reck, 1998); Ng'inja *et al*, 1998), soil erosion control (Ng'inja *et al,* 1998), building materials and shelter for poultry (Otuna *et al*, 1998). In addition, extracts from the plant are used to protect crops from damages caused by termites (Adoyo *et al,* 1997) and insects (Dutta *et al,* 1993). Also, the extracts are used as medicine for the treatment of hepatitis (Kue and Chen, 1997) and amoebic dysentery (Tona *et al,* 1998). Among the various uses of *Tithonia*, its medicinal value is one that farmers in Kenya frequently report.

In agriculture, *Tithonia* green biomass was previously recognized to be high in nutrients and effective as a nutrient source for lowland rice (Nagarajah and Nizar, 1982). Studies in the highlands of western Kenya identified *Tithonia* green biomass as an effective source of nutrients for maize (Gachengo, 1996; Niang *et al.*, 1996). Research works done in less than two decades ago in Malawi (Ganunga *et al.,* 1998) and Zimbabwe (Jiri and Waddington, 1998) have similarly reported *Tithonia* biomass to be an effective nutrient source for maize production. Research in western Kenya on *Tithonia* biomass as nutrient source for annual crops has stimulated tremendous interest among research workers. The biomass used for soil fertility improvement generally includes both leaves and green tender stems, but not the woody stems.

Opala *et al.* (2011) reported the following nutrient concentrations in *Tithonia* biomass: N (3.1%), P (0.3%), K (4.1%), Ca (2.0 %) and Mg (0.6%). These were in consistence with the findings of previous workers in Kenya and across the borders (Gachengo *et al.,* 1996; Jama *et al.,* 2000; George *et al.,* 2001; Partey *et al.* 2011). However, Ikerra *et al.* (2007 and 2011) and Olabode *et al.,* 2007) in Tanzania and Nigeria, respectively, reported some different values of the concentrations of these nutrients in *Tithonia* leafy biomass (Table 2.3).

Table 2.3: Variation in nutrient composition of *Tithonia* leaves as affected by variability in location.

Nutrient	N	P	K	Sources
Leafy nutrient	4.00	0.40	4.00	Ikerra *et al.* (2011), Tanzania
composition (%)	1.76	0.82	3.92	Olabode *et al.* (2007), Nigeria
	3.20	0.20	0.30	Mugwe *et al.* (2009), Kenya

From the preceded, it can easily be asserted that the concentrations of nutrients in *Tithonia* biomass vary with soil type and ecology in addition to plant-related factors, such as position of the leaves on a branch and age of the plant.

In general, green biomass of *Tithonia* biomass, as compared to the one from other shrubs and trees and some frequently used organic resources of animal origin, is relatively high in its nitrogen and potassium contents but however very low in P. The concentration of nutrients in *Tithonia* can conceivably be influenced by plant part, age of the plant, position of the leaf in the canopy, soil fertility and provenance (ecology). The concentration tends to be lower in senesced than green leaves.

As shown in Table 2.4, the variability associated with these nutrient concentrations can be high. The N concentrations are comparable to those found in N_2-fixing leguminous shrubs and trees, whereas the P and K concentrations are higher than those typically found in shrubs and trees. These averages and corresponding ranges in concentrations reported in table 2.4. for *Tithonia* are generally within the ranges of 3.2 to 5.5% N, 0.2 to 0.5% P, and 2.3 to 5.5% K reported by Nagarajah and Nizar (1982) for the analyses of 100 samples of *Tithonia* leaves plus tender stems in Sri Linka. *Tithonia* biomass is also high in nutrients other than N, P and K. Gachengo *et al.* (1999), for example, found 1.8% Ca and 0.4% Mg in green *Tithonia* biomass.

Table 2.4: Nutrient concentrations in the mostly used plant species (green leaves) and organics (the concentrations were measured on dry weight basis).

Nutrients	**N (%)**		**P (%)**		**K (%)**	
Sources	**Mean**	***Range***	**Mean**	***Range***	**Mean**	***Range***
Tithonia diversifolia	3.50	*3.1 - 4.0*	0.37	*0.24 – 0.56*	4.10	*2.7 – 4.8*
Calliandra calothyrsus	3.40	*1.1 - 4.5*	0.15	*0.04 – 0.23*	1.10	*0.6 – 1.9*
Crotalaria grahamiana	3.20	*3.0 – 3.6*	0.13	*0.13 – 0.14*	1.30	*0.9 – 1.6*
Lantana camara	2.80	*2.3 – 4.0*	0.25	*0.18 – 0.30*	2.10	*1.8 – 2.4*
Leucaena leucocephala	3.80	*2.8 – 6.1*	0.20	*0.12 – 0.33*	1.90	*1.3 – 3.4*
Sesbania sesban	3.70	*1.4 – 4.8*	0.23	*0.11 – 0.43*	1.70	*1.1 – 2.5*
Tephrosia vogelii	3.00	*2.2 – 3.6*	0.19	*0.11 – 0.27*	1.00	*0.5 – 1.3*
Poultry manure*	1.78	/	2.00	/	1.80	/
Cattle manure**	1.06	/	0.52	/	0.95	/
Swine manure**	1.69	/	1.32	/	0.76	/

(Sources: Gachengo *et al.*, 1999; * Togun and Akanbi, 2002; ** Hsieh and Hsieh, 1990)

Research in the mid-1990s in western Kenya generated awareness of *Tithonia* biomass as a source of nutrients of crops (Gachengo *et al.,* 1999); Niang *et al.,* 1996). These authors obtained higher maize grain yields in western Kenya following incorporation of *Tithonia* biomass than biomass of any other common shrubs and trees. Optimal maize grain yield occurred with *Tithonia* biomass applied at the rate of 5 t/ha on dry weight basis. Similar trends in maize grain yields were found by Mugwe *et al.* (2007 and 2009) following the application of *Tithonia* biomass in the highlands of Central Kenya. One recognized advantage of *Tithonia* is the ease of handling its biomass due to a total absence of thorns on its stems as compared to other shrubs and trees used, *Lantana camara*, for example.

Tithonia biomass, in comparison to biomass of other shrubs and trees, decomposes rapidly after incorporation into soil. Gachengo *et al.* (1996) reported a half-life of about one week for disappearance of dry matter in rainy season in western Kenya. This finding was latter on re-affirmed by Partey *et al.* (2011) in a litter bag decomposition experiment conducted in Ghana in which *Tithonia* was compared with *Senna spectabilis, Gliricidia sepium, Leucaena leucocephala* and *Accacia auriculformis*, which are the species commonly used at national level in biomass transfer system. Gachengo *et al.* (1996) found that the corresponding half-lives for nutrient release were about one week for N and two weeks for P. the N concentration in *Tithonia* leaves is higher than the critical level of 0.2 to 2.5% below which net mineralization of N would be expected (Palm *et al.,* 1997). The P concentration is higher than the critical level of 0.25% for net P mineralization (Blair and Boland, 1978; Palm *et al.,* 1997). Lignin (6.5%) and total extractable polyphenol concentration (1.6%) in *Tithonia* biomass (Palm and Rowland, 1997).

2.6 Maize cropping system on smallholder farms

Cereals, including maize, generally constitute the major staple food of the population of SSA and are grown either alone or in intercrop with other crops. Legume-cereal intercropping, especially maize-beans intercropping, is common throughout East and Southern Africa (Giller, 2001). Farmers intercrop to secure food production by averting risk, and to maximize utilization of land and labour (Woomer *et al.,* 1997; Mucheru-Muna *et al.,* 2010). The risk avoidance features of this system are sound in that bean leaves and green pods may be consumed early in the growing season, and dry beans mature rapidly. In addition, maize is drought-tolerant, therefore suitable for production in drought-prone areas but also in humid regions, and responds efficiently to the application of insufficient quantities of fertilizing inputs. A wide range of bean species are used in the intercrop system in Africa, including Kenya; these include common beans, cowpea, groundnut and pigeon pea, among others.

In Kenya, maize is ranked the first staple food crop and is frequently grown on smallholder farms in intercrop with legumes (beans). The crop is totally produced in a rain-fed system of agriculture. The annual total area of arable land cultivated with maize crop in the country is estimated at 1.5 million hectares with an annual production of about 2.5 million tons (Kibaara, 2005), putting the yield average at 1.6 t/ha against the world average of 10 t/ha.

When crops are complimentary in terms of growth pattern, aboveground canopy, root system, and their nutrient demand, intercropping effectively enables a more efficient utilization of available resources, such as sunlight, moisture, and soil nutrient, and can result in relatively higher yields than when crops are grown separately, as pure stands (Willey, 1979). Other benefits of intercropping are related to the better soil cover, which has advantage for weed control, and leads to reduced erosion and nutrient leaching. Because legumes can rely on atmospheric N, they are less likely to compete for N with the cereals (Fujita *et al.,* 1992; Fan *et al.,* 2006). The presence of a cereal exploiting the soil mineral N may even stimulate legumes to fix more N (Marschner, 1995).

2.7 Characterization of legumes

2.7.1 Legumes

Legume is a common terminology used to refer to any of the plants belonging to the family of Leguminosae, also called 'Fabaceae'. Most of these plants are characterized by their bearing of a seed pod equally referred to as 'legume'. *Phaseolus vulgaris* L., widely known as common bean or field bean, one of the two crops involved in the present study, belongs to this botanic family and is ranked according to the United States' Department of Agriculture (2010) as follows:

- Kingdom: plantae
- Order: Rosales
- Family: Leguminosae
- Subfamily: Papilionoideae

- Tribe: Phaseoleae
- Sub-tribe: Phaseolinae
- Genus: *Phaseolus*
- Species: *Vulgaris*

The genus *Phaseolus* includes approximately 35 species of which 5 are cultivated, namely: *P. lunatus* L. ("Lima bean"), *P. coccineus* L. ("runner bean"), *P. acutifolius* A. Gray ("tepary bean"), *P. polyanthus* Greeman, and *P. vulgaris* L ("common bean"). Of these, *P. vulgaris* L. is the most important vegetable protein source for humans. It appears to have been domesticated in Andean South America about 4,400 years ago and has been cultivated alongside maize in Central America for 2,500 years (Kaplan, 1981; Chacon *et al.*, 2005). So, legume usage in agriculture is an ancient and well-proven practice that has relevance in the modern world as workers search for sustainable ways to feed a voracious population that is expected to reach 10 billion by 2040 (UNDESA, 2009). The reason for the decision to grow legumes in integrated farming is more agronomically based than culturally based. Cereals, oilseeds, grasses and herbs produce higher yields when grown after, or in conjunction with, symbiotic legumes in depauperate soils (Mongi *et al.,* 1976; Tsubo *et al.,* 2005; Adu-Gyamfi *et al.,* 2007; Vesterager *et al.,* 2008).

As stated above, legume plant and seed tissue is relatively high in protein. This can be attributed to the plant's ability to supply most of its own nitrogen needs with the help of symbiotic *Rhizobia* bacteria living in its roots (USDA technical note No. 6). In a way, legumes' ability to fix atmospheric nitrogen is perhaps the notable aspect that sets them apart from other plants.

2.7.2 Symbiotically nitrogen fixation and soil acidification

2.7.2.1 Mechanism

Although dinitrogen (N_2) gas represents almost 80% of the earth's atmosphere, it is not directly available to plants. Biological N_2-fixation (BNF) is the process whereby a number of species of bacteria use the enzyme called *nitrogenase*, synthetized and secreted by the said bacteria, to convert atmospheric N_2 into NH_3, a form of nitrogen that can then be incorporated into organic components, e.g. protein and nucleic acids, of the bacteria and associated plants (Unkovich *et al.*, 2008). Thus, unreactive N_2 enters the biologically active part of the global nitrogen cycle. The reaction for BNF is:

$$N_2 + 8\,H^+ + 8\,e^- + 16\,\text{ATP} \longrightarrow 2\,NH_3 + H_2 + 16\,\text{ADP} + 16\,P_i$$

As depicted in the above chemical equation, the process is coupled to the hydrolysis of 16 equivalents of ATP and is accompanied by the co-formation of one molecule of H_2. It has to be noted, however, that after photosynthesis, N_2 fixation is probably the most important biologically mediated process on earth. There is a wide diversity of N_2-fixing organisms, called *diazotrophs,* of which some can fix N_2 in the free-living state, while others fix N_2 in association with plants. One of the diazotrophic species of bacteria which establish a N_2-fixing symbiosis with legumes are the *Rhizobia.* These latter are gram negative (-) *bacilli* that, during the interaction, are contained in intercellular compartments of a highly specialized organ, the nodule (Plate 2.3), where they fix N_2. While in a symbiotic state with plant organ they are referred to as *bacteroids.* The biologically N_2-fixation, therefore called the *symbiotic N_2-fixation* in accordance with the nature and type of the association between the organisms and the plant organ, will only start after a complete formation and full development of the first root nodules. Nodule formation is stimulated by inadequacy or deficiency of available nitrogen in soil in the presence of *rhizobia*.

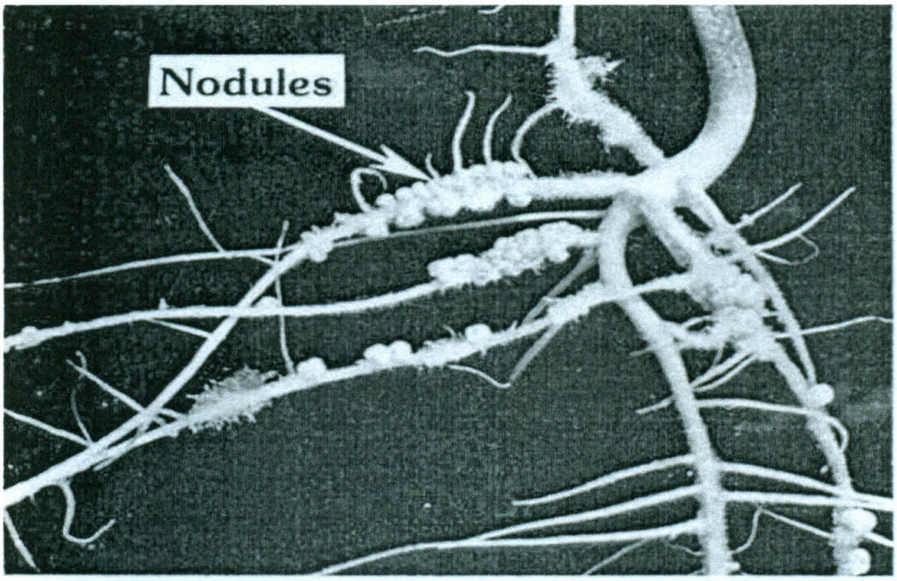

Plate 2.3: Nodulation of the bean root system

In contrast to non-legumes that depend solely on soil nitrogen stock, for their nitrogen nutrition, taken up as cation (ammonium – NH_4^+) and/or as anion (nitrate - NO_3), legumes show the particularity of supplying their nitrogen need, in a *rhizobia*-infested soil deficient in nitrogen, by fixing and utilizing atmospheric nitrogen. Nitrogen exists in the atmosphere in an inert form of dinotrogen (N_2) also referred to as neutral nitrogen. Many legumes, however, commonly export H^+ ions into their rhizosphere when actively fixing N_2 (Nyatsanga and Pierre, 1973; Van Beusichem, 1981). Part of the H^+ ions generated within the legume roots comes from the dissociation of the carboxyl groups of amino acid (Figure 2.4). The acidity generated by legume fixation of N_2 has been found to be equivalent to the excess uptake of cations over anions by the plant and to vary from 0.2 to 0.7 mol per H^+ per mol of fixed N_2 (Jarvis and Robson, 1983; Raven *et al*, 1991). The reason for this, when an ionic species of nitrogen have been taken up by the plant, is that basic cations have been imported into the legume in exchange for H^+ ions generated during carbon assimilation and in order to maintain a pH balance, these H^+ ions must be exported from the roots (Figures 2.4 and 2.5). The amount of H^+ ions released during N_2-fixation therefore depends mainly on the form and amount of amino acids and organic acids synthesized within the plant (Israel and Jackson, 1978).

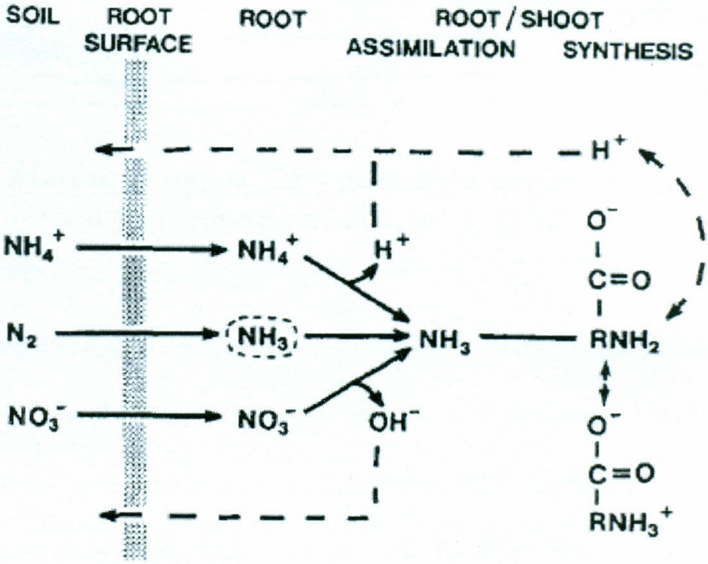

Figure 2.5: Proton (H+)/hydrogen ion and hydroxyl ion (OH-) generation during the uptake and assimilation of different forms of N into amino acids and subsequent dissociation of amino acids (Balon et al., 1991)

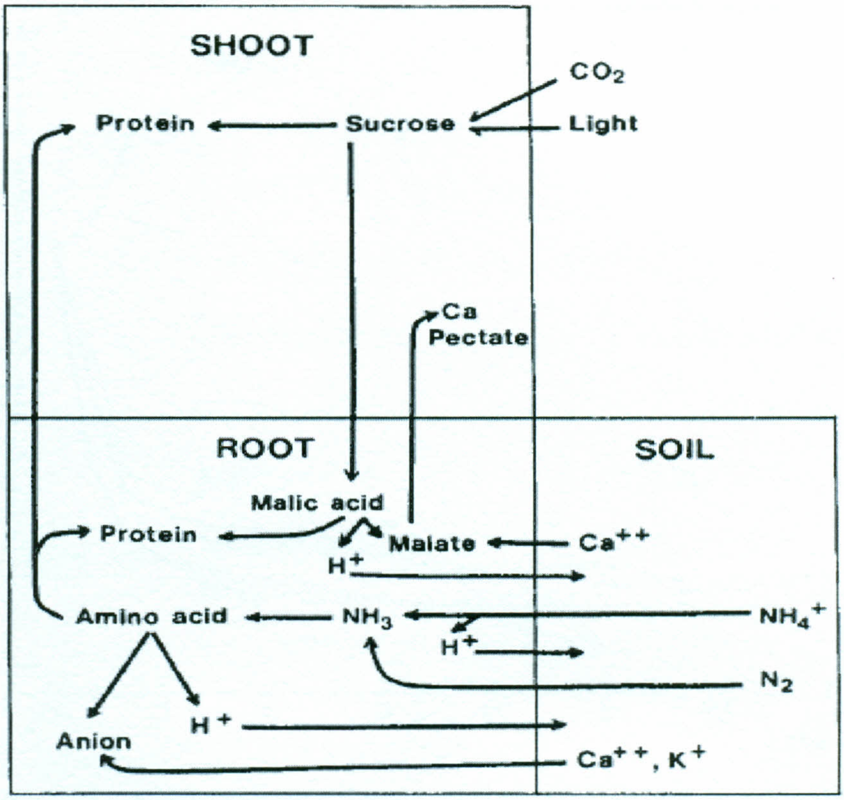

Figure 2.6: Process of proton (H+) generation during the assimilation of ammonium or fixed N in roots (Raven and Smith, 1976)

In a physiological perspective, di-nitrogen fixation as opposed to NO_3^-N nutrition of legumes and of all other plant species with the exception of buckwheat, is similar to a situation where the plant is supplied with NH_4^+ as the only or main source of nitrogen nutrition (Gweyi-Onyango *et al.*, 2005). Both the symbiotically nitrogen fixation and ammonium-based nutrition in legume species trigger the extrusion of H^+ ions into the rhizosphere, thus leading to a decline in pH of the rhizosphere and subsequently of the bulk soil (Figure 2.7).

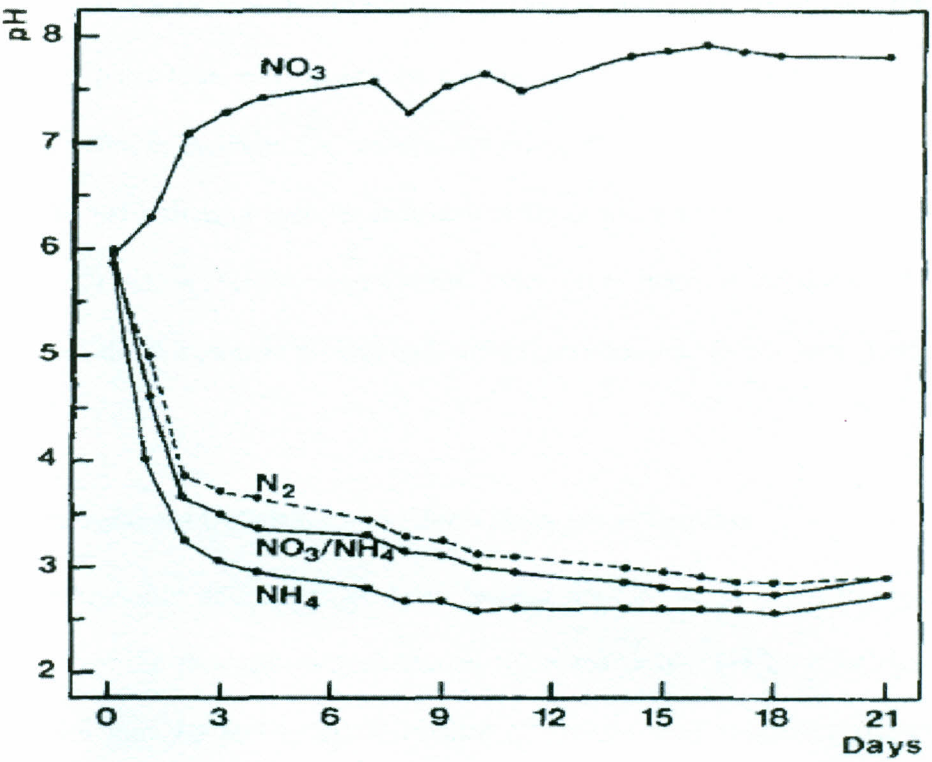

Figure 2.7: pH evolution of the nutrient solution (rhizosphere medium) during the growth of Alnus glutinosa as affected by the different forms of nitrogen nutrition (Troelstra et al., 1985)

There is a net variation between the amount of H^+ ions excreted per mol of N taken up and of that resulting from the fixation of 1 mol of N_2. The uptake and assimilation of 1 mol of NH_4^+ are associated with the excretion into the rhizosphere of 1.1 to 1.2 mol of hydrogen ions (Raven, 1993). As stated above, the fixation of 1 mol of N_2 lead to the production of 0.2 to 0.7 mol of H^+ ions.

