8-2014

INVESTIGATING THE EFFECT(S) OF CONTRASTING NITROGEN (N), PHOSPHORUS (P), AND POTASSIUM (K) FERTILIZER RATES ON CASSAVA TUBER YIELD AND QUALITY AND MAIZE GRAIN YIELD IN SOUTHERN AFRICA

Ivan Bernardo Cuvaca
University of Tennessee - Knoxville, icuvaca@vols.utk.edu

To the Graduate Council:

I am submitting herewith a thesis written by Ivan Bernardo Cuvaca entitled "INVESTIGATING THE EFFECT(S) OF CONTRASTING NITROGEN (N), PHOSPHORUS (P), AND POTASSIUM (K) FERTILIZER RATES ON CASSAVA TUBER YIELD AND QUALITY AND MAIZE GRAIN YIELD IN SOUTHERN AFRICA." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental and Soil Sciences.

Neal S. Eash, Major Professor

We have read this thesis and recommend its acceptance:

Forbes Walker, Dayton Lambert McGregor, Svetlana Zivanovic

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

INVESTIGATING THE EFFECT(S) OF CONTRASTING NITROGEN (N), PHOSPHORUS (P), AND POTASSIUM (K) FERTILIZER RATES ON CASSAVA TUBER YIELD AND QUALITY AND MAIZE GRAIN YIELD IN SOUTHERN AFRICA

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Ivan Bernardo Cuvaca
August 2014

ACKNOWLEDGEMENT

I would like to express my gratitude to Dr. Neal Samuel Eash for his guidance, patience, encouragement, friendship, and trust, which contributed largely to my success at the University of Tennessee. I would also like to express my sincere appreciation to Dr. Svetlana Zivanovic, Dr. Dayton Lambert, and Dr. Forbes Walker for serving on my graduate committee. My thanks also go to Dr. Philipus Pangoli and Bill Rustrick for their support and the friendly environment created around me throughout my work. I am also thankful to all BESS faculty, staff and graduate students for making my stay at UT enjoyable. My gratitude goes also to the farmers of Milha-14 for their help with harvesting the experiment.

ABSTRACT

Fertilizer is a major limiting factor to agriculture in southern Africa (SA). Coupled with this is lack of appropriate fertilizer recommendation rates for high productivity in existing agricultural systems. Field experiments were conducted to determine nitrogen (N), phosphorus (P), and potassium (K) fertilizer rates for high cassava tuber yield and quality for the coastal semiarid Dondo District of Mozambique, and high maize grain yields for both vertisol and inceptisol of Maphutseng in Lesotho. In general, the results showed that cassava tuber yield, cassava tuber quality as measured by tuber starch content, and maize grain yield were significantly increased by fertilizer addition ($p<0.05$), whereas cassava tuber cyanide (HCN) concentration was not significantly affected by addition of fertilizer ($p>0.05$). The results also showed that maize grain yield was not significantly affected by tillage practices ($p>0.05$). Combined applications of 60 kg N-60 kg P-0 kg K and 60 kg N-90 kg P-150 kg K kg per ha are suggested for high cassava tuber yield, and high cassava tuber starch content for the coastal semiarid Dondo District of Mozambique, respectively. Economically optimum maize grain yields (EOY) and profits (EOP) for the southwest lowlands of Maphutseng village, Mohale's Hoek District, Lesotho, were estimated at 222 kg, 182 kg, and 123 kg of N (applied as limestone ammonium nitrate) per ha for no-till vertisol, no-till inceptisol, and till vertisol maize systems, respectively. The results suggest that an application of 30 kg of P (P_2O_5) per ha is required for high grain yields in inceptisol maize system. The results also confirmed that the benefits of not tilling the soil are not immediate. On the whole, the results suggest that there is potential to increase productivity in existing agricultural systems with the use of fertilizer in both Mozambique and Lesotho. However, this will not be possible without increasing farmers' access to fertilizer given that fertilizer use in both countries is still very low (< 20 kg per ha).

Key words: Southern Africa, cassava, maize, fertilizer, and rates.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Lack of appropriate fertilizer use has resulted in a low productivity of the agricultural systems in sub-Sahara Africa (SSA) and of southern Africa (SA) in particular. Typical yields of major crops such as maize (*Zea mays*) and cassava (*Manihot esculenta* Crantz), do not exceed 1.2 and 10.5 tons per ha in Lesotho (MAFS, 2011) and Mozambique (FAO, 2011), respectively. As a result, most countries in SA are still far from meeting their food needs resulting in SA being among the most vulnerable and food insecure regions in the world.

In SA an increasing population applies continual pressure to grow more food and is causing farmers to intensify their production by shortening fallow periods, putting more land under production, and resorting to inappropriate multiple/mixed cropping and tillage systems, which result in decreased soil fertility due to continuous mining of nutrients (Henao and Baanante, 2006).

At the current conditions, increasing the agricultural productivity is the first step towards meeting the current and growing demand for food. However, this cannot be met without appropriate fertilizer use that utilizes research-based recommendations. Some of the issues associated with fertilizer use in SA include time and rate of fertilizer applied, fertilizer availability, and fertilizer price. Therefore, it makes an interesting case to investigate how incorporating fertilizer into SA agricultural systems could potentially increase both cassava-tuber and maize grain yields in the region.

The purpose of this study is to provide optimum nitrogen (N), phosphorus (P), and potassium (K) fertilizer rates for high cassava tuber yield and quality for the coastal semiarid Dondo District of Mozambique and high maize grain yields for Maphutseng Village of Mohale's Hoek District of Lesotho. The first chapter "Effect of Nitrogen (N), Phosphorus (P), and Potassium (K) Fertilizer Rates on Cassava Tuber Yield in the Coastal Semiarid Dondo District of Mozambique" aims at (1) determining cassava tuber yield response to different N, P and K fertilizer rates; and (2) determining an optimum combination of N-P-K fertilizer rates for high cassava tuber yields at Milha-14 in the coastal semiarid Dondo

Distrit of Mozambique. The second chapter “Cassava Tuber Quality as Influenced by Different Combinations of Contrasting Nitrogen (N), Phosphorus (P), and Potassium (K) Fertilizer Rates” aims at determining (1) a combination of N-P-K fertilizer rates for high cassava tuber starch content, and (2) low cassava tuber cyanide concentration. The last chapter “Effect of Nitrogen (N), Phosphorus (P) and Potassium (K) fertilizer rates, and contrasting soil types and tillage practices on maize grain yield in Lesotho” aims at identifying an optimum combination of N, P and K fertilizer rates and tillage practices for high maize grain yields for both black vertisol and inceptisol of Maphutseng in Lesotho.

CHAPTER I: EFFECT OF NITROGEN (N), PHOSPHORUS (P), AND POTASSIUM (K) FERTILIZER RATES ON CASSAVA TUBER YIELD IN THE COASTAL SEMIARID DONDO DISTRICT OF MOZAMBIQUE

ABSTRACT

Meeting an increasing demand for cassava (*Manihot esculenta* Crantz) in an emerging cassava industrial sector will require availability of basic agronomic information on fertilizer requirement and proper fertilizer recommendations for higher tuber yield and quality. A no-till study involving twenty fertilizer treatments consisting of different combinations of contrasting nitrogen (N), phosphorus (P), and potassium (K) fertilizer rates was initiated in 2013 at Milha-14, Sofala Province, Mozambique (19^{o} 25' 54.0" S, 34^{o} 43' 28.6" E). The objective of the study was to assess cassava yield performance under different soil fertility and smallholder farmer conditions. Cassava tuber yield (fresh) was significantly increased by combined fertilizer application ($p<0.05$). Applying 60 kg of N per ha (fertilizer combination: 60-0-0) yielded less (8.5 tons per ha) compared to the unfertilized control treatment (14.7 tons per ha); however, the combined application of 60 kg of N per ha with 60 kg of P per ha (fertilizer combination: 60-60-0) yielded highest (27.7 tons per ha). Combined application of 60 kg N-60 kg P-0 kg K per ha is therefore suggested for high cassava tuber yield at Milha-14.