In this specific case where only one species of bean, *P. vulgaris* L. is considered, the extent to which the root-induced changes in the pH of the rhizosphere and subsequently of bulk soil depends on soil factors (Marschner, 1995). The pH buffering capacity of soil and the initial pH (bulk soil) are the main factors determining the extent to which the plant roots can change the rhizosphere pH. The pH buffering capacity of soils depends not so much on clay content but primarily on initial pH and organic matter content - the pH buffering capacity is lowest at about pH 6 and increases to both lower and higher pH values (Schaller and Fischer, 1985; Nye, 1986). A difference of up to 2 units between the rhizosphere pH and bulk soil pH was reported (Marschner, 1985).

2.7.2.2 Phosphorus Deficiency and Rhizosphere pH of Legume

Phosphorus deficiency in some legume species has been demonstrated to induce/increase the rhizosphere acidification (Grinsted *et al.,* 1982; Dinkelaker *et al.,* 1989), which may be due to the imbalance of cations over anions uptake and also increases in organic acid excretion. Deficiency of some nutrients can affect nodulation and N_2-fixation (Marschner, 1995), and will then affect cation-anion balance and acid production indirectly. Leguminous plants that might be expected to replenish soil nitrogen supplies are particularly hard-hit by P deficiency, because low P supply inhibits effective nodulation and retards the biological nitrogen fixation (BNF) process thus, affecting the BNF-based rhizosphere acidification of legumes by reducing to some extent the intensity of this acidification.

2.8 Summary of Research Gaps

The studies reviewed here show a number of knowledge gaps in their findings on use of *Tithonia* leafy biomass with MPR to increase crop yields on P-deficient acid soils highly saturated with soluble Al:

i. There is no indication of how readily plant available N and P in the surface soils and N and P contents of the biomass are related; and of whether the variation in the N and P contents of *Tithonia* biomass observed in different areas is significant or not.

ii. Clear understanding is missing of the processes, including the nutritive and non-nutritive roles, by which *Tithonia* biomass and MPR applications leads to improved crop yields on P-deficient acid soils that are highly saturated with soluble Al.

iii. As maize is usually grown in intercrop with grain legumes (beans) on small scale farms, it is of great importance to understand the contribution of the legume intercropped with maize to the overall performance of the low input strategy which includes use of *Tithonia* leafy biomass with MPR to increase crop yields on P-deficient acid soils. The contribution of legume can hence be assessed with special emphasis on the roles played by the organic acid synthesized and secreted into the rhizosphere by the plant on the further solubilization of MPR. Further MPR solubilization can consequently lead to the release of more P into soil solution for uptake by maize. Use of *Tithonia* biomass with MPR to increase crop yields produced promising results under sole maize.

iv. There is still knowledge gap left by previous studies on maize agronomic response to *Tithonia* biomass and MPR applications under maize-bean intercrop. Such agronomic responses include performance of grain yields, relative growth rate and relative agronomic efficiency.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the study sites

3.1.1 Locations

This study was carried out in two locations with different soil types. One site was located at Muguga South in Kiambu County and another at Kavutiri in Embu County (Figure 3.1).

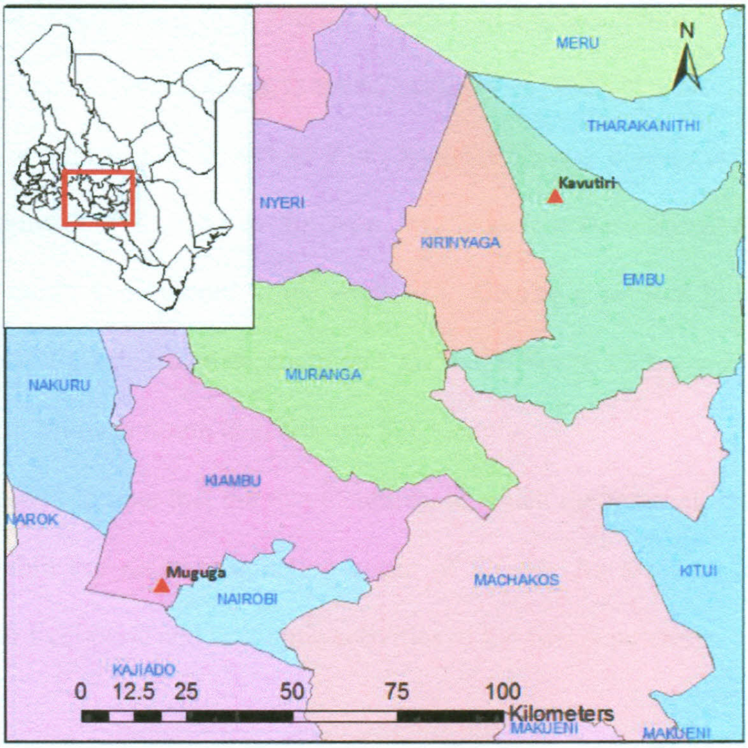

Figure 3.1: Location of study sites in Kiambu and Embu Counties

Kiambu County is situated in the central highlands of Kenya. Muguga site in Kiambu County is relatively higher in altitude with 2,100 meters above sea level (m.a.s.l) as compared to Kavutiri site with elevation estimated at 1,736 m.a.s.l. However, both sites fall within the southern hemisphere. Muguga falls on latitude 1° 14' south and longitude 36° 38' east while Kavutiri site, located on latitude 0° 25' south and 37° 30' east, is much closer to the Equator. Kavutiri is positioned North east of Muguga (Figure 3.1).

Situated in the eastern part of the country, Embu County borders Kirinyaga to the west, Kitui to the east, Tharaka Nithi to the north and Machakos County to the south. The County covers a total area of 2,818 Km^2 and is divided into five Sub Counties, *viz.* Embu North, Embu West, Embu East, Mbeere North, and Mbeere South. Kavutiri falls within Manyatta Division which belongs to the Sub County of Embu North.

Covering a total area of 2, 543.42 Km^2, Kiambu County borders six Counties. These include Nakuru and Kajiado to the west, Machakos to the east, Muranga and Nyandurua to the north, and Nairobi to the south. The County is located in the central highlands of Kenya. Its sub Counties comprises Gatundu North, Githunguri, Kiambu, Kikuyu and Limuru. Muguga South is in Kikuyu Sub County.

It is important to note that the two Counties, in which the research studies were conducted, fall within the maize production zones of Kenya. As a result, agriculture constitutes the main livelihood and economic activities of the two populations.

3.1.2 Rainfall and temperature patterns

Rainfall distribution over a year in both Embu and Kiambu Counties, where the research studies were conducted, is unequal. But the distribution patterns of rainfall in the two Counties are similar. Both Embu and Kiambu Counties enjoy a bimodal rainfall pattern with however unequally annual averages.

In Embu County, annual rainfall varies between 640 and 1,995 mm with an annual mean of 1,736 mm. A relatively lower mean annual rainfall of 1,000 mm was reported in Kiambu County (http://www.kenya-information-guide.com/kiambu-county.html, accessed on 24.08.2014). As in many places, including Embu County, the climate in Kiambu County is largely influenced by altitude. Rainfall ranges from 750 mm in lower areas of Ndeiya and Karai to over 1,300 mm in the County's upper regions (Makokha *et al.,* 2001). Rainfall is bimodal. In both Counties, the long rains (LR) and short rains (SR) seasons occur from March to June and from October to December, respectively. Rainfalls recorded at the two study sites during the two consecutive planting seasons (Figure 3.2) also complied well with the bimodal trend reported. The amount of rain received during the LR season was 593.2 mm at Kavutiri

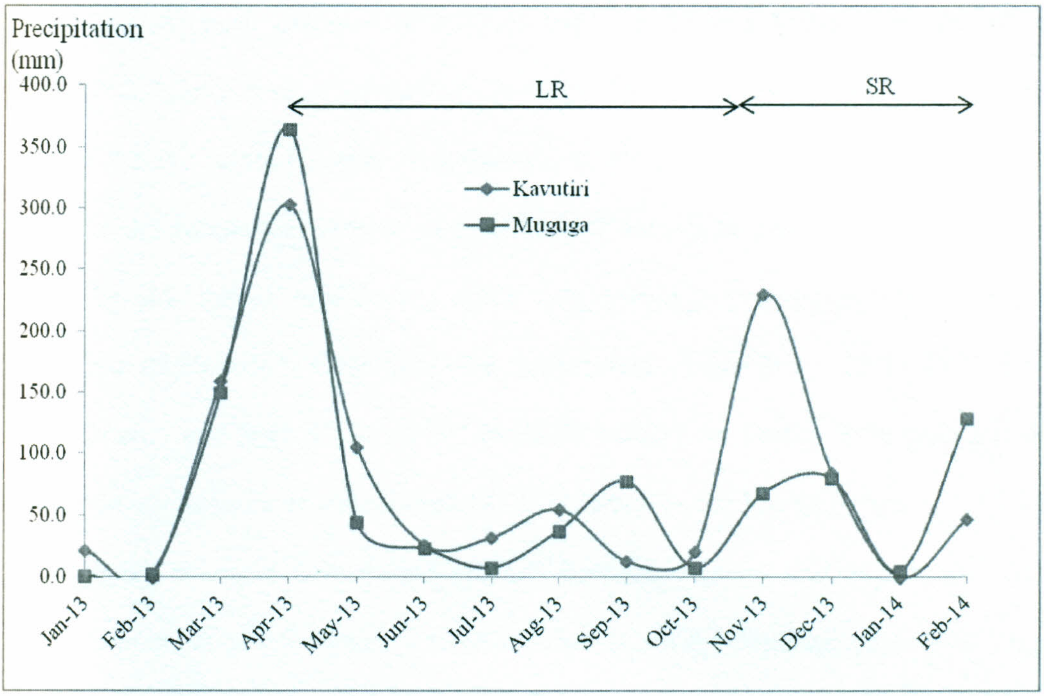

Figure 3.2: Rainfall distribution during the period of field trials (Source of rainfall data: KARI, 2014)

and 580.3 mm at Muguga. In the SR season, only 56.3% (333.2 mm) and 26.6% (154.6 mm) of the amount of rains of the LR season were recorded in Kavutiri and Muguga, respectively. Mean annual rainfall for that year (2013) was 1047.1 mm at Kavutiri and 860 mm at Muguga. All these rainfalls were found to be below the usual averages in the areas. These showed a decrease in the amounts of rains usually received in the areas in addition to their poor distribution over year. The decline noticed in the amount of annual rainfall usually received in those areas was accused to impact of the climate change. Consequently, it resulted to ending the field experiment half way, even before reaching grain formation phase. Thus, only the biomass yields, in lieu of grain yields, were considered for the evaluation of treatment effect. Peaks of rainfall were obtained in April for the LR season and in November for the SR season (Figure 3.2). In the LR season, amplitude of the peak obtained at Muguga (364.3 mm) was higher than the one at Kavutiri (302.7 mm). A reverse trend was however observed during the SR season.

Like the rainfall pattern, temperature trends in the two Counties show some similarities. An annual temperature mean of 15.9° C for Kiambu and 15° C for Embu are reported by the Kenya information guide (http://www.kenya-information-guide.com, accessed on 05.09.2014). Over year, the temperature ranges from 12 to 18.7° C in Kiambu County and from 12 to 30 ° C in Embu County. In Embu, September has the highest monthly average of temperature (27.1° C) whereas the lowest occurs in July (15° C). In Embu, warmest temperature prevails between January and March and again between September and October. A cold weather is always experienced between June and July.

Temperature ranges reported in both Counties are within the favourable ranges for growing most annual and perennial crops. These include maize, beans, vegetable, tea and coffee among others.

3.1.3 Soil characteristics

Soils at both sites were acidic with high content of organic Carbon (Table 3.1). The one from Kavutiri was relatively more acidic and highly saturated with exchangeable Al, but containing less readily plant available P, than the one from Muguga.

Table 3.1: Soil characteristics at Kavutiri and Muguga sites

Soil Parameter	Kavutiri	Muguga
Soil pH (H_2O) (1:2.5)	4.0	5.2
Organic Carbon (%)	2.85	2.46
Organic Matter (%)	4.91	4.24
Available P (mg P/Kg) (Bray II)	10.15	12.83
Total mineral N (mg N/kg)	60.04	75.62
Exchangeable Acidity (Cmol$_c$/Kg)	3.60	4.3
Exchangeable Al (Cmol$_c$/Kg)	2.70	1.95
Bases:		
Ca^{2+} (mg Ca^{2+} / Kg)	60.50	1432.40
Mg^{2+} (mg Mg^{2+} / Kg)	115.03	287.14
K^{+} (mg K^{+} / Kg)	140.12	1136.64
Na^{+} (mg Na^{+} / Kg)	Trace	Trace
ECEC (Cmol$_c$/ Kg)	5.22	16.63
Base saturation (%)	31	74.4
Al saturation (%)	51.7	11.7
Soil Texture (%):		
Sand	15	29
Silt	41	11
Clay	44	60
Soil textural class	Silty-clay	Clay
Soil classification	Ando-humic Nitisol	Humic Nitisol

Note: Soils used in incubation and greenhouse pot experiments were from Kavutiri, collected from the site where field trial was carried out. Therefore, the soils for the incubation and pot experiments had the same characteristics shown for Kavutiri in this table.

But both soils were found to be extremely deficient in readily plant available P (Landon, 1991). With the exception of Ca^{2+} only in soils from Kavutiri, concentrations of all the other basic cations were found to be above the deficient levels (Okalebo *et al.*, 2002). In addition to their Al saturation, the two soils mainly differed by their base saturation, texture and classification. Base saturation at Muguga was more than twice the level recorded at Kavutiri. Soil textures were clay and silty-clay at Muguga and Kavutiri, respectively. According to 'World Reference Base for Soil Resources' of FAO (2014) the two soils are classified as Ando-humic Nitisol (Kavutiri) and Humic Nitisol (Muguga).

3.1.4 Population and livelihood activities

Having more or less the same surface areas of 2,818 Km^2 for Embu against 2,543 Km^2 for Kiambu, the two Counties, however, greatly differ in their total populations and consequently their respective population densities. Relatively, Kiambu County is more populated than Embu County. Based on the figures reported by the Kenyan National Bureau of Statistics (KNBS, 2009), total population of Kiambu County is estimated at 1,623,282 people, resulting in a high population density of 683 people per Km^2. This population is more than three-folds the population of Embu County estimated at 516,212 people. Due to the smallness of the population size of Embu County, the population density is found to be quite low (183 people per Km^2). The relatively low population density reported in Embu County suggests that this County has more available land than Kiambu. The high population saturation of Kiambu is thought to be due to its proximity to Nairobi, the capital city.

Agriculture constitutes the backbone of the economy and livelihood of the two populations. This is favoured by the fertility of the soil, conduciveness of local agroecologies, culture of the people and high rates of unemployment. In Embu County, farming sector employs 70.1% of the total population. Total area under cultivation is estimated at 330 Km^2, equivalent to 11.7% of the total surface area of the County. From the total area being exploited for agriculture in the County, 140 Km^2 is used for production of food crops whilst the remaining farming area of 190 Km^2 is covered by cash crops.

Main crops grown in the two Counties include maize (*Zea mays*), beans (*Phaseolus vulgaris*), cowpea (*Vigna unguiculata*), bananas (*Musa ssp*), tomatoes

(*Solanum lycopersicum*), avocadoes (*Persea americana*) and citrus fruits - as food crops, and tea (*Camellia sinensis*) and coffee (*coffea ssp*) - as cash crops. Among the food crops, maize is ranked top in prevalence, followed by beans. According to the Economic Review of Agriculture (ERA, 2012), total area used for maize cultivation is estimated at 57,639 ha in Kiambu County and 45,086 ha in Embu County. Beans cover 29,438 ha and 25,587 ha in Kiambu and Embu Counties, respectively.

In addition to crop farming, livestock farming practice is also seen to be one of the predominant economic activities among the people. Animals reared are cattle, goats, sheep and chickens. Rabbit farming is also becoming an attractive venture to these farmers. Other economic activities include trades.

3.2 Description of the experiments

3.2.1 Soil nutrients – *Tithonia* leafy biomass quality relationship study

Leafy biomass from *Tithonia diversifolia*, comprising of a combination of tender green twigs + green leaves, were collected in six replicates from five areas, namely: Kavutiri and Embu town in Embu County; and Kikuyu, Zambezi and Limuru in Kiambu County. The biomass was each time sampled over an estimated area of 20m*20m (400m^2) and was kept separately in labelled paper bags. At the same time the surrounding soils, from around 1 m from the base of the sampled plant, were also sampled from the microbial-active layer, also called plough layer, of 0-20 cm deep and kept separately in labelled paper bags. At a distance of 1-2 m from the stem base of the plant, root hairs population was assumed to be more. The sampling was done during the Long Rains (LR) season of 2013 in the period corresponding to maize planting in the regional agricultural calendar. The sampling exercise was accomplished within a period of five days to avoid difference caused by the effect of aging in the biomass quality.

Soil samples were analysed for mineral N and available P whereas the plant samples were analysed for total N and P. The analyses were done in accordance with the laboratory methods described in the sub section 3.3.1.

3.2.2 Incubation experiment

An incubation experiment was conducted in an aerobic environment in the Chemistry Laboratory of the Kenya Agricultural Research Institute (KARI) centre of Muguga South. It was in a Completely Randomized Design (CRD) with five treatments replicated three times. Unlike the greenhouse experiment and field trial, this was a single factor experiment. Treatments applied consisted of the control (C), *Tithonia* leafy biomass alone (T) applied on dry matter basis at the rate of 5.76 g Kg^{-1}, MPR alone at 69.24 mg P Kg^{-1}, TSP alone at 69.24 mg P Kg^{-1}, and T and MPR combined at 5.76 g Kg^{-1} and 57.69 mg P Kg^{-1}, respectively. All the inputs were applied in a powder form and the treatments were thoroughly mixed with 100 g of soil. The mixtures were filled into polythene containers and then wetted to 60% of the field capacity with deionised water. Weights of all the filled containers were registered for further reference during readjustment to the initial level of moisture content of the incubated soils.

The filled containers were left open and kept in a darkroom at a room temperature (25° C). After every three days they were withdrawn from the darkroom, exposed to sunlight for three hours and the moisture content of the soils was readjusted to the initial level before they were taken back. The experiment lasted for a period of six weeks, as from September 7th to October 19th, 2013. Soil and biomass used for this experiment were collected from Kavutiri on the plot of land where the field trial was later on laid out.

Only one sampling was done at the end of the experiment, i.e. six weeks after the establishment of the experiment. Soil parameters measured were: mineral N (NO_3^- plus NH_4^+), available P, exchangeable K and Ca, pH, exchangeable acidity and exchangeable Al.

3.2.3 Greenhouse pot experiment

Pot experiment was conducted in a (6m*6m) greenhouse space at the Kenya Agricultural Research Institute (KARI) centre of Muguga South. The experiment was set in a split plot organized in a Randomized Complete Block Design (RCBD) with two factors consisting of cropping systems as main plot treatments and application of different inputs and their combination as subplot treatments. Main plot treatments consisted of sole maize and maize-bean intercrop whereas subplot treatments included the control (C), *Tithonia* leafy biomass (T) applied alone on dry matter basis at 5.7 g Kg^{-1}, MPR alone (69.24 mg P Kg^{-1}), TSP alone (69.24 mg P Kg^{-1}), and *Tithonia* biomass combined with MPR at 5.7 g Kg^{-1} and 57.69 mg P Kg^{-1}, respectively. All inputs were applied in a powder form. The subplot treatments in this case were an exact replication of the treatments previously used in incubation. Treatments were replicated three times.

The experiment was planted in 5-litre-polythene pots filled with 4.5 Kg of acid soil (pH = 4.0). Soil and biomass used for the experiment were both collected from Kavutiri. This was soil of surface layer (0-20 cm deep) collected at different spots spread over an area of half a hectare (ha), on the plot of land demarcated for field trials. The multiple sub samples were put together and thoroughly mixed up to form one composite sample which was then sundried, sorted, crushed, and used for the pot experiment.

Pots were filled with soils were wetted to 60% of the field capacity. Weights of every pot were registered for further reference while readjusting the moisture content of the soils. Moisture content readjustments were done after every three days starting from the day of establishment. Test plants of this experiment were maize (*Zea mays,* var. H 614 D) and common bean (*Phaseolus vulgaris*, var. GLP-X 1127 A). They were planted together a week following the establishment of the experiment. Four seeds for maize in both sole and intercropping and six seeds for bean were planted per pot. Thinning was done two weeks after planting (WAP). Maize was thinned to three plants per pot in sole cropping and one plant per pot in intercrop while the number of bean plants per pot was reduced to three from a maximum of six.

The experiment was continued for a period of eight weeks. During this period, two soil samplings were done, at 4 and 8 WAP. At the end of the experiment, maize shoots were harvested for dry matter content measurement. After harvest, the plant samples were oven-dried to constant weight at 70° C and weighed using electronic balance. The soils were analyzed for labile P and available P. The rhizosphere pH was also measured during the two sampling periods. The laboratory methods used in the chemical analyses are described in sub section 3.3.1.

3.2.4 Field trials

Field trials were conducted simultaneously at two sites for two consecutive planting seasons from 2013 to 2014. One of the sites was located in Muguga at the Kenya Agricultural Research Institute (KARI) centre of Muguga South in Kiambu County whereas another site was established at Kavutiri in Embu County. The trial was set during the long rains (LR) season of 2013 and ran for two consecutive seasons. Land preparation was done manually using hand hoes.

The trial was laid out in a split plot design with two factors which consisted of the maize cropping system as the main plot treatments and the application of different input sources and their combinations as the subplot treatments. Subplots were organized in a Completely Randomized Design (CRD). The trial was replicated four times.

Treatments consisted of sole maize (monocrop) and maize-bean intercrop for the main plots and of the following for the subplots: control (zero fertilizing input), *Tithonia* leafy biomass (T) incorporated at the rate of 5 t ha^{-1} on dry matter basis, MPR alone (60 Kg P ha^{-1}), TSP alone (60 Kg P ha^{-1}), the biomass combined (T) with MPR {T (5 t ha^{-1}) + MPR (50 Kg P ha^{-1})}, and also with TSP {T (5 t ha^{-1}) + MPR (50 Kg P ha^{-1})}. Blocks were distant 1.5 m apart. Subplots measured 4 m by 5 m each, spaced 0.5 m from one another within a block. The rate of 60 Kg P ha^{-1} used in this experiment was adapted from the recommendations of FURP & KARI (1994) for the two areas, Muguga and Kavutiri. The combination of *Tithonia* leafy biomass with either TSP or MPR used in this study was designed in such a way that *Tithonia* leafy biomass had to contribute 10 Kg P (per hectare) to supplement the 50 Kg P (per hectare) supplied by TSP/MPR.

Chopped fresh biomass was first spread uniformly over the appropriate plots and the incorporation was done immediately manually using a hand hoe. Biomass incorporation was done seven days before planting in order to avoid poor germination of seeds, induced by the initial phase of the biomass decomposition. Minjingu rock phosphate and TSP were locally applied in every hole for seeds at the time of planting. Four maize and five bean seeds were planted per hole. Number of maize seeds per hole in sole maize remained the same with the one in intercrop. Spacing of hills on a subplot in both sole and intercrop was 25 cm within a row and 0.8 cm between two adjacent rows. There were in total five rows on a subplot. Dates of planting and sampling are shown in Table 3.2.

Table 3.2: Dates of Planting and Sampling

Site	Planting date	1st Sampling	WAP	2nd Sampling	WAP	3rd Sampling	WAP	Harvest of Cobs
				Long Rains (LR) Season				
Kavutiri	03/04/13	15/05/13	6	26/06/13	12	07/08/13	18	10/10/13
Muguga	17/04/13	29/05/13		10/07/13		21/08/13		15/10/13
				Short Rains (SR) Season				
Kavutiri	02/11/13	14/12/13	6	25/01/14	12	/	18	/
Muguga	29/10/13	10/12/13		21/01/14		04/03/14		/

Thinning was done one month after planting. In both sole and intercropping, maize was thinned to two plants per hole while bean was reduced to three plants per hole. In total, three weeding was done per season in each of the two sites. Weeding was done manually using a hand hoe, i.e. at the vegetative, flowering and grain formation phases of maize development. It was immediately followed by samplings done at six, twelve and eighteen weeks after planting (WAP).

Only soil and maize from the net plots were sampled. On a plot, soil was randomly sampled at six spots each located between two hills of maize on a row. The six sub samples were each time thoroughly mixed up in a plastic bucket to form one composite sample considered as the soil sample of that particular plot. From the composite sample, a handful quantity of soil was withdrawn, filled into an appropriately labelled polythene bag and then taken to laboratory for analyses.

Both soil and maize were sampled at the same time. Maize was sampled for Relative growth rate (RGR) measurement done after oven-drying the samples at 70° C to constant weight. Parameters measured from the soil samples were labile and available P. At maturity during the first season (LR season of 2013), samples of maize cobs were harvested for grain yields measured at 12% moisture content. Unlike the LR season of 2013, in the following SR season of 2013/2014 the experiment was forcefully ended at the initial phase of cob formation due to a prolonged dry spell which occurred at the end of vegetative phase (beginning of flowering phase). Prolongation of the experiment in such a stressful condition was thought to lead to disappearance of treatment effect on plants as a result of the impact of an acute water stress. Thus, the biomass, in lieu of grain, was harvested and considered for yield analyses.

3.3 Analyses

3.3.1 Laboratory analyses

Soil pH was determined in water (1:2.5 soil:water ratio) with a pH-meter according to the method of McLean (1965). Exchangeable acidity and Al were extracted by 1M KCl solution and determined titrimetrically (McLean, 1965). Extraction of exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) was done using 1M NH_4OAC (ammonium-acetate) solution and the bases determined by an atomic absorption adjusted to specific wavelengths (422.7 nm for Ca^{2+}; 285.2 for Mg^{2+}; 766.5 nm for K^+; and 585.2 for Na^+), as described by Okalebo *et al.* (2002). For labile, soil samples were extracted by 0.5M $NaCO_3$ solution with the pH adjusted to 8.5. Labile P concentration in the extract was determined colorimetrically using a (UNICAM 8625 UV/VIS) spectrometer set to 882 nm wavelength (Okalebo *et al.*, 2002). Extraction of soil samples for available P was done by a mixture solution of 0.03N NH_4F and 0.1N HCl. The concentration of available P in the extracts was measured colorimetrically at 882 nm wavelength using a spectrometer. Soils for mineral nitrogen (NO_3-N and NH_4-H) were extracted by 2M KCl solution and determined using a 'Segmented Flow Analyzer' in accordance with the laboratory method; and the total mineral nitrogen (TMN) of a sample was calculated as the sum of the two fractions of mineral N (NO_3^- and NH_4^+). The method of Walkley and Black (1934) was used to determine soil Organic Carbon (OC) whereas Soil Organic Matter (SOM) was calculated from the soil OC content as established by Anderson and Ingram (1993).

Nitrogen (N) and phosphorus (P) in *Tithonia* leafy biomass were extracted by wet digestion. Total N and P in the digest were measured respectively by absorbency using Atomic Absorption Spectrometer (AAS) and colorimetrically using a UV/VIS Spectrometer as indicated above for labile P or available P.

3.3.2 Determination of agronomic parameters

The following agronomic parameters were computed as follows:

i. Relative Growth Rate (mg/g/d) = $[\ln(W_2) - \ln(W_1)] / (t_2 - t_1)$;

Where: W_1 and W_2 were the means of the dry weight in grams (g) of six maize shoots from the same plot, sampled at time t_1 and t_2 in days (d), respectively. By definition $t_1 < t_2$.

ii. Maize Shoot Dry Matter Yield (g/plant) = $\sum W/N$;

Where: $\sum W$ is the sum of all the dry weights in grams (g) of maize shoots sampled on the same plot; and N the number of the shoots weighed.

iii. Maize Shoot Biomass Yield (t/ha) = aY';

Where: Y' (biomass yield in Kg/m^2 of the net plot) = W_b/A; and a the conversion factor/coefficient from Kg/m^2 to t/ha. In this particular case $a = 10/9.6 \approx 1.04$; A (area of the net plot in m^2) = 2.4m*4m = 9.60 m^2; and W_b (Kg) = the dry weight of the maize shoot biomass harvested on the net plot. Note that: 2.4 m =(0.8 m)*3.

iv. Relative Agronomic Efficiency (RAE) (%) = $[(Y_t - Y_c)*100] / (Y_{TSP} - Y_c)$;

Where: Y_{TSP} and Y_c represented yield averages obtained on TSP-treated and controls plots, respectively. Y_t stood for a yield average of plots treated with *t* input or *t* input combination.

v. Maize Grain Yield (t/ha) = aY'';

Where: Y'' (grain yield in Kg/m^2 of a net plot) = W_g/A; and a the conversion factor/coefficient from Kg/m^2 to t/ha. As mentioned above (iii), $a \approx 1.04$ and A = 9.60 m^2. W_g (Kg) represented the weight of the maize grains harvest on the net plot.

3.4 Statistical analyses

Laboratory data of the samples of soils and *Tithonia* biomass collected from the five agroecological areas (Kavutiri, Embu town, Kikuyu, Zambezi and Limuru) were subjected to a number of statistical analyses, which included the analyses of variance (ANOVA), mean separation by Duncan's multiple range test (DMRT) at probability level $p \leq 0.05$, and Pearson correlation (section one). With the exception of Pearson correlation done using Microsoft Excel 2007, the other two statistical analyses were performed using the General linear model (GLM) procedure of the Statistical analyses software (SAS), version 9.3. The statistical analyses of section one described above were also applicable to data of incubation experiment in section two.

Statistical analyzes of data from the greenhouse experiment and field trial (sections three and four, respectively) were done using the GLM procedure of SAS, version 9.3. These included data of concentrations of labile P and available P, and maize shoot dry matter contents for greenhouse pot experiment and concentrations of labile P and available P, maize dry matter contents, relative growth rates, biomass yields and grain yields for section four (field trial). The data were subjected to ANOVA and mean separation. Mean separation within a column was done by DMRT at probability level ($p \leq 0.05$) and in a row by least significant difference (LSD) at either $p \leq 0.05$ or $p \leq 0.01$ probability levels. Tables of ANOVA for the data of any of the experiments conducted in the present study are provided in Appendix IV.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Overview

This chapter is divided into four sections. Section one (4.2) reports on, and discusses, findings related to the relationship between mineral nitrogen (N) and available phosphorus (P) in the surface soils and N and P contents of *Tithonia* leafy biomass. The second section (4.3) deals with the effect of *Tithonia* leafy biomass and MPR applications on soil nutrients, pH, exchangeable Al and soluble Al. Results pertaining to influence of the bean rhizosphere acidification on MPR solubilization are presented and discussed in section three (4.4). And finally in section four (4.5), results of field trials on the agronomic responses of maize to *Tithonia* leafy biomass and MPR applications under maize-bean intercrop are presented and discussed.

4.2 Objective 1: Relationship between Mineral N and Available P of the Surface Soil and the N and P Contents of *Tithonia* Biomass in Different Areas

4.2.1 Plant available N and P in the top soils and the N and P contents of *Tithonia* leafy biomass

Mean nutrient concentration in both soil and *Tithonia* leafy biomass samples differed significantly among the five sub regions (Tables 4.1 and 4.2). In the soil samples the concentrations of NO_3-N ranged from 26.68 mg N Kg^{-1} to 35.14 mg N Kg^{-1} while NH_4-N ranged from 28.02 mg N Kg^{-1} to 46.68 mg N Kg^{-1}. Soils collected from Zambezi recorded the highest mean concentration of nutrients while those from Embu township and Limuru recorded the lowest. Soil samples from Kavutiri contained highest mean concentration of NH_4-N while the lowest occurred in soils collected from Embu. Soils collected from Kavutiri and Zambezi recorded the highest mean concentration of total mineral N while the lowest was in soils collected from Limuru. For available P, whilst the lowest mean concentration was obtained in soils collected from both Kavutiri and Limuru, the highest occurred in soils collected from Embu township (Table 4.1).

Table 4.1: Concentration of mineral nitrogen (NO_3-N & NH_4-N) and available P in soils sampled from different sites

Site	**NO_3-N** (mg N Kg^{-1})	**NH_4-N** (mg N Kg^{-1})	**TMN** (mg N Kg^{-1})	**Av. P** (mg P Kg^{-1})
Kavutiri	31.80 b	46.68 a	78.48 a	3.60 d
Embu town	26.68 c	28.02 c	54.49 d	56.93 a
Kikuyu	31.18 b	38.16 b	69.34 b	28.84 b
Zambezi	35.14 a	40.12 b	75.26 a	7.33 c
Limuru	27.79 c	37.53 b	65.32 c	5.09 cd

TMN= Total Mineral Nitrogen. Av. P = available P

NB: Note that Kavutiri and Embu town are in Embu County while Kikuyu, Zambezi and Limuru are in Kiambu County.

In *Tithonia* leafy biomass samples, mean content of N and P ranged from 3.76% to 4.59% and from 0.26% to 0.42%, respectively. For nitrogen (N), the highest concentration occurred in the *Tithonia* leafy biomass collected from Kikuyu and the lowest in the leafy biomass samples collected from Embu township. The highest P content of *Tithonia* leafy biomass was obtained in samples collected from Kikuyu whilst the lowest was measured in the samples collected from Limuru (Table 4.2).

Table 4.2: Means of N and P contents of *Tithonia* leafy biomass samples collected from different sites

Site	N (%)	P (%)
Kavutiri	4.34 b	0.39 b
Embu town	3.76 c	0.29 c
Kikuyu	4.59 a	0.42 a
Zambezi	4.30 b	0.39 b
Limuru	3.60 d	0.26 d

It was interesting to note there was no concurrence between the trends of available N and P concentrations in the soils and the N and P contents of *Tithonia* leafy biomass. This may be an indication that Tithonia diversifolia has mechanisms of accessing these nutrients irrespective of the fertility of the soil. The above data shows that the levels of plant available N and P in the soil were not reflective of the *Tithonia* leafy biomass as in case soils sampled. A number of factors might have contributed to the scenario. One is variation in the levels of saturation of soluble Al in the soil. Intensity of the effect of soluble Al on the same species of plant depends on the level of concentration of soluble Al in the soil. The effect is always mild at a low concentration and severe at a high concentration. Nitrogen (N) and phosphorus (P) uptakes by *T. diversifolia* might have been partially affected by Al saturation in the soils and the intensity of effect varied with the levels of Al saturation. Level of Al saturation in a soil is reportedly said to be influenced by the level of soil acidity (Wright, 1989; Kinraide, 1991). Some of the soils, in particular the ones from Kavutiri and Limuru, were strongly acidic while others had slightly higher pH. Previous studies showed a strong negative linear association between soil acidity and the saturation of soluble Al in soils (Wright, 1989; Kinraide, 1991). Soluble Al is also known as the 'phytotoxic species of Al' or the 'monomeric species of

Al’. These species of Al was revealed to inversely increase with a decreasing soil pH; and vice versa (Wright, 1989; Kinraide, 1991). Soluble Al negatively affects plant growth and the overall performance through the damages it causes to root cells. Those damages therefore interfere with the physiological functions of a plant by limiting the uptake of nutrients and absorption of water and their subsequent translocation within a plant and accumulation in different plant organs (Lidon *et al.*, 2000; Horst *et al.,* 2010). This could partially explain the lack of concurrence between tissue minerals and soils since *Tithonia* in different locality was affected differentially.

In addition to variability in the concentration of soluble Al, a second factor contributing to the above mentioned phenomenon of inconsistence between the trends of N and P nutrients of the surface soils and *Tithonia* leafy biomass N and P contents would have been the interactions between different types of nutrient in the soil. Deficiency in one type of nutrient in the soil has been found to affect the uptake of another nutrient, whether from the same functional group of nutrient or a different one. Findings from previous studies showed that supplementation of P, for instance, led to an increase of its concentrations in soil (Cassman *et al,* 1981) and plant tissue Hussain *et al*, 2012) and an improvement of the availability of other nutrients in the rhizosphere (Zhu *et al,* 2001; Magani and Kuchinda, 2009). This finding actually concurred with the work of Nyoki and Ndakidemi (2014) who found that, the supplementation of P at different levels significantly improved the uptake of micronutrients in different tissues of cowpea grown under both screen house and field condition in Tanzania. The micronutrients measured in plant tissue in that study included Cu, Fe and Mn. In the present study, soil concentration of available P was generally found to be below the critical value of 50 mg P Kg^{-1}

established by Landon (1991) for the Bray-II based P extraction method. Although mean concentration of available P (56.93 mg P Kg^{-1}) which occurred in soil samples collected from Embu town was found to exceed the critical level, but the value was even still too close to the critical level. Variation in the deficiency levels of P in the soils was hence suspected to have differently affected the uptake of N by *Tithonia*.

Another factor explaining the inconsistence between the trend of N and P concentrations of surface soils and biomass N and P contents would also have been the high degree of root colonization by mycorrhizal fungi (*Glomus ssp.*) reported by Sharrock *et al.* (2004). The presence of mycorrhizal fungi on roots of *Tithonia* was reported by these authors to render the roots more effective in mobilizing P and other nutrients from the surrounding soil. Thus, the mycorrhizal fungi mobilized nutrients even from the sparingly available nutrient pools, especially in a situation of severe nutrient deficiencies, hence creating inconsistence between the trends of available nutrient pools of the surface soils and the quality (nutrient contents) of *Tithonia* leafy biomass. The association of *Tithonia* roots with the mycorrhizal fungi, in addition to the extensiveness of the root structure of the shrub, was underlined by the authors as what confers to the shrub the ability to grow well on poor soils, extremely deficient in many nutrients. These areas varied in soils and other climatic factors, and it is likely that even the mycorrhizal strains could be different.

4.2.2 Linear Correlation between mineral N and available P of the surface soils and N and P contents of *Tithonia* leafy biomass

Result of the linear regression analyses done to determine the strength of the association between available P of the surface soils (0-20 cm deep) and the leafy biomass P content of *Tithonia* showed that only 5% percent {$R^2*100 = (0.05)*100) = 5\%$} of the variation observed in the biomass P contents was accounted for by a linear function of the soil concentration of available P {Figure 4.1 (d)}. The result reflected the relatively lowest value of the coefficient of linear correlation (r) computed for the two data sets: soil available P and *Tithonia* leafy biomass P content, shown in Table 4.3 (iv). The association between the mineral N of the surface soils and the biomass N content revealed that, generally, linear functions of the concentrations of different forms of mineral N, including the total mineral N in the surface soils accounted for between 20 and 39% of the variation which occurred in the biomass N content {Figure 4.1 (a, b & c)}. These results indicated a positive linear correlation ($+ .47 \leq r \leq + .62$) between the pairs of data {Table 4.3 (i, ii & iii)}. In *Tithonia* leafy biomass, it was, however, found out that 90% of the variation in the biomass N content was explained by a linear function of the biomass content of P {Figure 4.1 (e)}, resulting to a highly strong positive linear correlation between the two biomass nutrient contents {Table 4.3 (v)}.

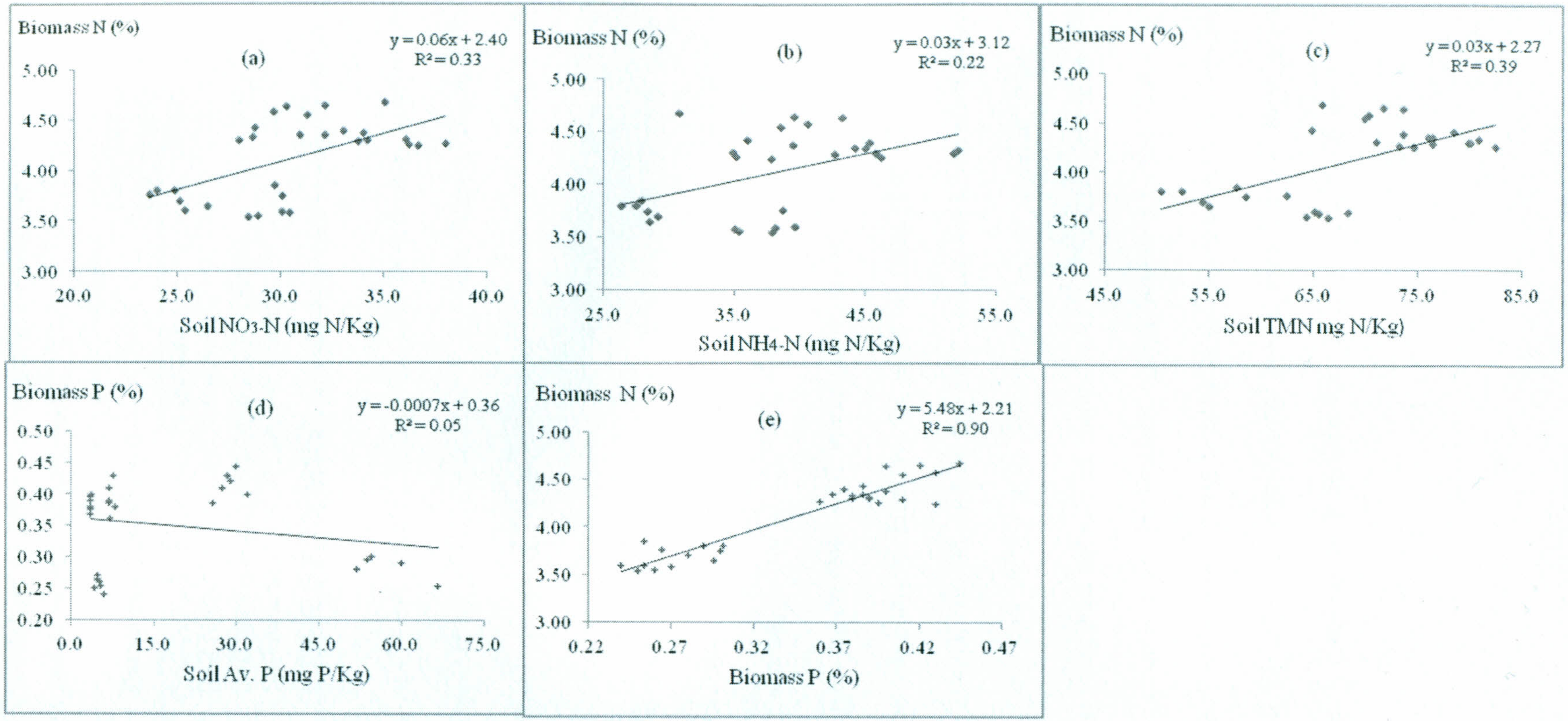

Figure 4.1: Linear relationship between soil and biomass, and biomass and biomass parameters

Table 4.3: Coefficient of linear correlation between soil and biomass, and biomass and biomass parameters

S/N°	Parameters correlated	Coefficient of correlation (*r*)
i)	Soil NO_3-N & biomass N content	+ .57
ii)	Soil NH_4-N & biomass N content	+ .47
iii)	Soil total mineral N & biomass N content	+ .62
iv)	Soil available P & biomass P content	- .22
v)	Biomass N & P contents	+ .90

The biomass N and P content ranges recorded in this study were in conformity with the results reported by previous authors. For instance, Nagarajah and Nizar (1982) indicated the nutrient ranges of 3.2 to 5.5% for N and of 0.2 to 0.5% for P for the analyses of 100 samples of *Tithonia* biomass harvested in different areas in Sri Lanka. In East Africa, the averages of 3.5% N and 0.3% P were reported by Jama *et al.* (2000). Similar results were also found by Ikerra *et al.* (2011) in Tanzania, George *et al.* (2001) in western Kenya and Mugwe *et al.* (2007) in the highlands of central Kenya. There is scanty information on the previous work in explaining the lack of correlation between the tissue P and N and soil contents. However the work of Jama *et al.* (2000) tried to guide the interpretation of such outcome, where the weak correlation achieved between the soil available nutrients (N and P) and their respective biomass contents could have been perceived as if the plant does not rely on surface soils for those two nutrients. Jama *et al.* (2000) in their research work in Western Kenya found out that *Tithonia* biomass production was well influenced by soil fertility as the biomass quantity obtained on soil fertilized with 50 Kg P/ha was significantly greater than the one from a severely P deficient soil which received no P fertilization. This is contrary to the current work.