INTRODUCTION

Cassava is a perennial, multiuse, subsistence crop originally from Brazil (Hillocks et al., 2002) that is widely grown in the tropics including Africa, Asia and Latin America (FAO, 2013). It is grown for its edible leaves and tubers (Li et al., 2010). Cassava is produced almost exclusively by small-scale, resource-poor farmers (El-Sharkawy, 2004) on nutrient-depleted soils (Mariscal, 1984) either in association with other crops or as a sole crop (El-Sharkawy, 2004). Due to the innate ability of cassava to produce reasonable yields in areas with poor fertility where other crops would not thrive (Fermont et al., 2009), the majority of farmers in Africa do not or under-fertilize cassava (El-Sharkawy, 2004). This practice results in decreasing soil fertility and resulting low tuber yields. Despite falling into the same category of countries that use little or no fertilizer in cassava production, Mozambique produces more cassava than it needs for food (FAO, Food Outlook of November 2011). Cassava alone contributes approximately six percent in the country's gross domestic product (GDP) (FAO-Mozambique, 2010) and 628 kcal per person per day. The latter contribution places Mozambique among the top three countries that most rely on cassava for caloric intake (El-Sharkawy, 2004). In the past, cassava has played an important role in Mozambique's diet (Promar Consulting, 2011). In the 1960s, cassava had a diet share of more than 45 percent but by 2006 (after independence) its diet share decreased to less than 30 percent. Because of this decrease, other products such as maize have an increased market share. Even with its decreased market share, cassava remains one of the main food products in the country (Promar Consulting, 2011). Maize, which had a high diet share in the early 2000s, has decreased from 25 to 20 percent share (Promar Consulting, 2011). This decrease was attributed mainly to lower yields and increased imports of other commodities such as wheat and rice (Promar Consulting, 2011). According to Gwarizimba (2009), about 75.3 percent of the economically active population in Mozambique is engaged in agriculture, and the vast majority are small-scale resource poor farmers who farm on approximately 1.78 ha average. Cassava is

produced throughout the country (Promar Consulting, 2011), and its production is almost entirely for household consumption (Gwarizimba, 2009). Unlike many crops, the cassava cropping season is variable. The growing period and time for harvesting depend greatly upon the type of cassava grown (Promar Consulting, 2011).

Cassava can be harvested almost continuously and in most cases the crop is harvested little by little over months or even years, depending on the farmer or family needs which makes cassava an important niche crop in the overall household food security (Donovan and Tostão, 2010). Cassava is typically planted in November, and harvested between July and October. Maximum cassava yields occur after 10-12 months of a frost free growing season.

Cassava Brown Streak Disease (CBSD) and African Cassava Mosaic Disease (ACMD) are two recent constraints to cassava production (Promar Consulting, 2011). It is estimated that CBSD disease alone, has affected more than 50 percent of the production with more aggravation in the Northern provinces of Nampula and Zambezia. To address this issue, the government of Mozambique has taken positive steps in identifying and promoting disease resistant varieties across the country (Promar Consulting, 2011). Presently, Mozambique is the fifth largest producer of cassava in Africa and second only to Angola in southern Africa (FAO, Food Outlook of November 2011) with an estimated annual national average tuber yield of approximately 6 tons per ha (Dias, 2012; Promar Consulting, 2011). Nonetheless, the current national average yield which is about 40 percent of the continent’s average (10 tons per ha (Mkamilo and Jeremiah, 2005)) fails to meet a growing demand for bioethanol, brewery, and an emerging cassava-based bread industry. According to EC-FAO (2007), there are several factors leading to this failure. Lack of improved cultivars and planting material, low soil fertility, nonexistent fertilizer recommendation rates, lack of appropriate farm tools, inadequate agronomic practices, drought, lack of transport and its prohibitive costs are some examples

that constrain the cassava value chain. Since most soils in Africa lack primary macronutrients (N, P, K, Ca, Mg, S) due to excessive rainfall, erosion, and mining of nutrients through exhausting farming practices (Maria, 2004), it is hypothesized that part of the failure to meet the growing demand for cassava is mainly due to two of the above factors: 1) low levels of soil fertility, and also 2) inexistence of fertilizer recommendation rates.

As several studies have shown, significant increases in cassava yield are possible if an adequate and balanced application of nutrients is undertaken (Howeler, 1981; Howeler and Cadavid, 1990; Malavota et al., 1954; Ezui et al., 2012). This is in agreement with Gomez et al. (1980) and Howeler et al., (2005) who reported cassava response to adequate soil fertility and adequate fertilizer. Kamaraj et al. (2008) also reported cassava response to an increased level of N-P-K fertilizer up to 150 percent over the normal recommended rate of 60-60-160 kg per ha for optimum yields in a study conducted in poor sandy loam and sandy clay loam soils (Typic Ustropepts) of northwestern agro-climatic zone of Tamil Nadu, India. This increased level of fertilizer, 90-90-240 Kg per ha, also yielded more tubers than a relatively higher rate of 120-120-320 kg N-P-K per ha. These studies also suggest that fertilizer recommendation rates for higher cassava tuber yields vary widely depending on the region and agro-ecological conditions as well as the nutritional status of the soil. According to CIAT (1992) at least 100 Kg per ha of N-P_2O_5-K_2O should be applied annually to sustain cassava yields in most tropical K-depleted soils. In soils with very low P, high rates of P level are recommended for one or two consecutive cropping seasons in order to increase the available P in the soil to a level above the critical, which is the point where yield is not limited by nutrient deficiency. Since cassava is highly efficient in P use and has low P uptake per ton, subsequent P applications can be gradually reduced. Howeler and Cadavid (1990) recommended the application of 50-100kg per ha of N per cropping season in soils with low organic matter and available N. Overall the current existing fertilizer application rates from cassava producing countries (South America and Asia), range from 30 to 100 kg of N per ha, 25 to

100 kg of P per ha, and 60 to 100 kg of K per ha (Howeler, 1981). These recommendations corroborate with those of FAO (2013), which range from 50-100 kg N, 10-20 kg P, and 65-80 kg K per ha depending on the nature of the soil and desired yield levels. Although many cassava producing countries still lack fertilizer recommendation rates for cassava production and higher cassava tuber yields, no universal rates can be determined or adopted without supporting research as each production area has soils and an agro-ecology specific to the locality and each variety is adapted to a specific production region or regions (Toro and Atlaa, 1980).

The objective of this study was to determine the optimum combination of N, P, and K fertilizer rates for high cassava tuber yields for Milha-14 site in Mozambique. To investigate the hypothesis afore proposed, a no-till fertilizer study was conducted to investigate how cassava tuber yield is influenced by different combinations of contrasting nitrogen (N), phosphorus (P), and potassium (K) fertilizer rates under smallholder farmer conditions in the coastal semiarid Dondo District of Mozambique.

MATERIALS AND METHODS

The experiment was conducted at Milha-14 (19^{o} 25’ 54.0” S, 34^{o} 43’ 28.6” E), in the coastal semiarid District of Dondo, Province of Sofala, Mozambique, over the 2013/2014 agricultural year. Mozambique is divided into ten agro-ecological regions (AER) (MAF, 1996) based upon climate, soil type, elevation, and farming system (Maria and Yost, 2006). Milha-14 falls within AER R5 (MAF, 1996) and has an altitude that ranges from 0-200 m above sea level, annual average temperature of 24^{o} C, rainfall index ranging from 1,000 to 1,400 mm, and soil texture ranging from sand to sandy loam. The soils at Milha-14 look relatively young, thus suggesting that they may have eroded and re-deposited by water. Field observations suggest that it is likely that the soils at the site (MIlha-14) are inceptisols with a high water table at or near the surface for most of the year which prevents drainage and leads to near continuous waterlogging due partly,

among many possible reasons, to a presence of clay and metal oxides thus suggesting that an aquept is likely the dominant suborder.