Based on this finding, the weak correlation obtained in the present study suggested that the amount of nutrients required by the plant for growth was mined from an extensive volume of soil. This was perhaps facilitated by the typically extensive root system of the shrub that therefore allowed it to explore and mined the required amount of nutrients from a large volume of soil. Canadell and Vilá (1992) reported lack of correlation between tissue nutrients and soil contents in *Quercus ilex* plants. Population studies on the pattern of variation in many plant species have revealed the existence of intra-specific differences in various aspects of morphological and physiological traits (Harper, 1977; Karlsson and Nordell, 1988). These differences can be on a very broad spatial scale (over hundred of kilometres) or on a very local scale (over just a few metres). In either case, patterns of population differentials tend to close patterns of environmental variation. There are two ways of responding to spatial environmental heterogeneity; firstly, plants may adjust phenotypically through plasticity and secondly may evolve locally adapted ecotypes (Canadell and Vilá, 1992).

Jama *et al.* (2000)'s finding was later on complemented by that of Sharrock *et al.* (2004) who studied *Tithonia* root samples collected from many countries, including Kenya, Rwanda, Equator, Nicaragua, Costa Rica, Colombia, Venezuela, Indonesia Mexico, Honduras and Philippines. In that study, the authors {Sharrock *et al.* (2000)} found a high degree of mycorrhizal colonization in the root of *Tithonia* that they claimed to therefore render the roots an effective accumulator of P and other nutrients from the soil, even from poor soils severely deficient in nutrients. As such, the present study underlined the combination of both the extensiveness of the root system of the shrub and the association of roots of *Tithonia diversifolia* and the mycorrhizal fungi, *glomus ssp* of the family of *Glomaceae*, to be the main reason for the good performance of the shrub observed on soils with severe nutrient deficiencies.

In the study by Jama *et al.* (2000) it was furthermore revealed that P fertilization unexpectedly did not lead to a significant rise in the biomass P concentration. Application of 50 Kg P ha^{-1} led to an increase of the biomass P content from 0.34 to only 0.36% P. Based on this result, the weakly negative correlation (r = - .22) obtained in the present study between the available P in the surface soils and *Tithonia* leafy biomass P content {Table 4.1 (iv)} was understood as in a situation of an extreme P deficiency (unavailability) in the soil, the shrub develops a mechanism that enables it to rely less on soil available P pool but more on the unavailable P stock for its P nutrition. And the plant gradually tends to reverse the mechanism when P availability improves to an acceptable level through P fertilization, for instance.

4.3 Objective 2: Determination of the Effect of *Tithonia* Leafy Biomass and MPR Applications on Soil Nutrients, pH, Exchangeable Acidity and Soluble Al

In this section, results of the incubation experiment, conducted to address objective two of the study, are reported and discussed. This includes treatment effect on soil nutrients (mineral N, available P, K and Ca), pH, exchangeable acidity and soluble Al.

4.3.1 Treatment Effect on Plant Available Nutrients in the Soil

There were significant effects of treatments on plant nutrients in the soil (Table 4.4). After the six weeks of incubation, variations of the mean concentration of nutrients were in the range of 58.42 to 76.17 mg N/Kg for total mineral N; 10.80 to 35.61 mg P Kg^{-1} for available P; 116.08 to 186.83 mg K Kg^{-1} for available K; and 57.79 to 101.14 mg Ca Kg^{-1} for available Ca (Table 4.4). Highest mean concentration of total mineral N was measured in soils treated with *Tithonia* leafy biomass applied alone or in combination with MPR while the lowest occurred in the control and also in soils which received sole application of both MPR and TSP. For available P highest concentration was recorded in soils treated with sole TSP and a combination of MPR with *Tithonia* leafy biomass whilst the lowest were obtained in the control and also in soils amended with sole *Tithonia* leafy biomass. Treatments with application of Tithonia recorded the highest amount of K. Lowest mean concentration of Ca was achieved in the control while the highest was measured in soils fertilized with MPR applied alone or in integration with *Tithonia* leafy biomass.

Table 4.4: Effects of inputs application on plant available nutrients in the soil

Treatment	**TMN** (mg N/Kg)	**Av. P** (mg P/Kg)	**K** (mg K/Kg)	**Ca** (mg a/Kg)
Control	58.42 b	10.80 c	136.69 b	57.79 d
Tithonia alone (5.76 g/Kg)	76.17 a	11.43 c	186.83 a	69.83 c
MPR alone (69.24 mg P/Kg)	61.68 b	28.48 b	118.83 bc	101.14 a
TSP alone (69.24 mg P/Kg)	61.92 b	35.61 a	116.08 c	81.88 b
Tithonia (5.76 g/Kg) + MPR (57.69 mg P/Kg)	76.04 a	30.49 ab	174.48 a	98.73 a
CV (%)	8.4	11.7	7.0	6.0
p	0.01**	<0.0001**	<0.0001**	<0.0001**

Means in the same columns followed by the same letter are not significantly different at 5% probability level according to DMRT. TMN = total mineral nitrogen. Exch. = exchangeable. *=significant at 5% probability level. ** = significant at 1% probability level.

Result of the present study suggested that N release from the biomass was not affected by MPR application. The good performance of the biomass of supplying the amended soil with enough N was thought to result from a number of factors which included a generally high N content of *Tithonia* leafy biomass (4.30% on average), and the concentration of lignin and polyphenol and the low C:N ratio in the biomass allowing net N immobilization. Critical levels were estimated between 2.0 and 2.5% for N (Palm *et al.*, 1997), at 20% for lignin, 3% for polyphenol (Brady and Weil, 2004), and 32:1 for C:N ratio. Okalebo *et al.* (2002) estimated the concentrations of lignin and polyphenol in *Tithonia* leafy biomass at 11.96% and 3.43%, respectively. These values are found to fall within the normal ranges.

The high concentration of available K in treatments that received *Tithonia* leafy biomass could be due to high K content of *Tithonia* biomass. Thus, the good performance of *Tithonia* leafy biomass in relation to its contribution to N and K concentration in the soil was partially attributed to the fact that the two nutrients (N and K) always occur at equal highest concentrations of around 4.0% for both N and K in the biomass (Mugwe *et al.,* 2009; Ikerra *et al.,* 2011), and there was a synchrony in their release and mineralization patterns (Gachengo *et al.*, 1999; Partey *et al.,* 2010). The inability of the individual application of MPR and TSP to lead to a significant difference ($p \leq 0.05$) in the soil concentrations of total mineral N and available K over the control was probably due to lack of N- and K-containing compounds in the chemical compositions of the two inputs.

The high Ca concentration in treatments that had MPR applied alone or in integration with *Tithonia* leafy biomass could mean that the biomass had no constraining effect on the release of Ca from MPR. Rock phosphate in generally has a high concentration of Ca (8-16% Ca) (Manoharan, 1997; FAO, 2004) that makes it an important source of Ca in addition to P. The two nutrients, P and Ca, sometimes occur in the rock at more or less a similar concentration. Application of MPR with *Tithonia* leafy biomass was furthermore revealed to have also contributed to a significantly highest rise in the concentration of available P equally to the level achieved with sole TSP application. This was probably due to the effect of rhizosphere acidification on the solubilization of MPR, which is an acid-soluble rock with high P content estimated to 13-15% of the total weight (Ikerra *et al.,* 2007).

From that result one could suggest that the rise in available P concentration which occurred in soils treated with a combination of MPR with *Tithonia* leafy biomass did not only result from the P supplied into the soil solution by the solubilizing MPR.

Other factors might also have contributed both directly and indirectly. The decomposing *Tithonia* leafy biomass co-applied with MPR was suspected to have played multiple roles by improving P availability through the release into the soil solution of a small amount of P, replacing the P adsorbed on the surface and edges of clayey mineral layers by organic compounds product of the decomposition, and solubilizing the calcium bound P (Ca-P) minerals in the soil. Ikerra *et al.* (2011) found out in an incubation experiment conducted in Tanzania using Chromic Acrisol that decomposing *Tithonia* leafy biomass, in addition to organic compounds, released Low Molecular Weight Organic Acids (LMWOA) that solubilized the calcium bound P minerals in the soil. The organic compounds released were revealed by the study not only to replace the P adsorbed onto the surface and edges of clayey mineral layers but also to highly compete with P for the adsorbing sites, hence significantly reducing P fixation. In the competition for the adsorbing sites, the organic compounds were shown to be favoured over phosphate ions.

4.3.2 Treatment Effects on Soil pH, Exchangeable Acidity and Soluble Al

Treatments significantly affected the levels of soil pH, exchangeable acidity and soluble Al {Figure 4.2 (a, b & c)}. Means ranged from 4.11 to 4.34 for soil pH, from 2.55 to 3.66 $\text{Cmol}_{(+)}\ \text{Kg}^{-1}$ for exchangeable acidity, and from 2.46 to 2.87 $\text{Cmol}_{(+)}\ \text{Kg}^{-1}$ for soluble Al. The highest pH rise was observed in soils treated with MPR alone while the lowest pH, which was even below the level of the control, occurred in soils treated with sole *Tithonia* leafy biomass. pH rises induced by other treatments were moderate. For exchangeable acidity, the highest rise in the concentration was recorded in the control treatment whilst the lowest was measured in soils which received a co-application of MPR with *Tithonia* leafy biomass. Whereas the lowest concentration of soluble Al was registered in soils treated with an integrated application of MPR with *Tithonia* leafy biomass, the highest was recorded in the control treatments and also in TSP-treated soils.

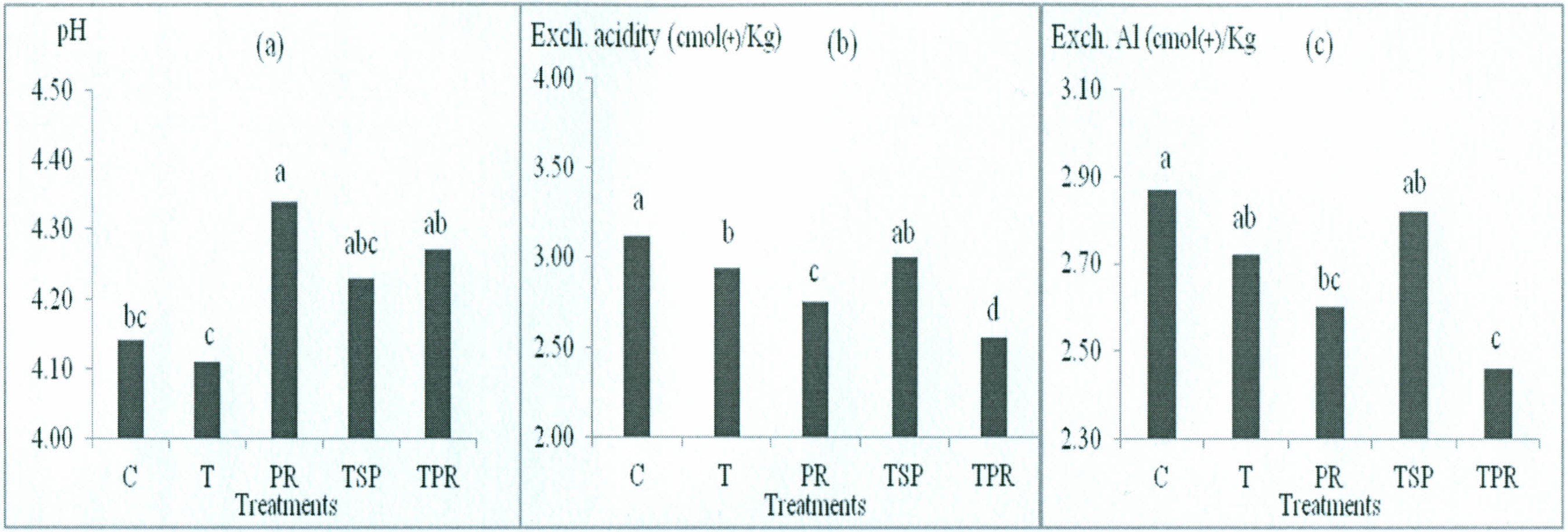

Figure 4.2: Graphic representation of the effects of input application on soil pH, Exchangeable acidity and soluble Al. Bars of a sub-figure (a, b or c) surmounted by the same letter are not significantly different by DMRT at 5% probability level. Ac. = acidity. Exch. = exchangeable.

As shown in Table 4.5, the two pairs of soil parameters, namely; exchangeable acidity and soil pH, and soluble Al and soil pH, were found to negatively correlate whereas the other two pairs, i.e. available P and soil pH, and soluble Al and exchangeable acidity, however, positively correlated.

Table 4.5: Linear correlation of the soil parameters measured in the incubation study

S. N°	Parameters correlated	Coefficient of correlation (*r*)
i)	Exchangeable acidity and soil pH	-.67
ii)	Soluble Al and soil pH	-.62
iii)	Available P and soil pH	+.89
iv)	Soluble Al and Exchangeable acidity	+.99

The weak correlation of soil parameters mentioned above could be also demonstrated indirectly by the results of simple linear regressions (Figure 4.3).

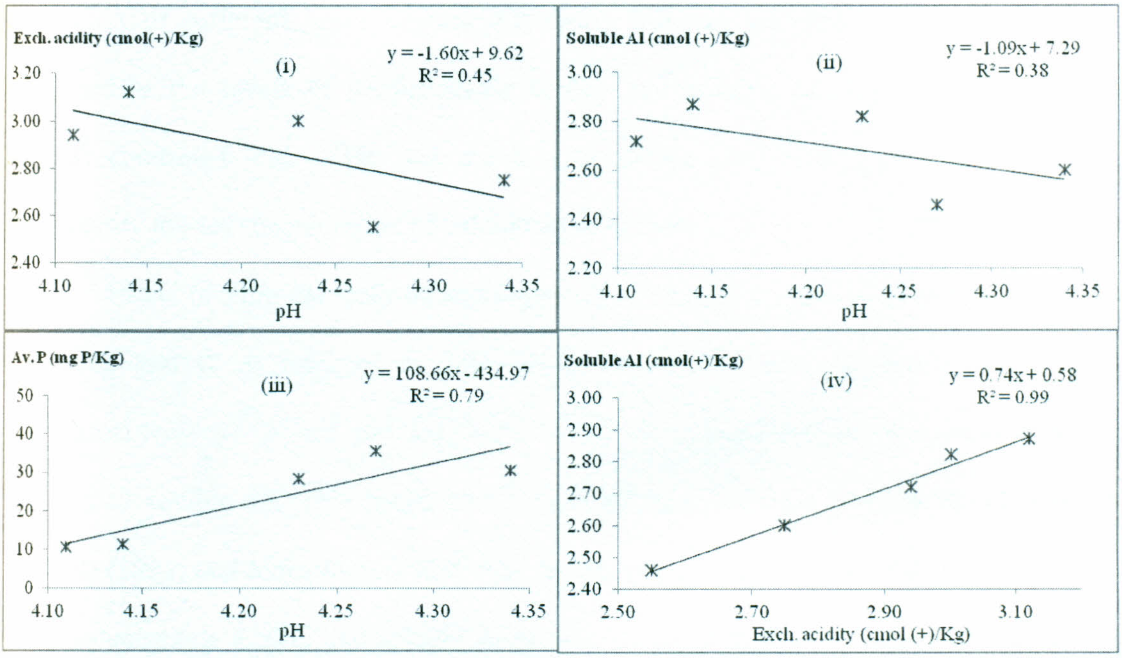

Figure 4.3: Graphs of simple linear regressions of soil parameters. Note: Av. P=available phosphorus; Exch.=exchangeable; Al=Aluminium.

The negative correlation found in this study between exchangeable acidity and soil pH (Table 4.5) was in agreement with the works of Kinraide (1991) and Marschner (1995) who in separate studies reported that, an increase in soil pH led to a decrease in the level of exchangeable acidity, and the rise in soil pH also resulted into a decline in the concentration of soluble Al. Those findings therefore implied a negative correlation between soil pH and exchangeable acidity as well as between soil pH and soluble Al. But nothing was however mentioned about the strength of the relationship by any of the two studies (Kinraide, 1991; Marschner, 1995). Results from the present study demonstrated that the strength of the relationship depended on the type of the treatment which led to the change in soil pH and on the degree of change caused in soil pH. For instance, application of different input sources differently affected soil pH in this study and consequently the levels of exchangeable acidity and soluble Al. However, *Tithonia* biomass combined with MPR was the best candidate here as it contributed to the significantly lowest concentration of soluble Al in the soil.

Effect of *Tithonia* leafy biomass application on soil parameters was found to be unique in that it, as opposed to other treatments, contributed simultaneously to a significant decrease of soil pH and reduction of the concentrations of exchangeable acidity and soluble Al. This result was in contradiction with the research findings of Kinraide (1991) and Marschner (1995) who, in separate studies, claimed that the levels of both exchangeable acidity and soluble Al inversely increased with a decreasing soil pH. The unidirectional evolution of soil pH and the concentrations of both exchangeable acidity and soluble Al might have been caused by the activity of the organic molecules/compounds released into the soils by the decomposing *Tithonia* biomass. The organic molecules/compounds might have legated or tied up the soluble Al to form organo-Al complex compounds, which resulted to the reduction of the concentration of soluble Al and consequently that of the exchangeable acidity. The biomass decomposition process probably resulted in the release into the soil of low molecular weight organic acids, such as oxalic, formic and tartaric acids (Ikerra *et al.,* 2011), contributing to rise of in their concentrations and consequently leading to lowering of soil pH. This affirmation was supported by findings from previous studies in which the soil pH was reported to first drop within a period of two months following application of *Tithonia* biomass before it (the soil pH) rose to a point situated above the initial level (Ikerra *et al.,* 2007; Opala *et al.*, 2012). Decline in pH was said to essentially occur during the decomposition phase of *Tithonia* biomass.

The high rise in soil pH induced by MPR application observed in the present study was attributed to an increase of the concentration of Ca. Phosphate rocks in general have a high content of Ca (above 30% in most cases) which is usually released upon dissolution of the rock (Manoharan, 1997; FAO, 2004). The calcium compounds released reacts with both the hydrogen ions (H^+) and the monomeric spices of aluminium (Al^{3+}) resulting in a significant pH decline and reduction of the concentration of soluble Al. It was mentioned above that a combined application of *Tithonia* leafy biomass with MPR resulted in a moderate rise of soil pH above the control. This combined application (MPR combined with *Tithonia* biomass), however, contributed to the lowest reduction of the concentrations of exchangeable acidity and soluble Al. That result was explained by the properties of the two input sources, MPR and *Tithonia* leafy biomass, which were combined. The properties of the two input sources with reference to their interactions with exchangeable acidity and soluble Al in the soil have been explained above.

Achievement of a strong positive correlation between soil pH and available P (r = + .89) was interpreted as the level of the concentration of available P was much influenced by soil pH. This implied that, at lower soil pH, P availability becomes a problem. The result matched well with the findings of Fageria *et al.* (1988) and Yang *et* *al.* (2009) who separately reported P deficiency to be a general characteristic of the acid soils of the tropics and sub tropics. On the other hand, the strong positive correlation revealed between exchangeable acidity and soluble Al was an indication of the dominance of exchangeable acidity by soluble Al rather than the hydrogen ion. This affirmation was backed by the work of FURP and KARI (1994) in which a high saturation of soluble Al, above 50%, was reported in the soil. A similar result was also found in the present study Table 3.1).

4.4 Objective 3: Assessment of the Influence of Bean (*Phaseolus vulgaris*) Rhizosphere Acidification on MPR Solubilization

Results of the greenhouse experiment are displayed and discussed in this section. The experiment was intended to address specific objective three of the study. Parameters measured included maize dry matter yields, readily plant available P and labile P pools in the soil, and rhizosphere pH.

4.4.1 Maize Shoot Dry Matter Yields

Maize shoot dry matter yields were significantly affected by both input application and the cropping systems (Table 4.6). The shoot dry matter yields ranged from 0.87 to 1.77 g shoot^{-1} in sole maize, and from 1.12 to 5.63 g shoot^{-1} in maize-bean intercrop. In the sole maize, the highest maize shoot dry matter yields were obtained in pots fertilized with sole TSP and *Tithonia* leafy biomass applied alone or in combination with MPR (Table 4.6). While in maize-bean intercrop, the significantly highest yields occurred only in pots treated with an integration of *Tithonia* leafy biomass with MPR. The significantly lowest shoot dry matter yields occurred in the control in sole maize but in both control and pots amended with sole *Tithonia* leafy biomass in maize-bean intercrop. There was a highly significant (p<0) interaction between the cropping systems (factor A) and input applications (factor B). Differences in maize shoot dry matter yields yielded between the two cropping systems were significant (p =0.05) for pots treated with sole MPR and highly significant (p=0.01) for pots which received sole application of TSP and a combination of *Tithonia* leafy biomass with MPR (Table 4.6).

Table 4.6: Effects of input application on maize shoot dry matter yield (g/shoot) in both sole maize and maize-bean intercrop

Input	**Cropping systems**		**Difference**
	Sole	**Mix**	
Control (no input)	0.87 c	1.12 c	0.25 ns
Tithonia alone (5.76 g/Kg)	1.77 a	1.94 c	0.17 ns
MPR alone (69.24 mg P/Kg)	1.31 b	2.21 bc	0.9*
TSP alone (69.24 mg P/Kg)	1.42 ab	3.19 b	1.77**
Tithonia (5.76g/Kg) + MPR (57.69mg P/Kg)	1.74 a	5.63 a	3.89**
Interaction (A * B)	<0.0001**		
LSD	(.05) = 0.79; (.01) = 1.09		

Mean separation in a column was done by DMRT at 5%, and in a row by LSD at either 5% or 1%. A = maize cropping system factor. B = input application factor

The change in trends in maize shoot dry matter yield performance observed in maize-bean intercrop was attributed to an interaction between main factor treatments and sub factor treatments probably as a result of the influence of bean rhizosphere acidification. This argument was supported mathematically by the high level of interaction ($p \leq 0.01$) attained between the two factors (A and B) of this experiment.

Influence of bean rhizosphere acidification on sub factor treatments was well reflected by the levels of yield attained in pots treated with TSP and MPR applied alone or integrated with *Tithonia* leafy biomass under maize-bean intercrop. The differences achieved between those three sub treatments (MPR, TSP and T+MPR) under the two cropping systems were thought to result from their capacities to concomitantly supply enough P to meet the growing demand of the plant, alleviate the phytotoxic effect of Al, and maintain soil pH within the suitable range for maize growth. These were actually considered to be the reason why maize shoot dry matter yields did not strictly follow the trend patterns of available P of neither the first nor the second sampling periods (Table 4.7). The phytotoxic effect of soluble Al is well documented (Fageria *et al*., 1988; Wright, 1989; Delhaize and Ryan, 1995). The pH range of 4.5 to 7.0 is said to be the most suitable for maize growth. Therefore, the soil pH ranges reported in this study (4.3.3) were found to fall within the favourable range for optimum maize growth.

4.4.2 Soil Available P and Labile P Fractions

In this study, the concentration of labile P (weakly fixed P) and available P (the P found in soil solution) in the soil were found to be significantly affected by both cropping systems and input application. For available P (Table 4.7), mean concentrations varied between 6.50 and 57.05 mg P Kg^{-1} and between 13.75 and 66.03 mg P Kg^{-1} under sole maize during the first and second sampling periods, respectively. Under maize-bean intercrop, variation in mean concentration of available P was in the range of 6.63 to 69.53 mg P Kg^{-1} and 14.40 to 74.87 mg P Kg^{-1} at the first and second sampling periods, respectively. During the two sampling periods, sole application of TSP consistently contributed to the highest rise in the concentration of available P under sole maize. The lowest concentrations were, however, recorded in the control and pots amended with sole *Tithonia* biomass. Under maize-bean intercrop, while the lowest concentration of available P occurred in the control and treatment amended with *Tithonia* leafy biomass, the highest concentration of available P were obtained in treatments fertilized with sole TSP and MPR applied alone or integrated with *Tithonia* leafy biomass. Interaction between the cropping systems and input applications were found to be highly significant ($p < 0.01$) during the two sampling periods. Differences in mean concentration of available P yielded as a result of the effect of cropping systems on the different inputs applied were consistently highly significant for MPR applied alone or in combination with *Tithonia* biomass during the two sampling periods.

Table 4.7: Effects of input application on available P (mg P Kg^{-1}) under both sole maize and maize-bean intercrop

Input	First sampling (4 WAP)			Second sampling (8 WAP)		
	Cropping systems		Diff.	Cropping systems		Diff.
	Sole	Mix		Sole	Mix	
Control (no input)	6.50 c	6.63 b	0.13 ns	13.75 c	14.40 c	0.65 ns
Tithonia alone (5.76 g/Kg)	9.31 c	11.80 b	2.49 ns	19.38 c	35.02 b	15.64**
MPR alone (69.24 mg P/Kg)	25.46 b	64.87 a	39.41**	36.52 b	70.08 a	33.56**
TSP alone (69.24 mg P/Kg)	57.05 a	67.33 a	10.28 ns	66.03 a	73.12 a	7.09 ns
Tithonia (5.76 g/Kg) + MPR (57.69 mg P/Kg)	38.39 b	69.53 a	31.14**	49.17 b	74.87 a	25.70**
Interaction (A * B)	<0.0001**			0.002**		
LSD	(.05) = 11.00; (.01) = 15.15			(.05) = 11.02; (.01) = 15.19		

Mean separation in a column was done by DMRT at 5% level and in a row between sole and mix for the same sampling period by LSD at either 5% or 1% level. Diff. = difference. A = maize cropping system factor. B = input application factor.

For labile P (Table 4.8), the ranges of variation of mean concentration achieved under sole maize were 5.50 to 22.84 mg P Kg^{-1} and 7.64 to 19.51 mg P Kg^{-1} during the first and second sampling periods, respectively. Under maize-bean intercrop, mean concentration varied between 6.04 and 25.63 mg P Kg^{-1} and between 8.13 and 22.39 mg P Kg^{-1}, respectively. Application of TSP alone under sole maize consistently contributed to the highest rise in the concentration of labile P. Under maize-bean intercrop, the highest concentration was measured in treatments fertilized with sole MPR and TSP. Only the differences of the concentration of labile P yielded by MPR under the two cropping systems were consistently found to be highly significant.

Table 4.8: Effects of input application on labile P (mg PKg^{-1}) under both sole maize and maize-bean intercrop

Input	**First sampling (4 WAP)**			**Second sampling (8 WAP)**		
	Cropping systems		**Diff.**	**Cropping systems**		**Diff.**
	Sole	**Mix**		**Sole**	**Mix**	
Control (no input)	5.50 c	6.04 d	0.54 ns	7.64 c	8.13 d	0.49 ns
Tithonia alone (5.76 g/Kg)	9.99 bc	11.51 cd	1.52 ns	7.84 c	11.40 c	3.56*
MPR alone (69.24 mg P/Kg)	10.44 bc	20.94 ab	10.50**	10.90 bc	19.40 a	8.50**
TSP alone (69.24 mg P/Kg)	22.84 a	25.63 a	2.79 ns	19.51 a	22.39 a	2.88 ns
Tithonia (5.76 g/Kg) + MPR (57.69 mg P/Kg)	13.49 b	14.12 bc	0.63 ns	12.35 b	14.80 b	2.45 ns
Interaction (A * B)	0.05*			0.01**		
LSD	(.05) = 5.52 ; (.01) = 7.60			(.05) = 2.97; (.01) = 4.10		

Mean separation in a column was done by DMRT at 5% level, and in a row between sole and mix for the same sampling period by LSD at either 5% or 1% level. Diff. = difference. A = maize cropping system factor. B = input application factor.

Tithonia leafy biomass, as other organic manures, has been reportedly said to be a poor P source due to its low P content generally estimated at less than 0.5% on dry weight basis (Gachengo *et al.,* 1999; Malama, 2001; Alabode *et al.,* 2007). The significant rise in the concentrations of available P over the respective control witnessed in pots amended with sole *Tithonia* biomass under maize-bean intercrop during the second sampling might probably be caused by a joint contribution from both *Tithonia* biomass and the effects of bean rhizosphere acidification. Rhizosphere acidification might have therefore significantly contributed to the release of more P into the soil solution through enhancement of the solubilization of soil inherent calcium bound P minerals. Phosphorus released as a result of the solubilization of calcium bound P minerals in the soil was suspected to have complemented the P contributed by the decomposed *Tithonia* biomass. That argument was supported by the insignificant rise in the concentration of P observed in the corresponding pots amended with sole *Tithonia* leafy biomass under sole maize.

The significant increase in the concentrations of available P which occurred under maize-bean intercrop in pots treated with MPR applied alone or in combination with *Tithonia* biomass was an indication of the influence exerted by the bean rhizosphere acidification on MPR solubilization. No such influence was, however, observable in TSP-treated pots. The absence of this influence in pots treated with TSP implied that TSP, as opposed to MPR, was irresponsive to the rhizosphere acidification. Triple super phosphate (TSP) is a water-soluble but acid-insoluble fertilizer. The influence of bean rhizosphere acidification on MPR might have been what led to the significance of the differences of the concentrations of available P achieved under the two cropping systems in pots treated with MPR alone or combined with *Tithonia* biomass. The significantly improved P availability recorded under maize-bean intercrop was therefore attributed to factors such as, enhanced MPR solubilization and reduction of P sorption capacities of the soil, particularly in the case where MPR was integrated with *Tithonia* biomass. Ikerra *et al.* (2011), in an incubation study conducted in Tanzania using Chromic Acrisol, reported a significant reduction of the P sorption capacity of the soil amended with *Tithonia* leafy biomass. This property of *Tithonia* biomass was attributed to its high content of oxalic acid which is released into the soil during decomposition.

Not attaining the highest concentrations of labile P in pots treated with an integration of MPR with *Tithonia* biomass under maize-bean intercrop, as for available P, suggested that application of *Tithonia* biomass might have contributed to limiting P sorption capacities of the soil. This result implied that the application of MPR with *Tithonia* biomass relatively led to the sorption of less P in the soil. The result therefore confirmed the above stated finding of Ikerra *et al.* (2011) on the P sorption limiting property of *Tithonia* biomass.

Furthermore, it was also found out that application of MPR alone under maize-bean raised the concentrations of labile P to the level observed in pots treated with TSP. The rise, which occurred in pots treated with MPR under maize-bean intercrop, might have been induced by an enhanced solubilization of MPR which resulted from the effect of bean rhizosphere acidification. This might actually be the reason why differences in the concentrations of labile P between the two cropping systems for MPR-treated pots were persistently (over the two sampling periods) found to be significant.

4.4.3 Rhizosphere pH

Input applications, in general, differently affected rhizosphere pH under the two cropping systems (Figure 4.4). During the first sampling period, ranges of the means of rhizosphere pH were from 4.26 to 4.72 under sole maize and from 4.52 to 4.77 under maize-bean intercrop showing pH was higher in intercropping than in sole maize. During the second sampling period, the pH means varied between 4.53 and 4.78 and between 4.67 and 4.76 under sole maize and maize-bean intercrop, respectively. Application of TSP consistently led to the highest rise in rhizosphere pH under sole maize while amendment of the soil with *Tithonia* biomass alone, however, contributed to the lowest rhizosphere pH. Under maize-bean intercrop irrespective of the sampling period considered, the highest rhizosphere pH was measured in pots treated with a combination of *Tithonia* biomass with MPR. The lowest rhizosphere pH was, however, recorded in pots amended with sole *Tithonia* biomass. But generally, values of rhizosphere pH recorded under maize-bean intercrop were lower than those measured under sole maize for similar input application.

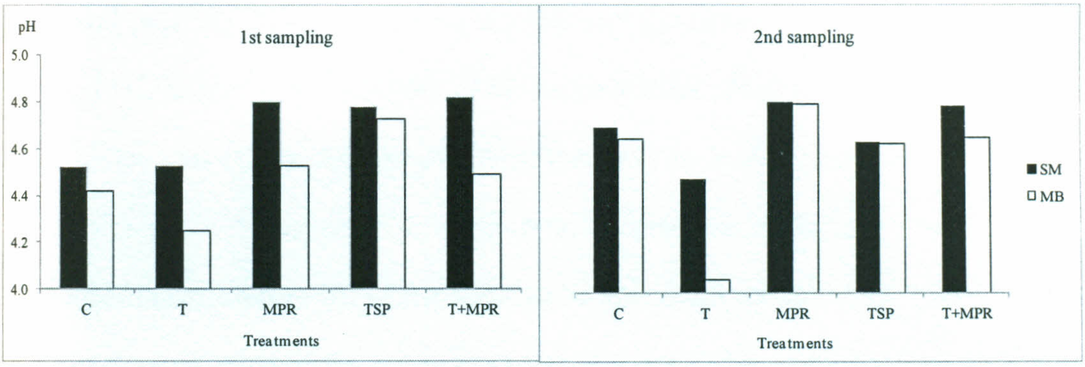

Figure 4.4: Effects of input application on soil pH under both sole and maize-bean intercrop at 4 (1st sampling) and 8 (2nd sampling) weeks after planting.

Rhizosphere acidification by grain legumes during biological nitrogen fixation has been previously reported by several workers, including Troelstra (1982), Troelstra *et al.* (1984) and Marschner (1995). In the present study, the difference in rhizosphere pH attained between the control under sole maize (without bean) and that under maize-bean intercrop. The argument here was that, without further soil acidification as a result of the effect of bean rhizosphere acidification, there could have not been any difference in rhizosphere pH between the two categories of controls. However, effect of the application of certain inputs, such as TSP, was sufficient enough to suppress the significance of the difference in rhizosphere pH attained between the two cropping systems.

The non-reoccurrence of the significance of differences in rhizosphere pH between sole maize and maize-bean intercrop in soils treated with MPR alone or integrated with the biomass during second sampling was attributed to an enhanced solubilization of MPR. Bean-rhizosphere acidification might have contributed to further solubilization of MPR which led to the release of a significant amount of calcium ion (Ca^{2+}) into the soil. The calcium ions released might hence react with hydrogen ions (H^+)

in the soil thus, significantly reducing the soil concentrations of the two different ions, Ca^{2+} and H^+. In particular, reduction of the concentration of hydrogen ions over the one of hydroxide ions (OH^-) was probably what induced rise in the rhizosphere pH. Rise in rhizosphere pH was suspected to result from suppression of the significance of the differences in rhizosphere pH which occurred in soils fertilized with MPR under the two cropping systems (sole maize and maize-bean intercrop). This argument was backed by the significance of the rhizosphere pH differences which occurred under the two cropping systems in soils treated with MPR alone or combined with *Tithonia* biomass during the first sampling period. First sampling was done at the time when the rhizosphere acidification activities of the bean crop were just starting and were less intensive and insufficient to influence MPR solubilization. Rhizosphere acidification by grain legumes was reported to intensify during flowering period but declined greatly towards maturity (FAO, 1983; Unkovich *et al.,* 2008).

The unique performance of *Tithonia* biomass, when applied alone, of lowering soil pH below the initial point observed in the present study was previously reported in separate studies by Ikerra *et al* (2007) and Opala *et al* (2012). Soil pH of the amended soil was reported to later on increase higher, above the initial point, after sometime. Bean rhizosphere acidification partially contributed to the soil acidification observed in pots amended with sole *Tithonia* biomass under maize-bean intercrop.

4.5 Objective 4: Evaluation of the Agronomic Responses of Maize to Applications of *Tithonia* Biomass and Minjingu Phosphate Rock under Maize-bean Intercrop

Reported and discussed in this section are the results of two-consecutive-season field trials conducted at Kavutiri and Muguga to evaluate the agronomic response of maize to application of *Tithonia* biomass and MPR under maize-bean intercrop as compared to sole maize (objective four). In the trial, both soil and plant (maize) parameters were measured. Plant (maize) parameters measured included maize grain and biomass yields, relative agronomic efficiency, maize shoot dry matter yields, and maize shoot relative growth rate. In soils, both readily plant available P and labile P pools were measured.

4.5.1 Maize Grain and Biomass Yields

Averages of maize grain yields at Muguga varied between 2.24 to 3.75 t ha^{-1} and between 2.53 and 5.58 t ha^{-1} in sole maize and maize-bean intercrop, respectively. At Muguga, means of maize grain yields ranged from 1.16 and 2.80 t ha^{-1} and from 1.54 5.58 t ha^{-1} in sole maize and maize-bean intercrop, respectively. Differences in maize grain yields between the two maize cropping systems for plots fertilized with *Tithonia* biomass, MPR and a combination of *Tithonia* biomass with MPR or TSP were highly significant ($p \leq 0.01$).

The maize biomass yields at Kavutiri ranged from 3.18 to 3.77 t ha^{-1} and from 3.67 to 6.32 t ha^{-1} in sole maize and maize-bean intercrop (Table 4.9), respectively. At Muguga the maize biomass yields ranged from 0.78 to 2.05 t ha^{-1} in sole maize, and from

0.78 to 2.85 t ha^{-1} in maize-bean intercrop. The highest maize biomass yield occurred on subplots amended with *Tithonia* biomass combined with MPR and TSP, while the lowest were consistently obtained in the control treatment and in sole *Tithonia* biomass (Table 4.9). At both sites for all treatments, the intercropping system gave higher maize grain yields over sole cropping system. The difference between the yields in the sole and intercropping systems were significant in all treatments except the control. This implies that the intercropping resulted to an increase in yields. Interaction between maize cropping systems and input application was highly significant for both maize grain and biomass yields.

The trends in biomass yields were almost similar to that of maize grain yields with treatments receiving inputs yielding higher than the control in both sites. For example, *Tithonia* biomass combined with MPR or TSP yielded the highest biomass yield during the short rains in Muguga site. In addition, intercropping system gave higher biomass yields that the sole cropping in all seasons with some of the treatments showing highly significant differences between the sole and intercropping systems (Table 4.9).

Table 4.9: Effects of input application on maize grain yields (t ha^{-1}) under both sole maize and maize-bean intercrop at Kavutiri and Muguga

Input	Kavutiri			Muguga		
	Cropping systems		Diff.	Cropping systems		Diff.
	Sole	Mix		Sole	Mix	
Grain Yields : Long Rains Season (2013)						
Control (no fertilizing input)	1.16 d	1.54 c	0.38 ns	2.24 c	2.53 d	0.29 ns
Tithonia alone (5t/ha)	2.27 bc	3.04 b	0.77**	2.77 bc	3.83 c	1.06**
MPR alone (60 Kg P/ha)	1.85 c	2.78 b	0.93**	2.65 bc	4.16 bc	1.51**
TSP alone (60 Kg P/ha)	2.40 ab	2.82 b	0.42 ns	3.32 ab	4.71 b	1.49**
Tithonia (5t/ha)+MPR (50 Kg P/ha)	2.80 a	4.28 a	1.48**	3.16 ab	5.53 a	2.37**
Tithonia (5t/ha) + TSP (50 Kg P/ha)	2.47 ab	4.15 a	1.68**	3.75 a	5.58 a	1.83**
Interaction (A * B)	0.002**			0.004**		
LSD	(.05) = 0.48; (.01) = 0.65			(.05) = 0.48; (.01) = 0.65		
Biomass Yields : Short Rains Season (2013/2014)						
Control (no fertilizing input)	3.18 b	3.67 c	0.49 ns	0.78 c	0.79 c	0.01 ns
Tithonia alone (5t/ha)	3.22 b	4.88 bc	1.66**	0.88 c	1.04 c	0.16 ns
MPR alone (60 Kg P/ha)	3.32 b	5.14 bc	1.82**	1.01 bc	1.78 b	0.77**
TSP alone (60 Kg P/ha)	4.66 a	5.27 bc	0.61 ns	1.53 ab	1.10 c	-0.43 ns
Tithonia (5t/ha) + MPR (50 Kg P/ha)	3.32 b	6.32 a	3.00**	1.67 a	2.70 a	1.03**
Tithonia (5t/ha) + TSP (50 Kg P/ha)	3.77 b	5.27 ab	1.50**	2.05 a	2.85 a	0.8**
Interaction (A * B)	0.0064**			0.0008**		
LSD	(.05) = 0.80; (.01) = 1.09			(.05) = 0.47; (.01) = 0.64		

Mean separation in a column was done by DMRT at 5% level and in a row between sole and mix for the same site by LSD at either 5% or 1% level. A= maize cropping system factor. B=input application factor. Diff. = difference. ns = non-significant. * = significant at 5% level. ** = significant at 1% level. Note: A negative value of difference in the table indicates decrease in the yield mean value in 'mix' over the corresponding value in sole.

There was consistence between the results of yields (Table 4.9) and available P in the surface soils (Tables 4.12 & 4.13). However, correlation results (not shown) revealed weak relationships between levels of available P in the surface soils and maize grain yields, and also between levels of available P in the surface soils and maize biomass yields. Based on the above stated results, increases of both maize grain and biomass yields could not be adequately explained by only an enhancement of P availability, especially on the subplots amended with *Tithonia* biomass alone or integrated with MPR or TSP. The weak correlation results suggested the interventions of other factors, for instance the alleviation of the phototoxic effect of Al. The Al phytotoxic alleviating effect of *Tithonia* biomass, whether applied alone or in combination with MPR, was reported here in the incubation study (4.2.2). The benefits of *Tithonia* biomass application on P-deficient acid soils is extensively covered by Hue *et al.* (1986), Ahmad and Tan (1986), Bessho and Bell (1992), Harper *et al.* (1995), Hue and Amien (1989), Muhrizal *et al.* (2003), Ikerra *et al.* (2011) and Opala and Okalebo (2012). Relatively, a higher Al saturation (51.7%) was reported in this study in soils collected from Kavutiri as compared to soils from Muguga in which Al saturation was quite low, 11.7% (Table 3.1). Result of Al saturation of this study was in agreement with the study finding by FURP and KARI (1994) estimating Al saturation in soils at Kavutiri at above 50%. The level of Al saturation in soils from Kavutiri was largely greater than the critical value of 20% reported for maize by Farina and Chanon (1991). According to the findings by the above stated authors (Farina and Chanon, 1991), Al saturation of more than 20% hinders maize growth and production. This therefore explains why levels of both maize grain and biomass yields achieved at Kavutiri were lower than the ones at Muguga.

The grain yield trend observed in maize-bean intercrop at all the two sites was postulated to have been caused by both the influence of bean rhizosphere acidification (enhancement of P availability) and the non-nutritive roles of *Tithonia* biomass. The non-nutritive roles of *Tithonia* biomass includes chelation of soluble Al and amelioration of soil parameters, such as water retention capacity, microbial population, soil structure, soil texture, soil temperature, and soil moisture content. These roles are essentially driven by organic compounds product of the biomass decomposition.

In addition to enhanced P availability, another factor which might have significantly contributed to the higher maize grain yields in maize-bean intercrop system, as compared to sole maize system, was speculated to be an improved Ca uptake. Further MPR dissolution induced by bean rhizosphere acidification might have led to the release of more Ca thus, increasing its availability and uptake by maize. Phosphate rocks are generally rich in P and also Ca minerals (Karanja *et al.,* 2004).

4.5.2 Relative Agronomic Efficiency

Values of Relative Agronomic Efficiency (RAE) computed for maize grain yields obtained in each of the two trial sites were found to be within the range of 38 to 214%. At Muguga, it ranged from 97 to 214% for sole maize and from 60 to 140% for maize-bean intercrop. While at Kavutiri, the values varied between 56 and 132% and between 38 and 140% for sole maize and maize-bean intercrop, respectively. The lowest RAE values were generally recorded for subplots treated with sole MPR, except for subplots amended with sole *Tithonia* biomass in maize-bean intercrop at Muguga. The difference between subplots treated with sole MPR and those amended with sole *Tithonia* biomass in this specific case was 15% only. The highest RAE values in the two maize cropping systems were, however, computed for subplots fertilized with an integration of *Tithonia* biomass with MPR or TSP. Although the integration of *Tithonia* biomass with MPR or TSP resulted in RAE values above 100% but the RAE values computed for subplots on which maize was intercropped with beans were every time greater than the values for sole maize. For these same input combinations (T+MPR; T+TSP), the RAE values obtained at Muguga were relatively less than the ones at Kavutiri (Figure 4.5).