The experiment was initiated in March 2013 and comprised twenty treatments consisting of different combinations of contrasting N, P, and K fertilizer rates (Table 1) arranged in a completely randomized design (CRD) with four replicates each. A plot size of 4 m x 4 m was adopted for each fertilizer combination or treatment. Planting was done manually by inserting stem-cuttings into the soil without tilling and hilling in contrast to local practices. The recommended planting distance of 1 m x 1 m was used. A local bitter variety named *Tapioca* was used for its resistance to ACMD. Fertilizer was applied manually. Urea, single super phosphate (SSP), and potassium chloride (KCl) were used as the N, P, and K source, respectively. N, P, and K were applied as basal fertilizer. Plots were weeded manually at the onset of the cropping season. Harvesting was also done by hand late in March 2014, and the harvestable area (net plot) consisted of four plants harvested from two central rows of a four row plot (four plants per row) (16 plants per plot total). The site received a total rainfall of 1831.6 mm which was unevenly distributed throughout the cropping season, 2013/14. As a result, the site remained waterlogged most of the cropping season due mainly to a high water table. Yield data was collected from the harvestable area and statistical analysis were performed using analysis of variance (ANOVA) and means compared at LSD 0.05.

Despite having agro-ecological characteristics that make it an area suitable for cassava production, Milha-14 lacks basic NPK fertilizer recommendations for cassava production and high cassava tuber yield, which is likely due to lack of soil testing facilities and research support. The fertilizer treatments were derived from general NPK fertilizer recommendation rates for cassava production in tropical regions (FAO, 2013; Howeler, 1981). N, P, and K were kept fixed at 60, 60, and 150 kg per ha, respectively. Each nutrient was applied as a single fixed rate (treatments 2 through 4), and/or (2) combined with two single fixed rates at an increasing rate (treatments 5 through 20). Maximum

fertilizer rates were defined based on maximum fertilizer response(s) reported in the literature (Howeler, 1981; Howeler and Cadavid, 1990).

RESULTS AND DISCUSSION

Table 1 shows a summary of average cassava fresh tuber yield response in tons per ha to different combinations of contrasting N, P, and K fertilizer rates at Milha-14 in the coastal semiarid Dondo District, Sofala Province, Mozambique over the 2013/14 cropping season.

Figure 1 shows cassava fresh tuber yield as influenced by different combinations of contrasting N, P, and K fertilizer rates. A significant increase in cassava tuber yield was observed due to fertilizer addition ($p<0.05$). Fertilizer Rates sharing superscripts are not statistically different ($p>0.05$). From the results it is evident that even under no-till systems (FAO, 2013) cassava responds to fertilizer application as was reported in several studies (Agbaje and Akinlosotu, 2004; Malavota et al., 1954; Krochmal and Samuels, 1966; Gomes and Howeler, 1980). A single fixed rate of 60 kg N per ha (60 kg N-0 kg P-0 kg K per ha) yielded lowest (8.5 tons per ha) compared to our unfertilized control treatment (0 kg N-0 kg P-0 kg K per ha) that yielded 14.7 tons per ha. The combined application of 60 kg N per ha with 60 kg P per ha (60 kg N-60 kg P-0 kg K per ha) yielded highest (27.7 tons per ha). This surpassed the yield obtained in the unfertilized control treatment almost twofold, and the national average yield (~6 tons per ha (Dias, 2012)) over fivefold.

It was further observed that, unlike P, increase in N and K rates led to a decrease in the overall cassava tuber yield (Figure 1: 0N trough 180K). These findings are in contrast with those of Malavota et al. (1954) who reported the poorest tuber yields from a study conducted in Campinas, Brazil, when P was omitted, and N response similar to that obtained when P was added, whereas response to K was much less significant.

Table 1. Summary of cassava tuber yield response on fresh weight basis

Treatment ID	Fertilizer Rate N	P	K	Estimated Average Yield in tons per ha	t Grouping
1	0	0	0	14.7	bcd
2	60	0	0	8.5	d
3	0	60	0	16.7	abcd
4	0	0	150	22.9	abc
5	0	60	150	25.5	ab
6	25	60	150	25.9	ab
7	50	60	150	24	abc
8	75	60	150	13.1	cd
9	100	60	150	20.6	abc
10	60	0	150	18.4	cd
11	60	30	150	17.3	cd
12	60	60	150	13.6	cd
13	60	90	150	22.8	abc
14	60	60	0	27.7	a
15	60	60	30	15.8	bcd
16	60	60	60	22.3	abc
17	60	60	90	21.5	abc
18	60	60	120	20.9	abc
19	60	60	150	19.8	abc
20	60	60	180	25.9	ab

Cassava response to P was also reported by Krochmal and Samuels (1966) and Gomes and Howeler (1980) whose findings suggest that application of P leads to increase in tuber yield and stimulates cassava's yield response to both N and K in Brazilian's situation. According to Malavota et al. (1954), this high cassava P response is probably due to phosphorylation of starch reserves necessary for vegetative growth in the early stages of development. On the other hand, this response to P may also reflect, to some extent, the amount of P present in the soils at Milha-14 site (Fermont, 2009) or the stem-cuttings when

they are set out in the field. Howeler and Cadavid (1990) also reported cassava response to P, with its best response found in infertile oxisols with exception of those soils with high mychorrizal population.

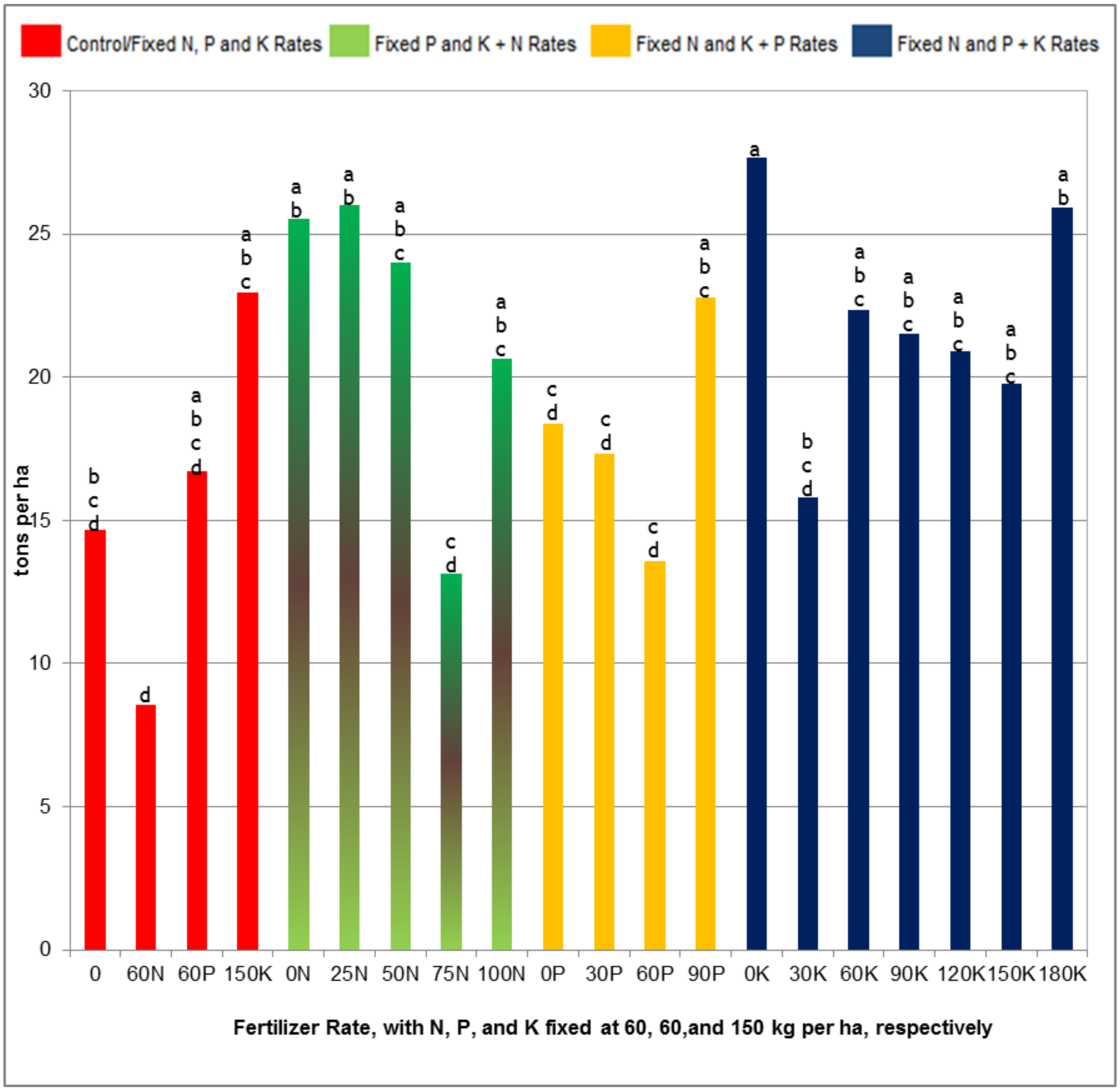


Figure 1. Cassava fresh tuber yield as influenced by different fertilizer rates

Results from this study suggest that, in spite of its role in cassava top growth and tuberisation (Agbaje and Akinlosotu, 2004) K does not seem to be limiting cassava production at Milha-14 (Figure 1). These findings disagree with