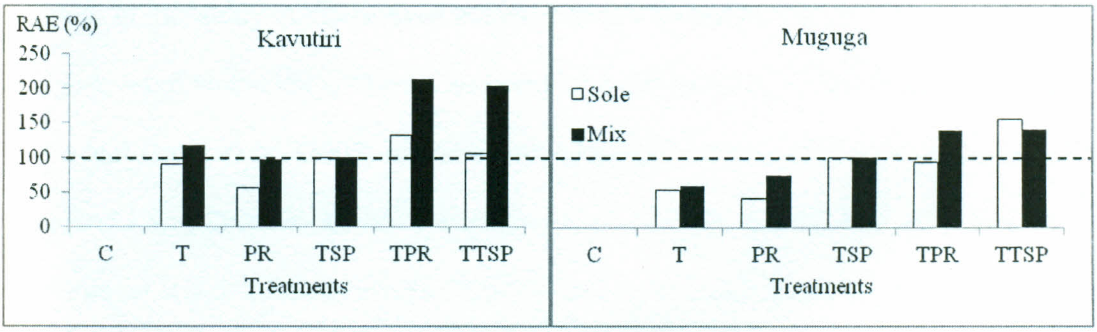

Figure 4.5: Relative Agronomic Efficiency of maize grain yields for both sole maize and maize-bean intercrop in the long rains season at Kavutiri and Muguga

The relatively higher performance of *Tithonia* biomass observed at Kavutiri could be attributed to the ability of the biomass to alleviate the phytotoxic effect of Al. In addition to P deficiency, Al phytotoxicity was reported to be a limiting factor to crop production in the soil (FURP and KARI, 1994). The current study also identified Al phytotoxicity as another major factor constraining crop production, particularly in maize, in the soils of Kavutiri. Relatively, a higher Al saturation (51.7%) was measured in the soils from Kavutiri against 11.7% in the soils from Muguga (Table 3.1).

The RAE results of this study were perceived to be in agreement with the work of Mutuo *et al.* (1999) conducted in western Kenya , in which MPR sole application contributed to RAE = 107% in the season of application. Ikerra *et al* (2007) in Tanzania found that the residual effect of MPR sole application contributed to RAE = 142% in the next season following the season of application. Relatively higher values of RAE equal to 204% and 214% for *Tithonia* biomass combined with TSP and MPR, respectively, were achieved in this study in maize-bean intercrop at Kavutiri in the season of application. The higher performance of the combination of *Tithonia* biomass with MPR or TSP achieved in this study in maize-bean intercrop in the season of application was attributed to high level of soil acidity. The previous experiments by Mutuo *et al.* (1999) in western Kenya and Ikerra *et al.* (2007) in Morogoro, Tanzania, were conducted on a Kandiudalf soil pH=5.1 and Chromic Acrisol pH=4.8, respectively. The soil pH in these studies were measured at 1:2.5 soil:water ratio. Soils at Kavutiri were found to be more acidic (pH=4.0) than any of those soils used in the previous studies.

Therefore, the lower RAE values, not exceeding 140%, obtained at Muguga could be explained by a low level of soil acidity (pH=5.2). The latter (low level of soil acidity) might have negatively impacted on the performance of the combination of *Tithonia* biomass with MPR or TSP at Muguga. This affirmation was supported by the RAE results obtained in maize-bean intercrop for the subplots amended with *Tithonia* biomass combined with MPR or TSP at the same site (Muguga). The RAE values achieved at Muguga in maize-bean intercrop for the combination of *Tithonia* leafy biomass with MPR or TSP were in general found to be greater than the ones in sole maize. The superiority of RAE values observed in maize-bean intercrop over the ones in sole maize was therefore attributed to the influence of bean rhizosphere acidification. Bean rhizosphere acidification resulted into an increase of soil acidity from the initial level as revealed in a greenhouse experiment (4.3.3) in the present study.

4.5.3 Maize Shoot Dry Matter Yields

Input application significantly affected maize shoot dry matter yields in the two maize cropping systems (sole maize and maize-bean intercrop) at both sites (Tables 4.10 and 4.11). At 6 WAP, treatments with an integration of *Tithonia* biomass with MPR and TSP gave the highest dry matter yields at Kavutiri during the long rains (Table 4.10). Similarly during the subsequent sampling periods (12 and 18 WAP) dry matter yields responded to input application. During the short rains, similar trends to that of the long rains were observed especially during 6 WAP (Table 4.11). During that season there was drought (see rainfall trends in Chapter 3) and hence complete harvesting was done before end of the season. Generally effects of input applications were shown to significantly differ within the individual maize cropping systems (sole maize and maize-bean intercrop). In sole maize, the significantly highest maize shoot dry matter yields were obtained on subplots fertilized with *Tithonia* biomass combined with TSP while the lowest was recorded in the control. The highest maize shoot dry matter yields in maize-bean intercrop therefore occurred on subplots treated with a combination of *Tithonia* biomass with MPR or TSP. The good performance of MPR applied alone was frequent.

Table 4.10: Effects of input application on maize shoot Dry Matter Yields (DMY) (mg/shoot) under both sole maize and maize-bean intercrop at Kavutiri

Input	First sampling(6 WAP)			Second sampling (12 WAP)			Third sampling (18 WAP)		
	Cropping systems		Diff.	Cropping systems		Diff.	Cropping systems		Diff.
	Sole	Mix		Sole	Mix		Sole	Mix	
Long Rains (LR): 2013									
Control (no fertilizing input)	2.73 d	3.09 d	0.36 ns	23.62 b	24.09 c	0.47 ns	90.65 d	102.59 c	11.94 ns
Tithonia alone (5t/ha)	3.65 c	6.50 c	2.85**	27.21 b	29.79 c	2.58 ns	106.81 bc	125.70 b	18.89**
MPR alone (60 Kg P/ha)	3.18 cd	6.45 c	3.27**	25.56 b	43.63 ab	18.07**	96.74 cd	130.23 b	33.49**
TSP alone (60 Kg P/ha)	3.63 c	7.23 b	3.60**	28.07 b	34.86 bc	6.79 ns	120.53 ab	136.92 ab	16.39*
Tithonia (5t/ha) +MPR (50 Kg P/ha)	6.11 a	8.71 a	2.60**	30.40 b	51.95 a	21.55**	110.70 bc	145.45 a	34.75**
Tithonia (5t/ha) + TSP (50 Kg P/ha)	4.95 b	9.28 a	4.33**	48.20 a	53.51 a	5.31 ns	133.51 a	148.59 a	15.08*
Interaction (A * B)	<0.0001**			0.02*			0.05*		
LSD	(.05) = 0.47; (.01) = 0.64			(.05) = 10.09; (.01) = 13.77			(.05) = 13.12; (.01) = 17.89		
Short Rains (SR): 2013-2014									
Control (no fertilizing input)	2.23 d	2.28 d	0.05 ns	18.13 b	20.61 b	2.48 ns	/	/	/
Tithonia alone (5t/ha)	4.06 c	4.73 c	0.67 ns	23.59 ab	26.45 b	2.86 ns	/	/	/
MPR alone (60 Kg P/ha)	2.33 d	5.71 bc	3.38**	23.63 ab	35.79 a	12.16**	/	/	/
TSP alone (60 Kg P/ha)	5.03 bc	7.96 b	2.93**	27.75 a	33.77 a	6.02*	/	/	/
Tithonia (5t/ha) +MPR (50 Kg P/ha)	6.51 b	10.75 a	4.24**	25.72 a	40.16 a	14.44**	/	/	/
Tithonia (5t/ha) + TSP (50 Kg P/ha)	8.57 a	10.31 a	1.74 ns	30.59 a	39.12 a	8.53**	/	/	/
Interaction (A * B)	0.03*			0.03*			/		
LSD	(.05) = 1.98; (.01) = 2.71			(.05) = 5.95; (.01) = 8.11			/		

Mean separation was done in a column by DMRT at 5% level and in a row by LSD at either 5% or 1% level. Diff.= difference. ns = non-significant. * = significant at 5% level. ** = significant at 1% level.

Table 4.11: Treatment effects on shoot Dry Matter Yields (DMY) (mg/shoot) at Muguga

Input	First sampling(6 WAP)			Second sampling (12 WAP)			Third sampling (18 WAP)		
	Cropping systems		Diff.	Cropping systems		Diff.	Cropping systems		Diff.
	Sole	Mix		Sole	Mix		Sole	Mix	
Long Rains (LR): 2013									
Control (no fertilizing input)	5.65 e	5.66 d	0.01 ns	58.56 e	67.47 e	8.91 ns	183.45 c	204.12 d	20.67 ns
Tithonia alone (5t/ha)	6.73 d	8.68 c	1.95**	93.51 c	126.67 c	33.16**	224.51 b	235.33 c	10.82 ns
MPR alone (60 Kg P/ha)	7.36 c	8.19 c	0.83**	70.37 d	106.89 d	36.52**	185.98 c	240.95 c	54.97**
TSP alone (60 Kg P/ha)	8.35 b	9.20 b	0.85**	104.30 b	152.43 b	48.13**	234.00 ab	251.89 c	17.89 ns
Tithonia (5t/ha) +MPR (50 Kg P/ha)	8.83 b	12.29 a	3.46**	105.12 b	186.08 a	80.96**	248.65 a	291.89 b	43.24**
Tithonia (5t/ha) + TSP (50 Kg P/ha)	10.25 a	12.33 a	2.08**	158.03 a	184.29 a	26.26**	251.15 a	326.23 a	75.08**
Interaction (A * B)	<0.0001**			<0.0001**			0.001**		
LSD	(.05) = 0.46; (.01) = 0.63			(.05) = 9.11; (.01) = 12.43			(.05) = 21.08; (.01) = 28.75		
Short Rains (SR): 2013-2014									
Control (no fertilizing input)	2.29 c	2.53 d	0.24 ns	86.57 a	87.07 c	0.50 ns	112.23 a	118.19 c	5.96 ns
Tithonia alone (5t/ha)	2.71 c	4.04 cd	1.33 ns	89.79 a	97.16 b	7.37 ns	114.51 a	132.65 b	18.14 ns
MPR alone (60 Kg P/ha)	2.58 c	5.40 c	2.82**	89.35 a	92.09 bc	2.74 ns	113.85 a	131.50 bc	17.65 ns
TSP alone (60 Kg P/ha)	3.88 b	6.00 bc	2.12*	92.80 a	99.11 b	6.31 ns	127.11 a	145.55 b	18.44 ns
Tithonia (5t/ha) +MPR (50 Kg P/ha)	4.96 a	8.15 ab	3.19**	93.84 a	112.79 a	18.95**	126.27 a	174.49 a	48.22**
Tithonia (5t/ha) + TSP (50 Kg P/ha)	5.10 a	8.48 a	3.38**	97.06 a	116.92 a	19.86**	130.13 a	176.48 a	46.35**
Interaction (A * B)	0.05*			0.03*			0.01**		
LSD	(.05) = 1.57; (.01) = 2.14			(.05) = 9.97; (.01) = 13.59			(.05) = 19.41; (.01) = 26.47		

Mean separation was done in a column by DMRT at 5% level and in a row by LSD at either 5% or 1% level. Diff. = difference. ns = non-significant. *=significant at 5% level. ** = significant at 1% level.

At Muguga, effects of the combination of *Tithonia* biomass with MPR or TSP on maize shoot dry matter yields under both sole maize and maize-bean intercrop (Table 4.11) were found to be similar to the trends reported at Kavutiri (Table 4.10). The highest maize shoot dry matter yields were obtained in maize-bean intercrop on subplots which received a combination of *Tithonia* biomass with MPR or TSP while the lowest were generally recorded in control treatments.

Maize shoot dry matter yield differences recorded between sole maize and maize-bean intercrop for subplots fertilized with MPR applied alone or with *Tithonia* biomass, and sometimes for subplots treated with TSP applied with *Tithonia* biomass, were found to be similar to the trends of available P (Table 4.12 and 4.13). That result led to the postulation that the increases in maize shoot dry matter yields recorded in maize-bean intercrop were partially caused by an improved P uptake. This argument is supported by the research findings of FURP and KARI (1994) and also the present study claiming P deficiency, in addition to Al toxicity, to be the major limiting factor to crop production in the soils of Kavutiri (eastern Kenya).

Effects of bean rhizosphere acidification on MPR solubilization were well reflected by the maize shoot dry matter yield levels achieved on subplots treated with MPR alone or combined with *Tithonia* biomass under maize-bean intercrop. This was indirectly demonstrated by the consistently significant differences in the means of maize shoot dry matter yields obtained between sole maize and maize-bean intercrop for subplots treated only with MPR applied alone or in combination with *Tithonia* biomass. The fact that such a result was not achievable on subplots fertilized with other types of input sources was further evidence to, and a confirmation of the affirmation. Achieving an equal result for MPR sole application and its combination with *Tithonia* biomass suggested that *Tithonia* biomass had no limiting effect on its contribution to the increases of maize shoot dry matter yields.

The contribution of sole *Tithonia* biomass to a significant rise in maize shoot dry matter yields over the control treatment was mainly attributed to the ability of the biomass to alleviate the phytotoxic effects of Al rather than its contribution to P availability. *Tithonia* biomass is a well known poor P source (Gachengo *et al.*, 1999; Jama *et al.* 2000; Mugwe *et al.,* 2007, Opala *et al.,* 2010; also this study). Thus, the contribution of *Tithonia* biomass to P availability is always insignificant. Achieving a significant rise in maize shoot dry matter yields on subplots amended only with *Tithonia* biomass was a practical evidence of the severity of the phytotoxic effect of Al in the soils. This result suggested that a sole application of mineral P fertilizers could not be expected to lead to the achievement of an optimum crop yields on the soils. And neither can an optimum crop yields be obtained by an amendment of the soil with sole *Tithonia* biomass. The effects of *Tithonia* biomass on soluble Al is extensively covered by previous studies (Delhaize and Ryan, 1995; Delhaize *et al.*, 2004; Yang *et al.,* 2009). Level of contribution of *Tithonia* biomass to the increase of maize shoot dry matter yields were more pronounced at Kavutiri than at Muguga. This was mainly attributed to the relatively higher level of Al saturation prevailing in the soils of Kavutiri.

4.5.4 Maize Shoot Relative Growth Rate

Results (Figure 4.6) showed that the Relative Growth Rate (RGR) of maize shoots was significantly affected by age of plants, input application and maize cropping systems. Generally, there were significant declines in the values of RGR measured at 18 weeks after planting (WAP) in relation to the ones calculated at 12 WAP. At Kavutiri, means of RGR at 12 WAP varied between 0.038 and 0.054 mg/g/day in sole maize and between 0.025 and 0.049 mg/g/day in maize-bean intercrop. At 18 WAP, they ranged from 0.024 to 0.035 mg/g/day in sole maize and from 0.025 to 0.035 mg/g/day in maize-bean intercrop. At Muguga, RGR means at 12 WAP differed between 0.054 and 0.065 mg/g/day in sole maize and between 0.061 to 0.067 mg/g/day in maize-bean intercrop. The variation recorded at 18 WAP was between 0.011 and 0.027 mg/g/day and between 0.011 and 0.023 mg/g/day in sole maize and maize-bean intercrop, respectively. Relative growth rate values recorded in maize-bean were shown to be less than those recorded in sole maize. An exception to this general trend was noted at Muguga at 12 WAP.

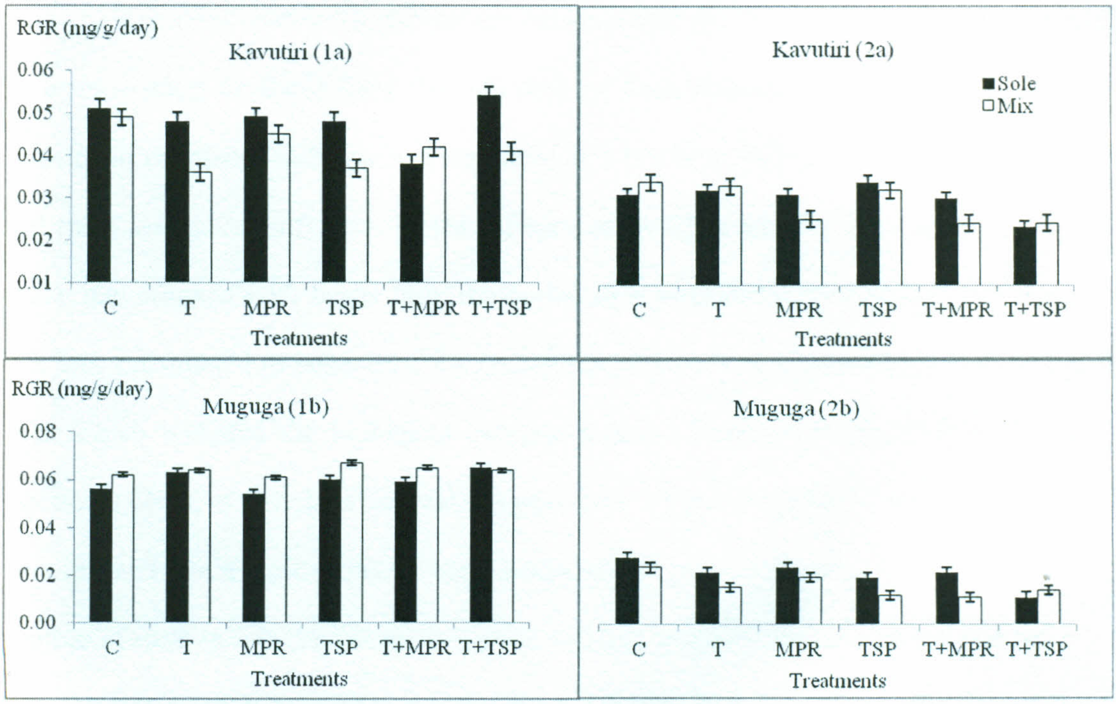

Figure 4.6: Effects of input applications on maize shoot relative growth rate in the long rains season at Kavutiri and Muguga
Note: Vertical bars indicate the standard error of means given that the variances were heterogenous.

Recording lower RGR values at 18 WAP as compared to the results obtained at 12 WAP suggested that tissue growth progressively decreased with the advancement of plant age. The growth is stopped at advanced level of maturaity. A similar result to this was reported in an experiment conducted on maize in Bangledesh by Tajul *et al.* (2013). The above cited authors indicated that the decreases in RGR observed were due to two factors of which one is the increase of metabolically active tissue which contributed less to plant growth. The second factor was prostulated to be the decrease in the net assimilation rate (NAR) of the plant.

The significant RGR differences between sole maize and maize-bean intercrop were understood to result from the influence of bean rhizosphere acidification. In an experiment conducted in Nigeria using maize as a test crop, Adeleke *et al.* (2013) found that there was no significance in the differences of RGR obtained in sole maize and maize intercropped with beans from the period of 6 to 8 WAP. The influence of beans was thus prostulated to depend on the occurence of some physiological functions of the plant which included the biological nitrogen fixation (BNF). The latter physiological function (BNF), which is a general characteristic of grain legumes, was reported to intensify and attain a pic at the flowering stage of the plant (Unkovich *et al.* 2008). The number of days to full (80-100%) flowering of grain legumes depends on the number of days to maturity from the day of planting of that particular species. For *Phaseolus vulgaris* (common bean), for instance, it is estimated at 40-60 days after planting (DAP). The number of days to full flowering of a plant, including grain legumes, may vary from one location to another as it also depends on the type of soil, altitude, rainfall patterns (amount and ditribution), temperature and light intensity (local agroecology).

The consistently significant RGR differences yielded between sole maize and maize intercropped with bean for the subplots fertilized with MPR and TSP both applied individually were thought to have been caused by an improved P uptake. Nitrogen application was revealed to lead to significant rises in RGR in a research study conducted by Tajul *et al.* (2013). An extrapolation of this result to other deficient nutrients in the soil, for instance P in the current study, can help understand why RGR significantly increased on subplots fertilized with MPR or TSP. An enhanced P uptake by maize was therefore thought to have contributed significantly to the maize shoot RGR increases observed in this study.

4.5.5 Available P and Labile P pools

Concentration of both available P (P found in soil solution readily available for uptake by plants) and labile P (weakly adsorbed P) were significantly affected by input application under the two maize cropping systems (sole maize and maize-bean intercrop) (Tables 4.12, 4.13, 4.14 and 4.15). Differences yielded in the concentrations of available P between sole maize and maize-bean intercrop were consistently insignificant for the control treatments but highly significant for the subplots treated with MPR alone or combined with *Tithonia* biomass (Table 4.12 and 4.13). Differences which resulted from a combination of *Tithonia* biomass with MPR or TSP were inconsistent but more frequent. The significantly high mean concentration of available P was consistently measured in the subplots treated with TSP alone or combined with *Tithonia* biomass under sole maize. Whilst under maize-bean intercrop, a combination of *Tithonia* biomass with MPR or TSP contributed to the highest mean concentration of available P. Under both sole maize and maize-bean intercrop, the lowest mean concentrations of available P occurred in the control and sometimes also on the subplots amended with sole *Tithonia* biomass.

For labile P (Tables 4.14 and 4.15), differences in mean concentrations between sole maize and maize-bean intercrop were, as for available P, consistently insignificant for the controls. The differences were, however, consistently significant for the subplots fertilized with MPR at Kavutiri and TSP at Muguga. Under both sole maize and maize-bean intercrop, application of TSP contributed to the highest significant rises in the concentrations of labile P. The lowest concentrations under both sole maize and maize-bean intercrop were consistently recorded in the control treatments.

Table 4.12: Effects of input application on soil available P (mg P/Kg) under both sole maize and maize-bean intercrop at Kavutiri

Input	First sampling(6 WAP)			Second sampling (12 WAP)			Third sampling (18 WAP)		
	Cropping systems		Diff.	Cropping systems		Diff.	Cropping systems		Diff.
	Sole	Mix		Sole	Mix		Sole	Mix	
Long Rains (LR): 2013									
Control (no fertilizing input)	5.39 d	5.59 f	0.20 ns	15.74 b	16.30 c	0.56 ns	18.54 b	19.03 c	0.49 ns
Tithonia alone (5t/ha)	6.16 c	8.69 e	2.53**	16.68 b	18.05 c	1.37 ns	19.47 b	19.18 c	0.49 ns
MPR alone (60 Kg P/ha)	7.39 b	10.41 d	3.02**	17.16 b	32.28 b	15.12**	21.52 b	53.46 b	31.94**
TSP alone (60 Kg P/ha)	10.24 a	12.06 c	1.82**	29.26 a	18.56 c	-10.7**	34.07 a	40.81 ab	6.74 ns
Tithonia (5t/ha) + MPR (50 Kg P/ha)	7.75 b	12.81 b	5.06**	19.16 b	41.98 ab	22.82**	25.36 b	43.33 ab	17.97**
Tithonia (5t/ha) + TSP (50 Kg P/ha)	9.87 a	14.18 a	4.31**	32.16 a	50.59 a	18.43**	41.20 a	48.36 a	7.16 ns
Interaction (A * B)	<0.001**			0.001**			0.02*		
LSD	(.05) = 0.37; (.01) = 0.50			(.05) = 7.45; (.01) = 10.16			(.05) = 8.38; (.01) = 11.43		
Short Rains (SR): 2013-2014									
Control (no fertilizing input)	13.77 d	14.37 d	0.60 ns	10.23 d	10.21 d	-0.02 ns	/	/	/
Tithonia alone (5t/ha)	15.86 cd	17.56 d	1.70 ns	13.36 c	13.45 cd	0.09 ns	/	/	/
MPR alone (60 Kg P/ha)	16.66 cd	26.73 bc	10.07**	11.22 cd	17.26 bc	6.04**	/	/	/
TSP alone (60 Kg P/ha)	22.58 ab	24.81 c	2.23 ns	17.84 b	16.55 c	-1.29 ns	/	/	/
Tithonia (5t/ha) + MPR (50 Kg P/ha)	20.25 ab	36.19 a	15.94**	18.58 b	22.62 a	4.04*	/	/	/
Tithonia (5t/ha) + TSP (50 Kg P/ha)	27.52 a	30.73 b	3.21 ns	21.77 a	21.13 ab	-0.64 ns	/	/	/
Interaction (A * B)	0.0008**			0.02*			/		
LSD	(.05) = 5.02; (.01) = 6.84			(.05) = 3.49; (.01) = 4.76			/		

Mean separation was done in a column by DMRT at 5% level and in a row between sole and mix for the same sampling period by LSD at either 5% or 1% level. Diff. = difference. ns = non-significant. * = significant at 5% level. ** = significant at 1% level. A= maize cropping system factor. B=input application factor. NB: A negative value of difference in the table indicates decrease in the value recorded under the 'mix' over the corresponding one under the 'sole'.

Table 4.13: Effects of input application on soil available P (mg P/Kg) under both sole maize and maize-bean intercrop at Muguga

Input	First sampling(6 WAP)			Second sampling (12 WAP)			Third sampling (18 WAP)		
	Cropping systems		Diff.	Cropping systems		Diff.	Cropping systems		Diff.
	Sole	Mix		Sole	Mix		Sole	Mix	
Long Rains (LR): 2013									
Control (no fertilizing input)	7.67 d	8.73 e	1.06 ns	5.55 d	6.37 d	0.82 ns	8.25 b	8.73 c	0.48 ns
Tithonia alone (5t/ha)	10.00 c	12.23 d	2.23 ns	5.65 d	8.45 cd	2.80*	8.91 b	9.00 c	0.09 ns
MPR alone (60 Kg P/ha)	11.69 b	17.86 c	6.17**	7.72 c	11.51 bc	3.79*	10.57 ab	13.86 b	3.29*
TSP alone (60 Kg P/ha)	13.49 a	19.80 bc	6.31**	10.66 a	12.59 bc	1.93 ns	9.92 ab	15.61 ab	5.69**
Tithonia (5t/ha)+MPR (50 Kg P/ha)	11.55 b	22.90 b	11.35**	8.46 bc	12.81 b	4.35**	10.30 ab	15.39 ab	5.09**
Tithonia (5t/ha) + TSP (50 Kg P/ha)	12.96 ab	27.17 a	14.21**	9.87 ab	16.94 a	7.07**	12.70 a	18.18 a	5.48**
Interaction (A * B)	<0.0001**			0.05*			0.01**		
LSD	(.05) = 2.44; (.01) = 3.33			(.05) = 2.78; (.01) = 3.80			(.05) = 2.73; (.01) = 3.72		
Short Rains (SR): 2013-2014									
Control (no fertilizing input)	4.48 c	5.34 d	0.86 ns	4.58 d	4.30 c	-0.28 ns	3.76 c	4.46 d	0.70 ns
Tithonia alone (5t/ha)	4.50 c	7.05 d	2.55 ns	6.07 cd	8.90 bc	2.83 ns	4.15 c	8.44 c	4.29*
MPR alone (60 Kg P/ha)	5.65 c	15.55 c	9.90 **	5.93 cd	15.50 ab	9.57**	13.89 b	17.81 b	3.92*
TSP alone (60 Kg P/ha)	12.05 b	18.38 bc	6.33**	11.34 b	12.90 ab	1.56 ns	18.78 a	16.28 b	-2.5 ns
Tithonia (5t/ha)+MPR (50 Kg P/ha)	15.29 a	22.94 a	7.65**	8.75 bc	19.06 a	10.31**	13.98 b	18.24 b	4.26*
Tithonia (5t/ha) + TSP (50 Kg P/ha)	13.59 ab	20.75 ab	7.16**	17.01 a	18.87 a	1.86 ns	21.49 a	22.86 a	1.37 ns
Interaction (A * B)	0.001**			0.008**			0.05*		
LSD	(.05) = 3.01; (.01) = 4.10			(.05) = 4.56; (.01) = 6.22			(.05) = 3.54; (.01) = 4.83		

Mean separation was done in a column by DMRT at 5% level and in a row between sole and mix for the same sampling period by LSD at either 5% or 1% level. Diff. = difference. ns = non-significant. *=significant at 5% level. **=significant at 1% level. A=maize cropping system factor. B=input application factor.

Table 4.14: Effects of input application on soil labile P (mg P/Kg) under both sole maize and maize-bean intercrop at Kavutiri

Input	First sampling (6 WAP)			Second sampling (12 WAP)			Third sampling (18 WAP)		
	Cropping systems		Diff.	Cropping systems		Diff.	Cropping systems		Diff.
	Sole	Mix		Sole	Mix		Sole	Mix	
Long Rains (LR): 2013									
Control (no fertilizing input)	7.18 c	8.97 d	1.79 ns	6.41 c	7.24 b	0.83 ns	8.34 c	8.57 d	0.23 ns
Tithonia alone (5t/ha)	8.79 c	9.87 d	1.08 ns	6.35 c	7.56 b	1.21 ns	9.07 bc	9.75 cd	0.68 ns
MPR alone (60 Kg P/ha)	10.85 bc	15.56 b	4.71*	15. 61 b	10.21 b	-5.4**	9.67 bc	15.13 b	5.46**
TSP alone (60 Kg P/ha)	19.66 a	17.47 a	-2.19 ns	19.79 a	15.95 a	-3.84*	14.30 a	20.57 a	6.27**
Tithonia (5t/ha) +MPR (50 Kg P/ha)	17.06 ab	10.66 cd	-6.40**	8.54 c	8.40 b	-0.14 ns	9.43 bc	10.31 cd	0.88 ns
Tithonia (5t/ha) + TSP (50 Kg P/ha)	16.07 ab	11.95 c	-4.12 ns	8.15 c	9.89 b	1.74 ns	11.04 b	11.27 c	0.23 ns
Interaction (A * B)	0.01**			0.05*			0.002**		
LSD	(.05) = 4.27; (.01) = 5.83			(.05) = 3.70; (.01) = 5.04			(.05) = 2.48; (.01) = 3.38		
Short Rains (SR): 2013-2014									
Control (no fertilizing input)	5.19 c	5.37 b	0.18 ns	3.34 b	3.57 d	0.23 ns			
Tithonia alone (5t/ha)	6.15 c	6.44 b	0.29 ns	4.07 b	4.75 cd	0.68 ns			
MPR alone (60 Kg P/ha)	5.42 c	10.26 a	4.84**	3.67 b	7.13 b	3.46**			
TSP alone (60 Kg P/ha)	9.20 b	13.39 a	4.19**	7.30 b	10.57 a	3.27**			
Tithonia (5t/ha) +MPR (50 Kg P/ha)	5.95 c	5.44 b	-0.51 ns	4.43 b	6.31 bc	1.88 ns			
Tithonia (5t/ha) + TSP (50 Kg P/ha)	13.31 a	12.70 a	-0.61 ns	6.04 a	6.27 bc	0.23 ns			
Interaction (A * B)	0.01**			0.04*					
LSD	(.05) = 2.54; (.01) = 3.46			(.05) = 2.07; (.01) = 2.82					

Mean separation was done in a column by DMRT at 5% level and in a row between sole and mix for the same sampling period by LSD at either 5% or 1% level. A= maize cropping system factor. B=input application factor. Diff. = difference. ns = non-significant. * = significant at 5% level. ** = significant at 1% level. NB: A negative value of difference in the table indicates decrease in the value recorded under the ‘mix’ over the corresponding one under the ‘sole’.

Table 4.15: Effects of input application on soil labile P (mg P/Kg) under both sole maize and maize-bean intercrop at Muguga

Input	First sampling(6 WAP)			Second sampling (12 WAP)			Third sampling (18 WAP)		
	Cropping systems		Diff.	Cropping systems		Diff.	Cropping systems		Diff.
	Sole	Mix		Sole	Mix		Sole	Mix	
Long Rains (LR): 2013									
Control (no fertilizing input)	2.50 d	2.60 d	0.10 ns	3.98 a	2.89 d	-1.09 ns	2.55 c	3.84 c	1.29 ns
Tithonia alone (5t/ha)	2.93 d	2.80 d	-0.13 ns	4.27 a	4.54 cd	0.27 ns	4.26 bc	5.62 bc	1.36 ns
MPR alone (60 Kg P/ha)	5.69 b	10.62 b	4.93**	4.22 a	7.60 b	3.38**	3.37 c	8.93 a	5.56**
TSP alone (60 Kg P/ha)	8.59 a	15.31 a	6.72**	4.80 a	9.92 a	5.12**	7.55 a	10.61 a	3.06**
Tithonia (5t/ha) + MPR (50 Kg P/ha)	4.59 c	6.35 c	1.76*	4.45 a	5.08 c	0.63 ns	4.40 bc	5.12 bc	0.72 ns
Tithonia (5t/ha) + TSP (50 Kg P/Kg)	5.29 bc	11.00 b	5.71**	4.69 a	5.42 c	0.73 ns	5.97 ab	6.16 b	0.19 ns
Interaction (A*B)	<0.0001**			<0.0001**			0.003*		
LSD	(.05) = 1.61; (.01) = 2.20			(.05) = 1.52; (.01) = 2.08			(.05) = 1.86; (.01) = 2.54		
Short Rains (SR): 2013-2014									
Control (no fertilizing input)	7.09 d	7.11 d	0.02 ns	3.68 c	3.83 b	0.15 ns	3.51 c	4.84 d	1.33 ns
Tithonia alone (5t/ha)	7.28 d	8.61 cd	1.33 ns	5.37 abc	4.19 b	-1.18 ns	5.26 abc	6.62 cd	1.36 ns
MPR alone (60 Kg P/ha)	8.75 c	10.19 bc	1.44 ns	4.68 bc	6.16 b	1.48 ns	4.22 bc	8.93 ab	4.71**
TSP alone (60 Kg P/ha)	9.71 c	12.33 b	2.62**	5.06 bc	5.75 b	0.69 ns	7.88 a	10.61 a	2.73*
Tithonia (5t/ha) + MPR (50 Kg P/ha)	11.33 b	16.19 a	4.86**	5.94 ab	4.71 b	-1.23 ns	5.06 bc	6.12 cd	1.06 ns
Tithonia (5t/ha) + TSP (50 Kg P/ha)	13.02 a	16.44 a	3.42**	7.20 a	10.67 a	3.47**	6.97 ab	7.16 bc	0.19 ns
Interaction (A*B)	0.02*			0.05*			0.05*		
LSD	(.05) = 1.87; (.01) = 2.56			(.05) = 2.31; (.01) = 3.16			(.05) = 2.06; (.01) = 2.80		

Mean separation was done in a column by DMRT at 5% level and in a row between sole and mix for the same sampling period by LSD at either 5% or 1% level. A= maize cropping system factor. B=input application factor. Diff. = difference. ns = non-significant. * = significant at 5% level. ** = significant at 1% level. NB: A negative value of difference in the table indicates decrease in the value recorded under the 'mix' over the corresponding one under the 'sole'.

The differences in the concentration of available P obtained between sole maize and maize-bean intercrop for subplots treated with MPR applied alone or integrated with *Tithonia* biomass was attributed to the solubilizing effect on MPR of the bean rhizosphere acidification. That result clearly indicated that bean rhizosphere acidification was actually effective in enhancing MPR solubilization. The rhizosphere acidification thus led to further release of P into the soil solution from both MPR and the inherent soil calcium bound P minerals. The general phenomenon in the soil is that when P is released it is then shared unequally among the available P, labile P and non-labile P pools (Buresh *et al.,* 1997). Based on this, the result achieved for MPR applied alone or in combination with *Tithonia* biomass indicated that less amount of the P released from MPR were then adsorbed or fixed while the biggest proportion of the P remained in soil solution readily available for uptake by plants. This affirmation was made based on the understanding that had much of the P released was adsorbed or fixed, there could be no significance in the differences obtained between sole maize and maize-bean intercrop.

No result similar to that of MPR in terms of the consistently significant differences obtained between sole maize and maize-bean intercrop was achievable by the application of other inputs, including *Tithonia* biomass, TSP or a combination of the two. The insensitivity to bean rhizosphere acidification of the other inputs used was therefore thought to be the main reason underlying the insignificance of their respective differences. Of great importance to note here that MPR, as any other phosphate rocks, differs from the other input sources used in the study by its water insoluble but acid soluble property (Buresh *et al.,* 1997; FAO, 2004). This, of course, was thought to be the reason why the MPR was able to significantly respond to bean rhizosphere acidification in relation to the other input sources used.

The best performance in terms of increasing P availability of the combination of *Tithonia* biomass with MPR or TSP was attributed to the P sorption limiting ability of the decomposing *Tithonia* biomass. The P sorption limiting ability of a decomposing *Tithonia* biomass was previously reported in an experimental study by Ikerra *et al.* (2011). These authors attributed the best performance of *Tithonia* biomass on enhancing P availability to its ability to significantly reduce P sorption of the amended soil. According to the study, the ability to limit P sorption was conferred to the biomass by its high concentration of oxalic acid. In the present experiment, the performance of *Tithonia* biomass was further boosted under maize-bean intercrop by the influence of bean rhizosphere acidification on the solubilization of the soil inherent Ca bound P minerals. This contributed significantly to the rise in the concentrations of available P observed under maize-bean in relation to the levels recorded under sole maize.

As mentioned above, the differences yielded by concentrations of labile P between sole maize and maize-bean intercrop were consistently significant for MPR applied alone. In essence, one of the outstanding differences between labile P and available P results was the effects produced on their respective concentrations by the co-application of MPR with *Tithonia* biomass. The co-application (T+MPR) resulted into a significant increase of the concentration of available P whereas it, however, led to a significant decrease of the concentrations of labile P. This was therefore a clear evidence of the ability of the decomposing *Tithonia* biomass to limit the P sorption capacity of the amended soil. This result was in agreement with the finding of Ikerra *et al* (2011) who found that application of *Tithonia* biomass led to a significant reduction of the P sorption capacity of the amended soil. This reduction in the concentration of labile P was coupled with a significant rise in the concentrations of available P.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of key findings and conclusions

Results from the nutrients (N and P) of the surface soils and *Tithonia* biomass quality relationship studies (4.1) showed that there was variation in the biomass (N and P) quality in different areas. *Tithonia* biomass nutrient contents ranged from 3.54 to 4.68% for N and from 0.25 to 0.44% for P. There was a strong positive linear correlation (r = + .95) between the N and P within *Tithonia* biomass. Differences in the N and P contents of *Tithonia* biomass among areas were significant. Due to the significance of the variability of *Tithonia* biomass N and P contents in different areas, the study therefore concluded that the amount of biomass to be incorporated in order to supply a certain amount of a specific nutrient to the soil should be decided based on the results of a chemical analysis of the biomass samples from the area.

A combined application of *Tithonia* leafy biomass and MPR on a P-deficient acid soil highly saturated with soluble Al (above 50%) contributed to the increase in the concentrations of N, P, K and Ca in the soil and decreased the concentration of soluble Al. As such, the combination of *Tithonia* biomass with MPR was shown to have more advantage over that of sole mineral P fertilizer (TSP). The contribution of TSP was solely limited to P supply to the soil. Thus, it was concluded that the increased crop yields usually achieved on P-deficient acid soils result from both the direct and indirect contributions of the inputs (*Tithonia* biomass and MPR) combination. Direct contribution is attributed to its ability to increase nutrient availability in the soil (nutritive role) through the input of more nutrients while the indirect contribution (non-nutritive role) implies favouring crop production on the soil through alleviation of the phytotoxic effect of Al and also raising soil pH to a level suitable for optimum crop growth and production.

In the greenhouse pot experiment (4.3), the maize dry matter yields recorded in treatment where maize was intercropped with beans was significantly above those of their counterparts in pots where maize was planted in monocrop. Differences in maize dry matter yields achieved between the two maize cropping systems (sole maize and maize-bean intercrop) were significant for the pots fertilized with MPR alone or combined with *Tithonia* leafy biomass. Across the maize cropping systems (both sole maize and maize-bean intercrop), the highest maize dry matter yields occurred in intercrop in pots fertilized with a combination of *Tithonia* leafy biomass with MPR. This was postulted to be the result of both an improved nutrient uptake, including P, and the alleviation of the phytotoxic effect of Al. In the pots fertilized with a combination of *Tithonia* biomass with MPR under maize-bean intercrop, P availability was further increased by an enhanced MPR solubilization resulting from the effect of bean rhizosphere acidification. Based on these findings, the study established that integrating *Tithonia* leafy biomass with MPR on a P-deficient acid soil is more effective in increasing maize dry matter yields in maize-bean intercrop than in sole maize. Use of the integrated low input approach to increase crop yields on P-deficient acid soils was the best alternative to the mineral P fertilizers.

In the two maize cropping systems (sole maize and maize-bean intercrop) under field trials, the highest maize grain yields were obtained under maize-bean intercrop on subplots treated with an integration of *Tithonia* biomass with MPR or TSP. The high performances of this type of input integration resulted in high Relative Agronomic Efficiency, above 100%. Of great importance to note here that 100% was the level for TSP. But performances of the input integration recorded at Kavutiri on a strongly acidic soil (pH=4.0) were above the ones at Muguga where soil was weakly acidic (pH=5.2). This led to the conclusion that the effectiveness of the integration of *Tithonia* biomass with MPR or TSP depends on the levels of soil acidity and consequently of Al saturation. This type of low input integration is more effective in soils with high acidity and high Al saturation.

5.3 Recommendations

The following recommendations can be made from this study:

- There is need for developing a *Tithonia* biomass quality database for all the agro-ecologies in the country. It is also recommended that the database should be available online with an open access to the public.
- Farmers, especially small scale farmers should be sensitized on use of *Tithonia* biomass with MPR to improve crop yields on P-deficient acid soils highly saturated with soluble Al, and thus trained to grow the shrub, even on their farms, for the purpose of soil fertility management;
- To make sure that MPR is extensively available to farmers at very low costs, the product should be zero-rated in terms of tax and its importation to the country should be also encouraged and subsidized.

- The government through the ministry of agriculture should incorporate the low input strategy into its policy for promoting sustainable agriculture, increasing food production and alleviating poverty.

5.4 Areas for further research

It is important that research studies should be conducted focusing on some areas of research interest that may not have been covered by the present study. This includes:

- Further research study to determine the relationship between *Tithonia* biomass quality and the nutrient levels of deeper soil layers.
- a) A similar research study on the combination of MPR and biomass from other plants of the same family with *Tithonia diversifolia*, for instance *Tithonia rotundifolia*. Note that *Tithonia diversifolia* belongs to the botanic family of Asteraceae. b) Further research on other non-nutritive but beneficial roles to crops of the application of *Tithonia* biomass with MPR. These may include but not limited to the effects of this integrated application (of *Tithonia* biomass with MPR) on soil moisture content, soil water retention capacity, soil temperature and microbial biomass population.
- A long term evaluation of the impact of this specific low input approach on the build-up of soil fertility and nutrient capital is necessary.

- a) A research study to evaluate the effectiveness of the low input approach on soils with an equal level of soil acidity but different buffering capacities. b) Further research to investigate other mechanisms behind the positive effect of intercrop, for instance the regulation of soil temperature, the minimization of the evaporation of water from the soil and the impact on soil microbial population.