those from a study conducted in West Africa by Ezui et al. (2012) where K was found to be the primary cassava tuber yield limiting nutrient with its requirement ranging from 140 to 160 kg per ha (CTCRI, 1983a). Furthermore, we have observed that, unlike N and P, increased K rates resulted in relatively lower tuber yields than that obtained when K was omitted, which agrees with Agbaje and Akinlosotu (2004), that only sufficient K levels are required to stimulate cassava response to other nutrients such as N as their excess may result in more biomass at the expense of tuber production. On the other hand, Howeler and Cadavid (1990) reported significant cassava tuber yield response to K when it was grown continuously in the same field, which suggests that N and P, as well as K play individually an important role in the overall cassava tuber production with its requirements depending more on the agro-ecology of the area where its production is intended, and management practices adopted.

Field observations suggest that several biotic and abiotic factors some of which aforementioned may have contributed to the large variability in the experimental results (Table 1). The high water table and excessive rainfall, lack of land preparation, and planting material are examples of some of these factors, which are briefly discussed as follows.

Over the cropping season, the experimental site (Milha-14) received a total of 1831.6 mm of unevenly distributed rainfall (Figure 2). It was observed that the site was waterlogged most of the cropping season likely due to its shallow water table and the fact that the amount of rainfall received during the study period (1831.6 mm) was approximately 50 percent greater than the average rainfall of that area (1,200 mm annually; MAF, 1996). It is believed that the fact that the site (Milha-14) is located in a coastal area near Beira, which is at or below the average sea level (Kusangaya, n.d.), makes it prone to waterlogging. According to Agbaje (2004), although cassava can thrive in unfavorable conditions, excessive rainfall can affect the lifespan of added fertilizer in the soil, its retention and availability to the crop, and consequently may affect tuber formation and its constituents. Likewise, in studying the influence of nitrogen

fertilizer on sugar-beet (*beta vulgaris* L.) production in a wet year, Moraghan and Horsager (1991) have reported leaching of added N fertilizer followed by N deficiency as a result of excessive rainfall. This soil nutrient deficiency due to excessive rainfall can result in low cassava tuber yield (Duluora, 2012; FAO, 2013) and may also affect its quality.

In contrast to traditional practices, land preparation did not include tilling the plots and hilling - a strategy used to keep the roots above the water table (FAO, 2013). As a result, during harvest which consisted of digging and pulling the tubers out of the ground, traces of charcoal were uncovered in the subsoil. We think it is likely that the site was used for making charcoal - a major source of income for rural communities in Mozambique (Saxena, 2013). Charcoal production has many impacts on the environment (Msuya et al., 2011) including soil compaction due to wood transportation. According to FAO (2013), the risk of waterlogging is very high in shallow and poorly drained and heavily compacted soils especially if the first rains are intense.

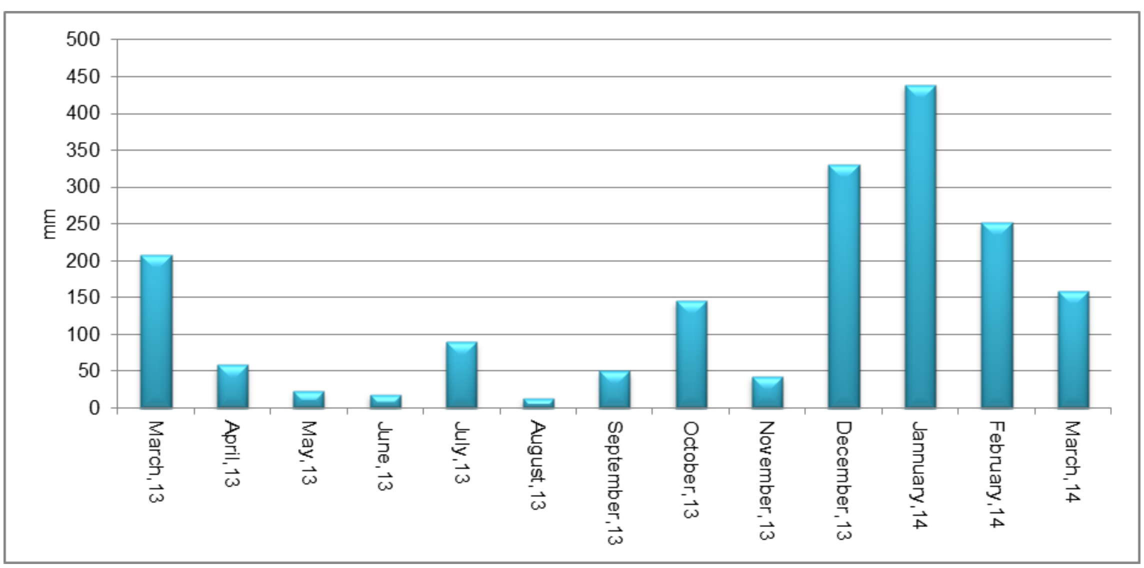


Figure 2. Total monthly rainfall (mm) recorded in 2013/14 cropping season in Dondo

The presence of charcoal in the soil has also been associated with added fertilizer use efficiency. For instance, in studying effects of charcoal as a slow release nutrient carrier on N, P, and K dynamics and soil microbial population, Steiner et al. (2009) observed that less N was leached only when ammonium sulphate was applied in charcoal containing pots whereas P was not leached, but K was leached in charcoal containing pots due to charcoal chemical composition (rich in K). Likewise, Steiner et al. (2008) reported increased retention of applied N fertilizer on a highly weathered Amazonian Ferralsol with organic amendments including charcoal. These findings suggest that once in the field, charcoal adsorption sites can compete with cassava for N and increase available K. Thus, the added fertilizer/nutrient use efficiency and its dynamic in the soil can be affected.

Another important observation was the lack of planting material of quality (i.e. robust, middle brown-skinned portions of the stem, 20-25 cm long with 5-8 nodes (James et al, 2000)). According to the FAO (2013), low quality plant material is one of the major reasons for poor cassava tuber yields in Africa and Latin America. Owing to an increased incidence of ACMD and CBSD in Northern and Central Mozambique (Promar consulting, 2011), successful cassava production in these areas requires that disease free and/or resistant material are used. However, due to limited availability of such material, stem cuttings of poor quality (taken from the top green and bottom portions of the plant) were used so a plant density equivalent to 10,000 plants per ha could be met. According to James et al. (2000) stem cuttings from the bottom and top portions of the plant dehydrate very quickly, are less hardy that are less resistant to pests and diseases, hence they are not suitable for planting and production of high quality tuber(s). Similarly, in relating the growth and productivity of cassava grown from different portions of cassava stem to climate parameters in southeastern Nigeria, Eke-Okoro et al. (1999) reported poor growth and productivity from stem cuttings taken from the top green and bottom portions of the plant. Coupled with site variability, depth to water table, and variability of stem cuttings used for planting

material, tree stumps have impacted the overall yield response to added fertilizer and led to a large variability in the data (Appendix I).