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APPENDIX I

Plant Nutrients, their Classification and Source(s) of Supply

S. N°	Nutrients	Symbol	Classification	Supplier(s)
1.	Carbon	C	N/A	Air and Water
2.	Hydrogen	H		
3.	Oxygen	O		
4.	Nitrogen	N	Primary Nutrients	Soil, lime and Commercial Fertilizers
5.	Phosphorus	P		
6.	Potassium	K		
7.	Calcium	Ca	Secondary Nutrients	
8.	Magnesium	Mg		
9.	Sulfur	S		
10.	Boron	B	Micronutrients	
11.	Chlorine	Cl		
12.	Copper	Cu		
13.	Iron	Fe		
14.	Manganese	Mn		
15.	Molybdenum	Mo		
16.	Zinc	Zn		

Source: Tucker M.R. (1999)

APPENDIX II

Primary and Secondary Nutrient Deficiency Symptoms, the Causes and Method of Correction

Nutrient	General Deficiency Symptoms	Probable Cause of Deficiency	Method of Correction
Nitrogen (N)	Yellow leaves, stunted growth, lower leaves turn brown, leaves abort	Low soil N, leaching from the soil, inadequate N applied	Apply N fertilizer
Phosphorus (P)	Small plants, reddish-purple leaves, slow growth, loss of plant vigour	Low soil P; cool, wet soils; inadequate P applied	Apply P fertilizer
Potassium (K)	Small plants, brown margins on lower leaves, small weak stems, lodging of plants, poor yield and quality	Low soil K, leaching from the soil, inadequate K applied	Apply K fertilizer
Calcium (Ca)	Small plants, deformed buds, distorted leaves, failure to grow, poor fruit development.	Low soil pH, leaching from the soil, inadequate lime applied	Apply lime or Ca fertilizer
Magnesium (Mg)	Lower leaves—in severe cases, entire plants—turn yellow with green interveinal areas	Low soil pH, leaching from the soil, no Mg applied in lime or fertilizer	Apply dolomitic lime or Mg fertilizer
Sulfur (S)	Yellow plants, slow growth, low vigour, no response to applied nitrogen, low crop yield and quality	Low soil S, leaching from the soil, low organic matter content, no S fertilizer applied	Apply S fertilizer

(Source: Tucker M.R., 1999)

APPENDIX III

Micronutrient Deficiency Symptoms, the Probable Cause and Method of Correction

Nutrient	General Deficiency Symptoms	Probable Cause	Method of Correction
Manganese (Mn)	Interveinal chlorosis of leaves, stunted plants, yellow cast over deficient areas, reduced yield & quality	Low soil Mn, high soil pH due to over liming	Lower soil pH, apply foliar spray or add Mn to soil
Zinc (Zn)	Chlorotic leaves, slow growth, reduced vigour, white streaks parallel to leaf blade	Low Zn in soil, high soil pH, high soil P	Lower soil pH, apply foliar spray, or add Zn to soil
Copper (Cu)	Reduced growth, leaf-tip dies back, leaf tip breaks down, leaves ragged	Low soil Cu, high organic matter	Apply foliar spray or add Cu to soil
Boron (B)	Terminal bud dies, multiple lateral branches (rosette with short internodes, older leaves thick and leathery, petioles short, twisted, and ruptured), hollow heart (in vegetables), small deformed fruit (in grapes), cork spot (in apples)	Low soil B, esp. on sandy soils	apply foliar spray or add B to soil
Molybdenum (Mo)	Reduced growth; pale green colour; necrotic areas adjacent to midrib, between veins and along leaf edges; twisted stems	Low soil pH, low Mo content in soil	Inoculate seed with Mo, apply foliar spray, or add Mo to soil
Chlorine (Cl)	Reduced growth; stubby roots; interveinal chlorosis; nonsucculent tissue (in leafy vegetables)	Low soil Cl, especial in soils subject to leaching	Apply Cl-containing fertilizer

(Source: Tucker, M.R., 1999)

APPENDIX IV

Soil nutrient-*Tithonia* Biomass Quality Relationship Study

- Biomass N content (%)

Source	DF	SS	MS	F Value	P>F
Replication	5	258.39	51.68	1.00	0.4445
Site	4	200.14	50.03	0.97	0.4478

- Biomass P content (%)

Source	DF	SS	MS	F Value	P>F
Replication	5	0.0345	0.0069	1.62	0.2013
Site	4	4.1675	1.041878	234.87	0.0001

- Soil available P (mg P Kg^{-1})

Source	DF	SS	MS	F Value	P>F
Replication	5	14.877	2.97547	0.36	0.8679
Site	4	12557.4965	3139.35491	382.69	0.0005

- Soil total mineral N (mg N Kg^{-1})

Source	DF	SS	MS	F Value	P>F
Replication	5	49.0987	9.819789	1.12	0.3830
Site	4	2079.912	519.977988	59.15	0.0001

- Soil nitrate (mg N Kg^{-1})

Source	DF	SS	MS	F Value	P>F
Replication	5	60.98444	12.196888	2.24	0.0901
Site	4	273.8795	68.4698867	12.58	0.0001

- Soil ammonium (mg N Kg^{-1})

Source	DF	SS	MS	F Value	P>F
Replication	5	118.043507	23.608701	2.14	0.1021
Site	4	078.224353	269.556088	24.46	0.0001

Incubation Experiment

- Soil total mineral N (mg N Kg^{-1})

Source	DF	SS	MS	F Value	P>F
Replication	2	245.40945	122.7047267	3.85	0.067
Treatment	4	880.6918267	220.1729567	6.91	0.0104

2. Soil available P (mg P Kg^{-1})

Source	DF	SS	MS	F Value	P>F
Replication	2	16.900053	8.450027	1.14	0.3667
Treatment	4	1581.672973	395.418243	53.36	0.0001

Soil available K (mg K Kg^{-1})

Source	DF	SS	MS	F Value	P>F
Replication	2	1046.75201	523.37601	4.91	0.0406
Treatment	4	12587.14769	3146.78692	29.52	0.0001

3. Soil available Ca (mg Ca Kg^{-1})

Source	DF	SS	MS	F Value	P>F
Replication	2	12.168120	6.084060	0.25	0.7865
Treatment	4	4141.201427	1035.300357	42.12	0.0001

Greenhouse Pot Experiment

a. Available P (mg P Kg^{-1})

- First sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	10.8738	5.4369	0.13	0.8748
Syst	1	2089.34	2089.3376	51.79	<.0001
Error a			40.342491		
Trt	4	15637.1	3909.2799	96.9	<.0001
Syst*Trt	4	1862.57	465.64125	11.54	<.0001
Error b			40.350194		

- Second sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	85.87985	42.93992	1.06	0.3675
Syst	1	2047.984	2047.984	50.51	<.0001
Error a			40.54612		
Trt	4	13411.34	3352.837	82.69	<.0001
Syst*Trt	4	1074.026	268.5066	6.62	0.0018
Error b			40.55990		

b. Labile P (mg P Kg^{-1})

- First sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	11.322587	5.661293	0.56	0.5822
Syst	1	76.736013	76.736013	7.56	0.0132
Error a			10.150266		
Trt	4	1115.4984	278.87462	27.47	<.0001
Syst*Trt	4	104.85568	26.213922	2.58	0.0723
Error b			10.160434		

- Second sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	10.63022	5.31511	1.8	0.1935
Syst	1	95.83681	95.8368	32.49	<.0001
Error a			2.94973		
Trt	4	628.5312	157.132	53.26	<.0001
Syst*Trt	4	53.18415	13.2960	4.51	0.0107
Error b			2.94812		

- Maize Shoot Dry Matter Yield (g shoot^{-1})

Source	DF	SS	MS	F Value	Pr > F
Rep	2	1.360826	0.6804133	3.23	0.0632
Syst	1	14.60216	14.602163	69.37	<.0001
Error a			0.2104968		
Trt	4	23.77044	5.9426116	28.23	<.0001
Syst*Trt	4	14.14288	3.5357216	16.8	<.0001
Error b			0.2104596		

Field Trials

A Kavutiri

A.1 Long Rains Season

- Maize grain yields

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.72115	0.360577	4.56	0.022
Syst	1	8.04667	8.046677	101.82	<.0001
Error a			0.079028		
Trt	5	18.1480	3.629617	45.93	<.0001
Syst*Trt	5	2.17775	0.435551	5.51	0.0019
Error b			0.079047		

- Dry matter yields, 1st sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.019	0.009	0.13	0.8771
Syst	1	72.42	72.42	958.1	<.0001
Error a			0.075		
Trt	5	81.71	16.34	216.22	<.0001
Syst*Trt	5	13.83	2.766	36.6	<.0001
Error b			0.075		

- Dry matter yields, 2nd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	84.657	42.328	1.2	0.3191
Syst	1	749.66	749.66	21.32	0.0001
Error a			35.162		
Trt	5	2810.2	562.05	15.98	<.0001
Syst*Trt	5	558.20	111.64	3.18	0.0263
Error b			35.107		

- Dry matter yields, 3rd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	61.9202	30.9601	0.52	0.6003
Syst	1	4457.342	4457.34	75.21	<.0001
Error a			59.2652		
Trt	5	6685.329	1337.06	22.56	<.0001
Syst*Trt	5	649.6822	129.936	2.19	0.0918
Error b			59.3317		

- Relative growth rate, 2nd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.000008	0.0000043	0.19	0.8302
Syst	1	0.000354	0.0003546	15.26	0.0008
Error a			2.32431E-05		
Trt	5	0.000443	0.0000886	3.81	0.0122
Syst*Trt	5	0.000327	0.0000654	2.82	0.0411
Error b			2.32021E-05		

- Relative growth rate, 3rd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.000031	0.000015	1.07	0.3591
Syst	1	0.000023	0.000023	1.61	0.2171
Error a			1.45093E-05		
Trt	5	0.000462	0.000092	6.4	0.0008
Syst*Trt	5	0.000111	0.000022	1.54	0.2181
Error b			1.4474E-05		

- Available P, 1st sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.0079	0.00395	0.09	0.9186
Syst	1	71.740	71.7409	1546.81	<.0001
Error a			0.04637		
Trt	5	179.76	35.9524	775.17	<.0001
Syst*Trt	5	22.914	4.58297	98.81	<.0001
Error b			0.04638		

- Available P, 2nd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	81.302	40.651	2.12	0.1434
Syst	1	566.59	566.59	29.61	<.0001
Error a			19.135		
Trt	5	2620.5	524.11	27.39	<.0001
Syst*Trt	5	1241.9	248.38	12.98	<.0001
Error b			19.136		

- Available P, 3rd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	17.852	8.926233	0.37	0.6962
Syst	1	528.69	528.69	21.81	0.0001
Error a			24.240		
Trt	5	3197.3	639.47	26.38	<.0001
Syst*Trt	5	392.23	78.447	3.24	0.0244
Error b			24.212		

- Labile P, 1st sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	7.1754	3.5877	0.57	0.5738
Syst	1	6.5963	6.5963	1.05	0.3172
Error a			6.2822		
Trt	5	421.86	84.372	13.4	<.0001
Syst*Trt	5	127.44	25.489	4.05	0.0093
Error b			6.2936		

- Labile P, 2nd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	7.434	3.717	0.79	0.4669
Syst	1	7.896	7.896	1.68	0.209
Error a			4.700		
Trt	5	554.1	110.8	23.51	<.0001
Syst*Trt	5	65.79	13.15	2.79	0.0424
Error b			4.716		

- Labile P, 3rd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	8.3098722	4.1549361	1.97	0.1638
Syst	1	47.2427111	47.2427111	22.36	0.0001
Error a			2.1128225		
Trt	5	314.6853222	62.9370644	29.78	<.0001
Syst*Trt	5	58.3968889	11.6793778	5.53	0.0019
Error b			2.112003219		

A.2 Short Rains Season

- Biomass yields

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.13708	0.0685	0.89	0.4245
Syst	1	1.29201	1.2920	16.8	0.0005
Error a			0.0769		
Trt	5	13.6529	2.7305	35.5	<.0001
Syst*Trt	5	2.48942	0.4978	6.47	0.0008
Error b			0.0769		

- Dry matter yields, 1st sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	1.264	0.6321	0.47	0.6337
Syst	1	42.29	42.293	31.17	<.0001
Error a			1.3568		
Trt	5	236.6	47.324	34.87	<.0001
Syst*Trt	5	19.87	3.9754	2.93	0.0356
Error b			1.3568		

- Dry matter yields, 2nd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	40.631	20.315	1.66	0.2124
Syst	1	540.48	540.48	44.26	<.0001
Error a			12.211		
Trt	5	970.13	194.02	15.89	<.0001
Syst*Trt	5	179.30	35.861	2.94	0.0353
Error b			12.197		

- Relative growth rate, 2nd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.000003	0.0000017	0.11	0.8977
Syst	1	0.000069	0.0000694	4.3	0.05
Error a			1.61488E-05		
Trt	5	0.002152	0.0004304	26.66	<.0001
Syst*Trt	5	0.000202	0.0000405	2.51	0.0608
Error b			1.61394E-05		

- Available P, 1st sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	61.257039	30.628519	3.53	0.0467
Syst	1	284.709378	284.709378	32.84	<.0001
Error a			8.669591291		
Trt	5	1097.04322	219.408644	25.31	<.0001
Syst*Trt	5	276.243522	55.248704	6.37	0.0008
Error b			8.673265934		

- Available P, 2nd second sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	39.763	19.881	4.74	0.0194
Syst	1	16.946	16.946	4.04	0.0569
Error a			4.1947		
Trt	5	572.24	114.44	27.28	<.0001
Syst*Trt	5	65.443	13.088	3.12	0.0281
Error b			4.1950		

- Labile P, 1st sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	23.295	11.647	5.25	0.0137
Syst	1	17.528	17.528	7.9	0.0102
Error a			2.2187		
Trt	5	307.29	61.458	27.71	<.0001
Syst*Trt	5	45.072	9.0145	4.06	0.0092
Error b			2.2203		

- Labile P, 2nd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	4.886	2.4432	2.18	0.1368
Syst	1	23.74	23.749	21.2	0.0001
Error a			1.1202		
Trt	5	105.2	21.047	18.78	<.0001
Syst*Trt	5	16.35	3.2700	2.92	0.0361
Error b			1.1198		

B Muguga

B.1 Long Rains Season

- Maize grain yields

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.8040	0.4020	2.6	0.0965
Syst	1	18.318	18.318	118.69	<.0001
Error a			0.1543		
Trt	5	20.371	4.0742	26.4	<.0001
Syst*Trt	5	3.7589	0.7517	4.87	0.0038
Error b			0.1543		

- Dry matter yields, 1st sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.5868	0.2934	4	0.033
Syst	1	21.114	21.114	287.72	<.0001
Error a			0.0733		
Trt	5	127.65	25.531	347.92	<.0001
Syst*Trt	5	11.162	2.2324	30.42	<.0001
Error b			0.0733		

- Dry matter yields, 2nd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	219.134	109.567	3.83	0.0374
Syst	1	14876.6	14876.6	519.9	<.0001
Error a			28.6145		
Trt	5	42698.5	8539.71	298.44	<.0001
Syst*Trt	5	3650.75	730.151	25.52	<.0001
Error b			28.6109		

- Dry matter yields, 3rd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	15.404	7.70203	0.05	0.9511
Syst	1	12395.	12395.8	80.89	<.0001
Error a			153.243		
Trt	5	37422.968	7484.59	48.84	<.0001
Syst*Trt	5	4693.3050	938.661	6.13	0.0011
Error b			153.125		

- Relative growth rate, 2nd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.000016	0.0000083	2.76	0.0851
Syst	1	0.000186	0.0001867	61.69	<.0001
Error a			3.02772E-06		
Trt	5	0.000234	0.0000468	15.47	<.0001
Syst*Trt	5	0.000086	0.0000172	5.7	0.0016
Error b			3.02456E-06		

- Relative growth rate, 3rd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.0000081	0.000004	1.11	0.3483
Syst	1	0.0002054	0.000205	55.69	<.0001
Error a			3.68899E-06		
Trt	5	0.0006076	0.000121	32.94	<.0001
Syst*Trt	5	0.0001355	0.000027	7.35	0.0003
Error b			3.68844E-06		

- Available P, 1st sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	10.4915	5.2457	2.56	0.1004
Syst	1	426.973	426.97	208.03	<.0001
Error a			2.0524		
Trt	5	564.766	112.95	55.03	<.0001
Syst*Trt	5	195.056	39.011	19.01	<.0001
Error b			2.0521		

- Available P, 2nd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	2.80181	1.4009	0.52	0.5988
Syst	1	107.709	107.70	40.36	<.0001
Error a			2.6687		
Trt	5	235.995	47.199	17.69	<.0001
Syst*Trt	5	35.4172	7.0834	2.65	0.0504
Error b			2.6729		

- Available P, 3rd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.4057	0.2028	0.08	0.924
Syst	1	101.30	101.30	39.6	<.0001
Error a			2.5581		
Trt	5	206.82	41.364	16.17	<.0001
Syst*Trt	5	47.876	9.5752	3.74	0.0133
Error b			2.5602		

- Labile P, 1st sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	4.4760	2.2380	2.5	0.1053
Syst	1	90.979	90.979	101.53	<.0001
Error a			0.8960		
Trt	5	389.98	77.996	87.04	<.0001
Syst*Trt	5	66.619	13.323	14.87	<.0001
Error b			0.8960		

- Labile P, 2nd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	1.70515	0.85257	1.06	0.3622
Syst	1	20.4002	20.4002	25.46	<.0001
Error a			0.80126		
Trt	5	54.7674	10.9534	13.67	<.0001
Syst*Trt	5	39.3624	7.87248	9.82	<.0001
Error b			0.80167		

- Labile P, 3rd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.51703	0.2585	0.22	0.8071
Syst	1	37.1896	37.189	31.14	<.0001
Error a			1.1942		
Trt	5	117.161	23.432	19.62	<.0001
Syst*Trt	5	29.4367	5.8873	4.93	0.0035
Error b			1.1941		

B.2 Short Rains Season

- Maize biomass yields

Source	DF	SS	MS	F Value	Pr > F
Rep	2	1.21541667	0.60770833	2.8	0.0824
Syst	1	26.50533611	26.50533611	122.21	<.0001
Error a					
Trt	5	6.61139167	1.32227833	6.1	0.0011
Syst*Trt	5	4.74974722	0.94994944	4.38	0.0064
Error b					

- Dry matter yields, 1st sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	4.1865	2.09327	2.47	0.108
Syst	1	42.684	42.6844	50.3	<.0001
Error a			0.84859		
Trt	5	92.191	18.4382	21.73	<.0001
Syst*Trt	5	10.983	2.19671	2.59	0.0549
Error b			0.84815		

- Dry matter yields, 2nd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	50.049463	25.024731	0.73	0.4925
Syst	1	776.504667	776.504667	22.7	<.0001
Error a			34.20725405		
Trt	5	1755.58313	351.116626	10.27	<.0001
Syst*Trt	5	506.77087	101.354174	2.96	0.0341
Error b			34.241275		

- Dry matter yields, 3rd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	343.7109	171.8554	1.32	0.2864
Syst	1	5987.406	5987.406	46.14	<.0001
Error a			129.7660		
Trt	5	7411.105	1482.221	11.42	<.0001
Syst*Trt	5	2246.856	449.3712	3.46	0.0185
Error b			129.8760		

- Relative growth rate, 2nd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.00020	0.000102	3.39	0.0519
Syst	1	0.00063	0.000633	21.06	0.0001
Error a			3.00741E-05		
Trt	5	0.00183	0.000366	12.19	<.0001
Syst*Trt	5	0.00019	0.000038	1.3	0.3018
Error b			2.99692E-05		

- Relative growth rate, 3rd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.0000185	0.00000925	1.55	0.2351
Syst	1	0.0000466	0.00004669	7.81	0.0106
Error a			5.97823E-06		
Trt	5	0.0000222	0.00000445	0.74	0.5986
Syst*Trt	5	0.0000078	0.00000156	0.26	0.9294
Error b			0.000006		

- Available P, 1st sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	7.214606	3.607303	1.16	0.3327
Syst	1	296.7006	296.7006	95.2	<.0001
Error a			3.116603		
Trt	5	1070.957	214.1914	68.73	<.0001
Syst*Trt	5	85.85949	17.17189	5.51	0.0019
Error b			3.116496		

- Available P, 2nd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.24900	0.1245	0.02	0.9828
Syst	1	166.926	166.92	23.25	<.0001
Error a			7.1796		
Trt	5	679.644	135.92	18.94	<.0001
Syst*Trt	5	150.708	30.141	4.2	0.0079
Error b			7.1765		

- Available P, 3rd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.67043	0.33521	0.08	0.9257
Syst	1	36.1601	36.1601	8.36	0.0085
Error a			4.32538		
Trt	5	1462.05	292.411	67.63	<.0001
Syst*Trt	5	54.6616	10.9323	2.53	0.0593
Error b			4.32108		

- Labile P, 1st sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	20.495	10.247	8.46	0.0019
Syst	1	46.899	46.899	38.72	<.0001
Error a			1.2112		
Trt	5	286.42	57.284	47.29	<.0001
Syst*Trt	5	22.095	4.4190	3.65	0.0149
Error b			1.2106		

- Labile P, 2nd sampling

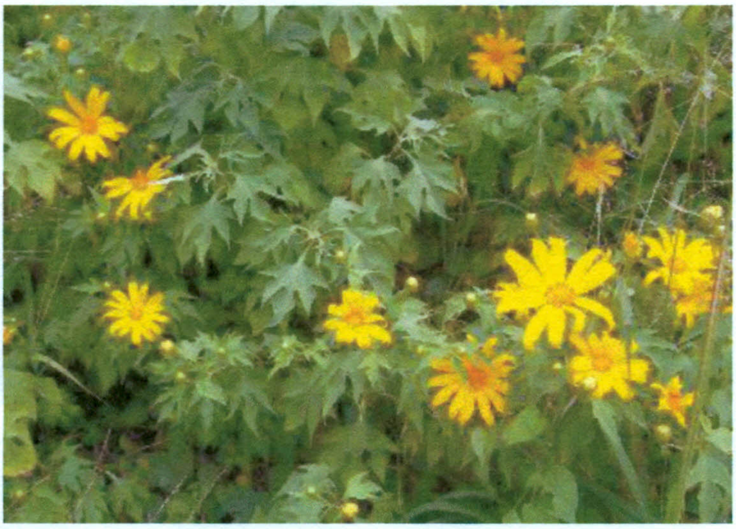
Source	DF	SS	MS	F Value	Pr > F
Rep	2	0.9548	0.4774	0.26	0.7747
Syst	1	2.8392	2.8392	1.54	0.2283
Error a			1.8436		
Trt	5	92.062	18.412	9.96	<.0001
Syst*Trt	5	23.617	4.7234	2.56	0.0573
Error b			1.8450		

- Labile P, 3rd sampling

Source	DF	SS	MS	F Value	Pr > F
Rep	2	3.05802	1.5290	1.05	0.3669
Syst	1	32.3571	32.357	22.21	0.0001
Error a			1.4568		
Trt	5	86.3639	17.272	11.86	<.0001
Syst*Trt	5	19.2437	3.8487	2.64	0.0512
Error b			1.4578		

APPENDIX V

Tithonia diversifolia



Leaves and Flowers of *Tithonia diversifolia*

Seeds of *Tithonia diversifolia*