CONCLUSIONS AND RECOMMENDATIONS

Cassava tuber yield was significantly influenced by fertilizer addition. Combined application of 60 kg N-60 kg P-0 kg K per ha is suggested for high cassava tuber yields at Milha-14 in the short term. However, taking into consideration the fact that cassava tubers remove relatively larger amounts of K than those of N and P, further research is needed to verify if this fertilizer combination (rates) can sustain high tuber yields in the long term. The combined applications of 60 kg N-0 kg P-0 kg K per ha, 75 kg N-60 kg P-150 kg K per ha, and 60 kg N-60 kg P-150 kg K per ha yielded less compared to unfertilized control treatment. Results from this study show clearly that there is potential to increase cassava tuber yields towards meeting the growing demand for bioethanol, brewery and an emerging cassava-bread industry with the use of fertilizer.

CHAPTER II: CASSAVA TUBER QUALITY AS INFLUENCED BY DIFFERENT COMBINATIONS OF CONTRASTING NITROGEN (N), PHOSPHORUS (P), AND POTASSIUM (K) FERTILIZER RATES

ABSTRACT

Cassava (Manihot esculenta Crantz) is an important subsistence crop for many rural poor families in Africa. Cassava contains cyanogenic glucosides (linamarin and lotaustralin) which liberate cyanide (HCN) during tuber processing. Once liberated, the HCN attaches to the processed tuber. Consumption of processed tuber containing high HCN concentration coupled with low protein intake can cause Konzo – a paralytic disorder that impacts children and women of child bearing age. Blanching and fermentation are two common methods to reduce HCN concentration during tuber processing. Both of these methods result in high starch losses, and therefore may lead to an underestimation of not only the actual cassava starch content (CSC) but the actual HCN concentration present in the tubers as well. It is also unclear what the relationship is between fertilizer rates, tuber starch content and tuber HCN concentration. To address this issue, a study consisting of twenty treatments of different combinations of contrasting nitrogen (N), phosphorus (P), and potassium (K) fertilizer rates was initiated in 2013 at Milha-14, Dondo District, Mozambique. The treatments were laid out in a completely randomized design (CRD) with four replicates. The plots were established using no-till where the planting material was just inserted into the soil without hilling in contrast to local practice. Cassava quality was assessed by measuring both starch content and HCN concentration present in unprocessed tubers. CSC was estimated using a quick commercial cassava starch estimation procedure based on specific gravity (SG). The SG was determined by measuring the decreased peeled tuber weight when submerged in water in contrast to mass weight in air. Estimates from three equations used in this quick commercial CSC estimation procedure were assessed using the Megazyme total starch procedure as a base to verify whether the equations could be used as an alternative means to estimate CSC in remote areas that lack lab facilities. HCN concentration was determined using the alkaline picrate method. CSC estimated using the three equations used in the quick commercial CSC estimation procedure did not differ statistically. However,

significant differences were observed between CSC due to fertilizer addition (combined fertilizer), sample size (CSC estimates from 3 kg vs 5 kg samples), and procedure used (CSC determined from Megazyme Total Starch procedure vs CSC estimates from 3 kg and 5 kg samples using the quick commercial estimation procedure). No statistical differences were detected between cassava-tuber HCN's concentration due to fertilizer rates. This suggests: a) the equations used in the quick commercial CSC estimation procedures can be used interchangeably; b) CSC is or can be influenced by addition of fertilizer; c) sample size can lead to an over or underestimation of CSC based on SG; d) 5 kg sample size and quick commercial CSC estimation procedures can further underestimate the actual CSC compared to 3 kg sample size; and e) the concentration of HCN present in the tubers is not influenced by fertilizer addition. It is hypothesized that the cassava-tuber HCN concentration is more related to the physiology of the crop itself rather than the environment or conditions under which the crop is grown.

INTRODUCTION

Cassava is a perennial tuber crop that originated in South America (Hillocks et al., 2002). Cassava is a major staple and source of calorie (Rosethal, 2012) to more than half a billion people in Africa, Asia, and Latin America (FAO, 2013). Its introduction in Africa dates back to the 1550s and today Africa is the foremost cassava producing region with over half of the global production with Nigeria being the world's largest producer (FAO, 2013). Cassava was introduced in Mozambique in the 1750s (Benesi, 2005). Today Mozambique is the fifth largest producer of cassava in Africa and second only to Angola in Southern Africa with an estimated average annual yield of ~6 tons per ha (Dias, 2012). Cassava production is mostly confined to poor soils and small scale resource poor farmers (El-Sharkawy, 2004) who own on average less than 4 hectares (Gwarizimba, 2009). Cassava is a major food crop, and is the second most important crop in Mozambique after maize (DNC of MIC, 2004). According to Gwarizimba (2009), cassava contributes 6 percent in the country's GDP and 45 percent of the diet, with approximately 628 kcal per person a day (Promar Consulting, 2011).

Despite being ranked one of the largest producers of cassava in Africa (FAO, 2011), cassava production in Mozambique can be severely limited due to two main virus diseases: African Cassava Mosaic Disease (ACMD) and Cassava Brown Streak Disease (ACBSD) (Hillocks et al., 2010). CBSD is largely confined to coastal regions of eastern and southern Africa (Hillocks, 2010), and its recent proliferation has caused yield losses up to 50 percent in Northern provinces of Nampula and Zambezia, Mozambique (Promar Consulting, 2011) where most of the production is concentrated (Hillocks et al., 2002).

Traditionally, cassava is grown in low input systems and nutrient poor soils either in association with other crops (such as maize and pigeon-pea (*Cajanus cajan*) (Hillocks et al, 2002)) or as a sole crop, without any addition of fertilizer (El-Sharkawy, 2004) which leads to continuous mining of nutrients and subsequent soil degradation. Cassava contains two cyanogenic glucosides

(linamarin and lotaustralin) that liberate HCN upon tissue disruption (Magnuson, 1997). Their presence in the plant (tuber) has been associated with the poor conditions under which the crop is grown, with drought being one of the few parameters that has been investigated (de Bruijn, 1973; Nwosu and Onofeghara, 1991). Cassava HCN protects the plant against animal and insect predation, and is also an important element in defining tuber quality and use. Based solely on the content of HCN cassava varieties are either bitter (high HCN) or sweet (low HCN). Bitter varieties are mainly used in nonfood industry whereas sweet varieties are mainly used for food. Despite its sweetness, sweet varieties can still be as dangerous to humans if poorly processed tubers are used for human consumption (Braidotti, 2011). According to Speijers (n.d.) and Braidotti (2011), continuous consumption of poorly processed cassava (tuber) products coupled with low protein intake will result in Konzo – a chronic dietary disease caused by high cassava HCN that impacts mainly young women and children in poor cassava-producing countries in eastern Africa (Braidotti, 2011). Blanching or washing and fermentation (Nambisan, 2011) are two common methods used to lower cassava HCN (Lambri et al, 2013). Although these methods are very common and well diffused among cassava producing countries, the growing number of Konzo victims in eastern Africa raises questions on their effectiveness in lowering the tuber HCN concentration to or below the level the human body can tolerate (10 mg per kg (Magnuson,1997)). Associated with this is the impact these methods have on cassava starch content (CSC) which is another important element in defining cassava tuber quality. Cassava starch can be lost to the water during the processing; however, the losses can be minimized by harvesting the starch retained in the water used in the lowering of the HCN. To avoid underestimation of the actual CSC in the tubers, a real time on-field method called the underwater weight method (ISI, 199) was developed and made available for use in cassava-starch commercialization. However, to date, there is very little literature on studies undertaken to assess the relationship between cassava starch and HCN and fertilizer rates. Thus, it is hypothesized that nutrient

depleted soils and smallholder farmers' inability to replenish soil nutrients with mineral fertilizer are also associated with the concentration of HCN and starch present in the tubers. To investigate the proposed hypothesis, a no-till fertilizer study was initiated in 2013 to determine nitrogen (N), phosphorous (P), and potassium (K) fertilizer rates for optimum cassava quality (low tuber HCN and high starch) for the coastal semiarid Dondo District of Mozambique. An underwater weight (ISI, 1999) and alkaline picrate (Sarkiyayi and Argar, 2010) methods were used for estimating the actual CSC (%) and HCN, respectively.

MATERIALS AND METHODS

The experiment was conducted at Milha-14 (19^{o} 25' 54.0" S, 34^{o} 43' 28.6" E), in the coastal semiarid Dondo District, Sofala Province, Mozambique, over the 2013/14 agricultural year. Mozambique is divided in ten provinces and an equal number of agro-ecological regions (MAF, 1996) identified based on climate, soil type, elevation, and farming system (Maria and Yost, 2006). Milha-14 falls within the agro-ecological region R5 (MAF, 1996). R5 has low altitude ranging from 0-200 m above sea level, annual average temperature of 24^{o}C, rainfall index ranging from 1,000 to 1,400 mm, and soils ranging from sand to sandy loam. The soils at Milha-14 look relatively young, thus suggesting that they may have eroded and re-deposited by water. Field observations suggest that it is likely that the soils at the site (MIlha-14) are inceptisols with a high water table at or near the surface for most of the year which prevents drainage and leads to near continuous waterlogging due, partly, among many possible reasons to a presence of clay particles and metal oxides which suggests that an aquept is likely the dominant suborder.

Twenty fertilizer treatments consisting of different combinations of contrasting doses of N, P, and K (Table 2) were laid out in a completely randomized design (CRD) with four replicates each. A bitter cassava variety, *Tapioca*, was manually planted on no-tilled plots at a row by plant spacing of 1m

by 1 m (~10,000 plants per ha) to investigate the effect of added N, P, and K fertilizer on both cassava HCN and CSC present in the tubers. Planting and fertilizer application were done manually using urea as the N source, single super phosphate (SSP) as the P source, and potassium chloride (KCl) as the K source. N, P, and K were applied as basal fertilizer. Manual weeding was completed at the onset of the cropping season. Plants were harvested manually and the harvestable area (net plot) consisted of four plants harvested from two central rows of a four row plot with four plants each (16 plants per plot total).

Cassava starch content (CSC) of fresh tubers was determined using a method known as the underwater weight method (ISI, 1999), used in cassava commercialization to estimate both the content of starch present in the tubers and its respective price. CSC was estimated on a dry weight basis (DWB) by determining root (or tuber) specific gravity (SG). The middle portion of the tuber(s) was selected, and SG was determined from tuber samples of approximately 3 kg or 3 kg and 5 kg depending on the below ground fresh tuber weight harvested in each plot by measuring the weight lost by peeled tubers submerged in water. CSC was estimated using three cassava starch estimation equations (EE) used for estimating CSC in cassava commercialization which are presented below, and their estimates were compared among themselves, and then assessed by comparison with the starch content obtained from a parallel analysis ran on a portion of eight samples randomly picked from each plot. The parallel analysis consisted of an enzymatic procedure known as Megazyme Total Starch procedure which has its basis on the AOAC Method 996.11 and AACC Method 76.13 with improvements (MII, 2011).

I. CSC (%) = (SG – 1.00906)/0.004845 (Sungzikaw, 2008)

II. CSC (%) = (SG - 1.01506)/0.0046051 (ISI, 1999)

III. CSC (%) = (210.8 * SG) – 213.4 (Kanthavong et al., 2012)

To determine HCN content, the samples were peeled, cleaned, chopped into 3-mm slices, air/sundried first, and then brought to a constant weight with an oven (at 75^{o} C for 72 hours). Following this, the samples were ground into flour, and 5 g of each were drawn for analyses. The concentration of HCN present in the tubers was estimated using a standard agronomic procedure for estimating cyanide by reaction with alkaline picrate (described by Sarkiyayi and Argar, 2010). Cassava HCN concentration present in the extract was determined by measuring absorbance using a spectrophotometer at 490 nm.

Starch and cyanide data were analyzed using SAS 9.3, Cary NC. Statistical analysis was performed using analysis of variance (ANOVA) and means compared at LSD 0.05.

RESULTS AND DISCUSSION

A summary of the results of both CSC and HCN concentration (on dry weight basis) analysis is presented in Table 2. The results of the two quality parameters analyzed in this study which consists of (1) the percent estimate of the content of starch (CSC%) and (2) the concentration of HCN (g per 100 g) present in the tubers as presented in Table 2 show that CSC estimates from underwater weight method differed significantly due to fertilizer addition. Addition of 60 kg N per ha-90 kg P per ha-150 kg K per ha (treatment 13) yielded the highest CSC (55.7 percent) whereas addition of 60 kg N per ha-0 kg P per ha-0 kg K per ha (treatment 2) yielded the lowest CSC (23.8 percent).

Overall, a decreasing CSC (%) trend was observed with increasing addition of N (treatments 5 through 9) and K (treatments 14 through 20), and an increasing trend with increased addition of P (treatments 10 through 13). According to Gardner et al (1985), the above ground plant weight is directly related to N. Therefore, excess N or adding N alone can favor more biomass production at the expense of tuber as added N may promote vegetative growth while simultaneously limiting carbohydrate storage in the tuber.

Table 2. Summary of both CSC (%) and HCN analysis (results reported in dry weight basis)

Fertilizer Combination (kg per ha)			Treatment ID	3 kg Sample			5 kg Sample			Megazyme Total Starch Procedure	HCN mg per 100g
N	P	K		EE I	EE II	EE III	EE I	EE II	EE III		
0	0	0	1	60.7	62.6	61.3	49.9	51.3	50.4	72.5	76.3
60	0	0	2	62.6	64.6	63.3	-	-	-	71.9	56.8
0	60	0	3	63.9	65.7	64.6	49.1	50.4	49.5	72.2	46
0	0	150	4	54.4	55.9	54.9	44.5	45.6	44.8	73.4	95.2
0	60	150	5	59.2	60.9	59.8	49	50.3	49.4	70.8	70.7
25	60	150	6	63.5	65.5	64.1	48.8	50	49.1	-	74
50	60	150	7	47.7	48.8	47.9	42.5	41.8	42.7	-	71.2
75	60	150	8	57.5	59.2	59.2	44.2	45.2	39.9	-	64.7
100	60	150	9	52.1	53.6	52.6	45.7	46.8	45.1	-	67.9
60	0	150	10	58.9	60.7	59.5	48.2	49.4	48.9	-	63.9
60	30	150	11	62.8	64.7	63.4	48.1	49.3	48.4	-	72.3
60	60	150	12	59.5	61.3	60.1	-	-	-	73.9	62.4
60	90	150	13	61.4	63.3	62.6	48.6	49.8	49.5	-	76.3
60	60	0	14	57.3	58.9	57.8	36.8	37.4	32.9	-	70.2
60	60	30	15	63.1	65.1	63.8	49.8	51.1	49.4	-	50.7
60	60	60	16	59.6	61.4	60.2	49.9	51.3	50.4	72.7	56.8
60	60	90	17	63.8	65.9	64.5	50.4	51.8	50.8	-	62.7
60	60	120	18	56.9	58.6	57.4	53.4	54.8	53.8	-	53.3
60	60	150	19	60.8	62.7	61.4	49.1	50.4	49.5	76.8	57.4
60	60	180	20	53.1	54.6	53.6	44.1	45.1	44.3	-	62.5

EEI: Estimation Equation I: CSC = (SG - 1.00906)/0.004845 (Sungzikaw, 2008) LSD = 42.1

EE II: Estimation Equation II: CSC = (SG - 1.01506)/0.0046051 (ISI, 1999)

EE III: Estimation Equation III: CSC = 210.8*SG - 213.4 (Khanthavong et al., 2012)

Figures 3 and 4 show that CSC (%) estimates from the three estimation equations (I, II, and III) adopted in underwater weight method did not differ significantly within each sample size (3 kg and 5 kg sample). CSC (%) estimates ranged from approximately 47 percent to slightly above 66 percent for 3 kg sample, and approximately 40 percent to slightly above 50 percent for 5 kg sample. However, significant differences were detected between CSC (%) estimates of the two sample sizes (3 kg and 5 kg sample, Figure 5). These differences in CSC (%) estimates due to sample size disagree with the findings of Sungzikaw (2008) who did no detect any significant difference in CSC (%) estimates by changing the size of cassava tuber samples from 1 kg to 3 kg, and 5 kg.

Figure 6 shows a comparison between CSC (%) estimates obtained from equations I, II, and III which are used in underwater method (for both sample sizes: 3 kg and 5 kg samples) and Megazyme total starch procedure. It was observed that Megazyme total starch procedure had relatively higher CSC (%) than all equations estimates for both sample sizes: 3 kg and 5 kg. This suggests that the estimation equations I, II, and III underestimate the actual CSC (%) when compared to the Megazyme total starch procedure. The results also show that the actual CSC (%) estimates using estimation equations I, II and III can be underestimated even further if a 5kg sample is used in place of a 3 kg sample.

Figure 7 shows cassava HCN concentration as influenced by different combinations of contrasting N, P, and K fertilizer rates, with Cassava HCN concentration ranging from 46.0 mg (treatment 3: 0 kg N per ha-60 kg P per ha-0 kg K per ha) to 95.2 mg (treatment 4: 0 kg N per ha-0 kg P per ha-150 kg K per ha) per 100 g (Table 2). It was observed that the HCN concentration present in the tubers was not significantly changed by fertilizer addition ($p>0.05$). In contrast, in studying factors influencing cyanogenesis, de Bruijn (1973) found that cassava HCN concentration present in the tubers increased with N, decreased with K, and did not change with P. Likewise, CARDI (1992) reported higher cassava tuber HCN concentration and bitterness due to increased N

addition as compared to addition of K. It is likely that no significant changes in the HCN concentration present in the tubers were detected with added NPK rates due to the large variability in the data (LSD = 42.11, Table 2) which is believed to have occured due to several biotic and abiotic factors that that could not be controlled including: (1) a predominantly high water table throughout the cropping season (cassava is very susceptible to waterlogging (FAO, 2013)), and (2) lack of disease free material of good quality (chapter 1).

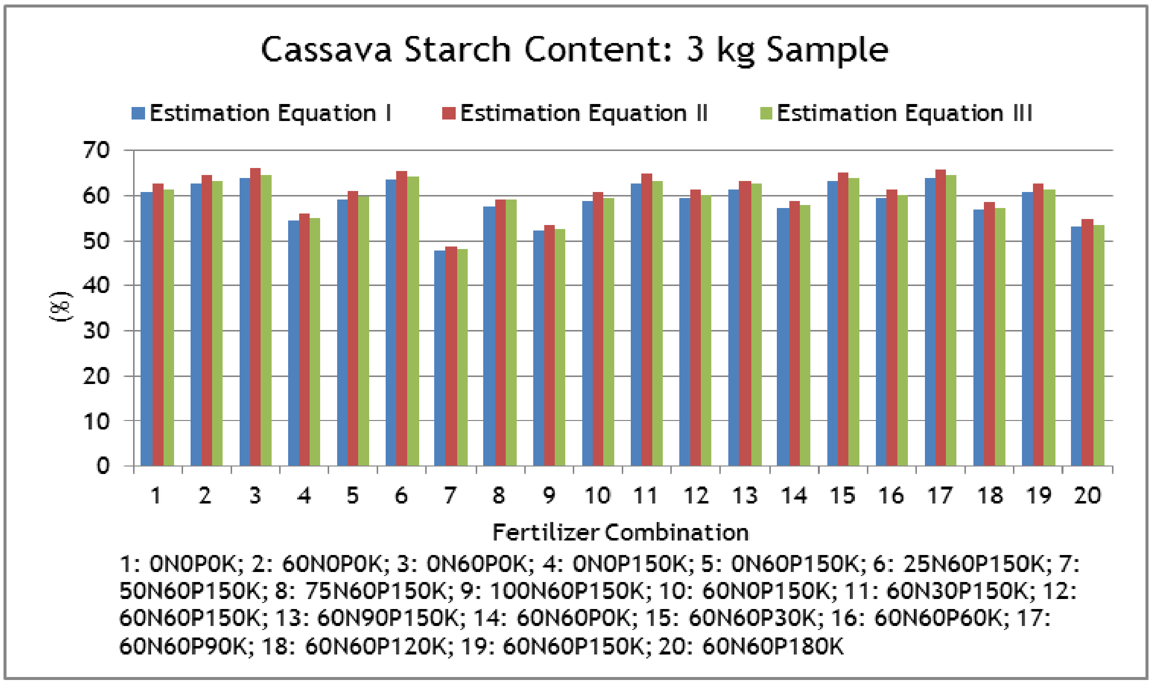


Figure 3. Cassava starch content estimation (dry weight basis) from 3 kg sample

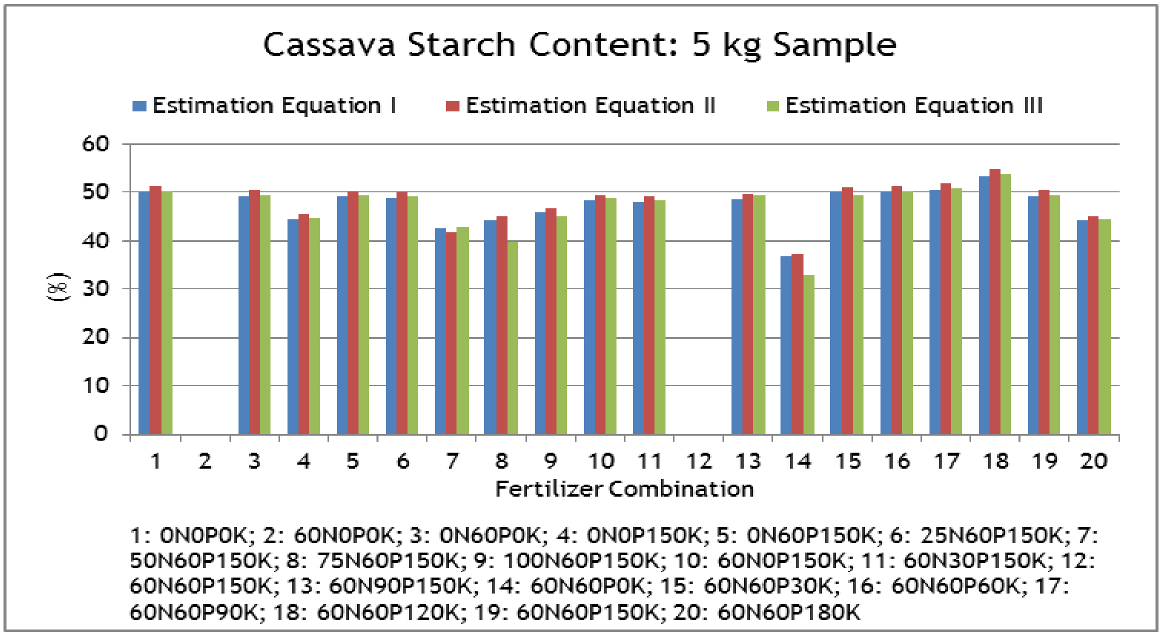


Figure 4. Cassava starch content estimation (dry weight basis) from 5 kg sample

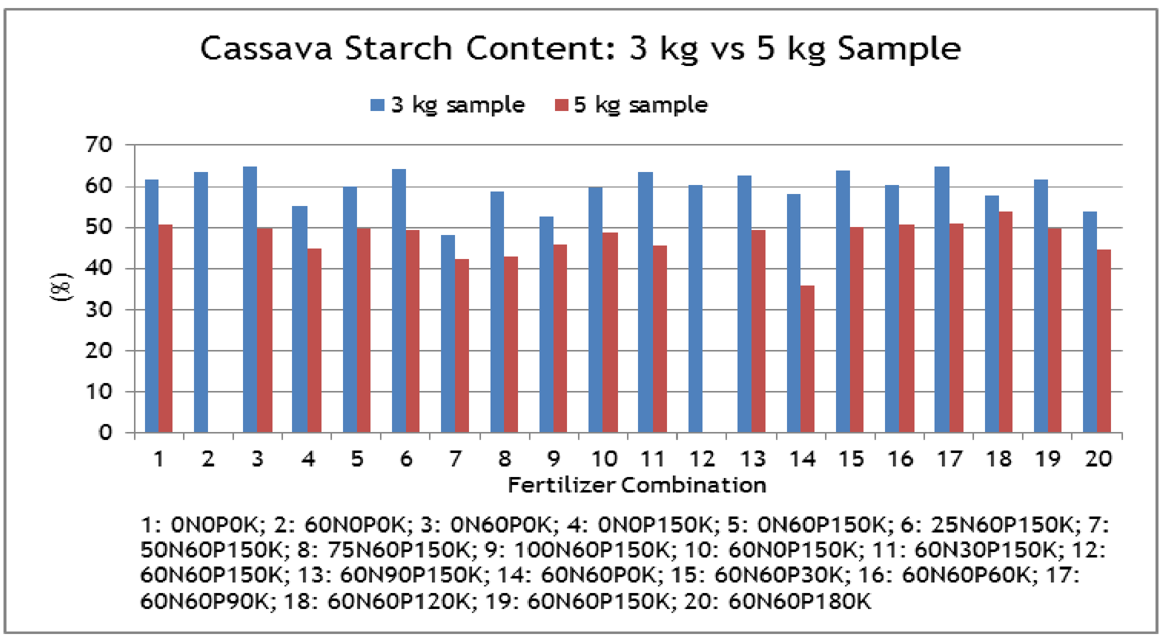


Figure 5. Cassava starch content estimations (dry weight basis) from contrasting sample sizes

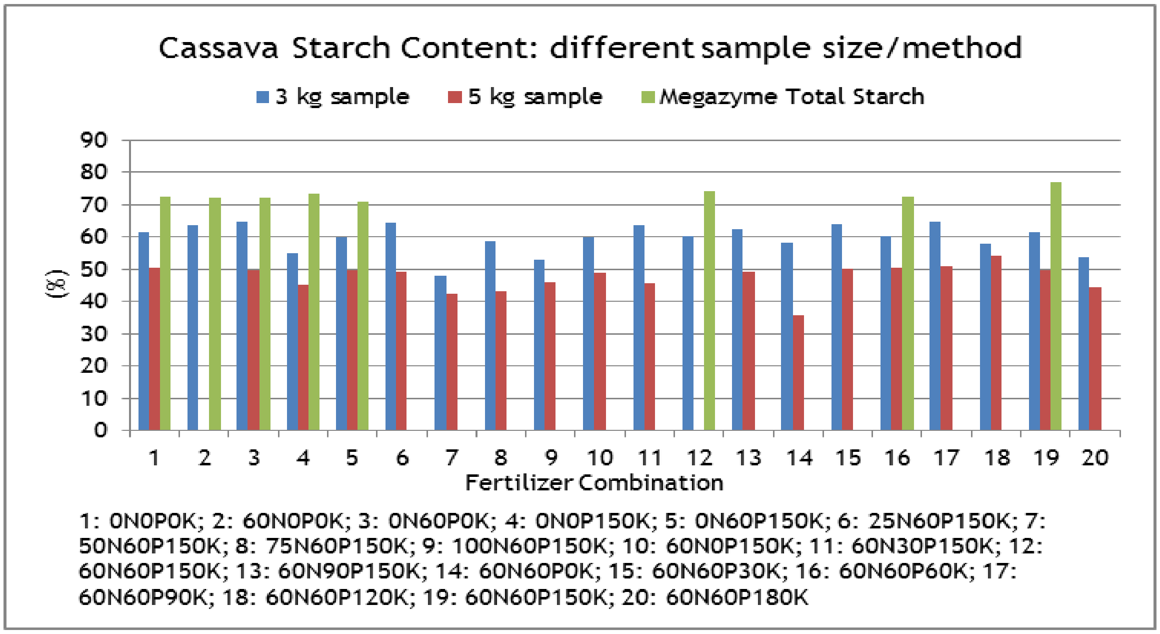


Figure 6. Cassava starch content estimations (dry weight basis) from contrasting sample sizes and procedures

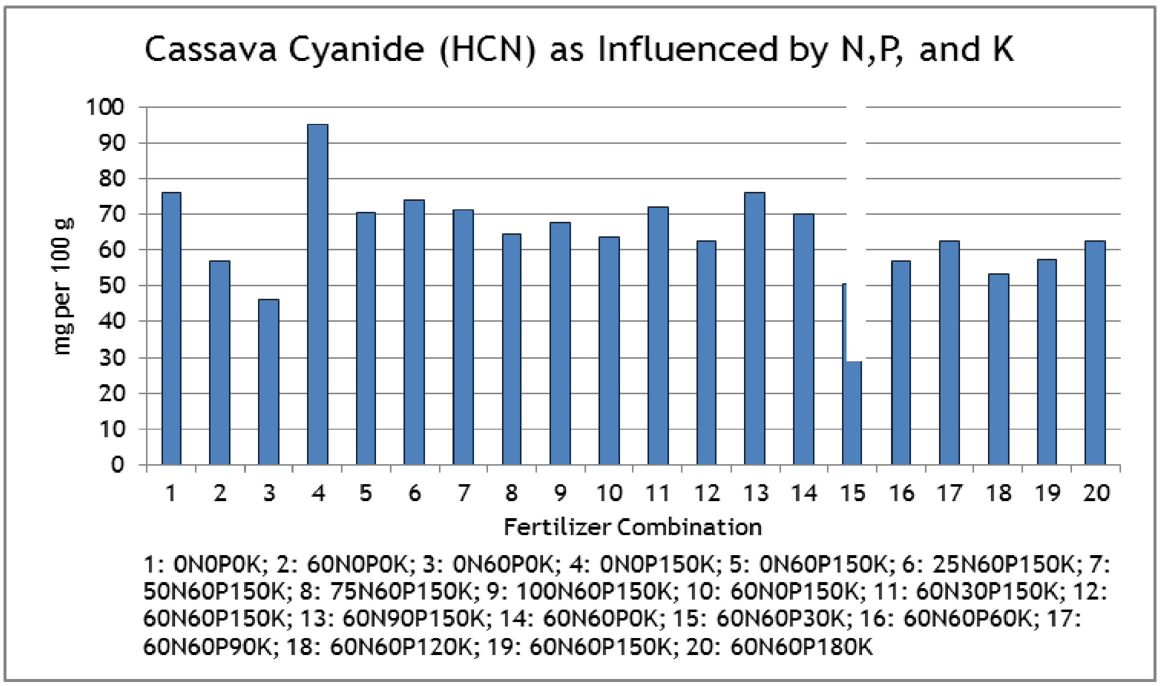


Figure 7. Cassava HCN concentration on dry weight basis as influenced by different combinations of contrasting N, P, and K fertilizer rates

Field observations suggest that several biotic and abiotic factors may have contributed to the lack of clarity or significance in the CSC and tuber HCN response to added fertilizer (Table 2). Due to lack of disease free planting material, stem cuttings taken from the top green and bottom portions of the plant were used so that a plant density equivalent to 10,000 plants per ha could be met. As several studies observed, stem cuttings taken from other portions of the plant than the central part dehydrate very quickly, give less vibrant shoots, and are less resistant to pests and diseases. And as a result, their growth and productivity are poor (James et al., 2000; Eke-Okoro et al., 1999; FAO, 2013) and so is the quality of the tuber. Excessive and sporadic rainfall impacted our results and resulted in substantial waterlogging. During the study period, the site received a total rainfall of 1,831.6 mm which is approximately 50% above its typical average (1,000-1,400 mm). Rainfall distribution was very uneven with more rainfall concentrated during the first two to three months after planting and again at the end of the study period. This coupled with a very shallow water table and a soil texture with low nutrient retention capacity (sand to sandy loam) resulted in leaching of added nutrients from the soil due to seasonal waterlogging. Additionally, in contrast to local practices, land preparation did not include tilling the plots and hilling prior to planting. As a result, the belowground part of the plant or tubers stayed very close to the water table most of the cropping season resulting in inefficient fertilizer/nutrient use by the crop and limited tuber growth and development.

Another factor that contributed to the lack of clarity in the CSC and tuber HCN response to added fertilizer is the fact that there were very limited options in terms of experimental sites which led to no observation of some important criteria for site selection. As a result, upon harvesting it was realized that the site has been used for charcoal production in the past. As several studies have shown, charcoal can impact nutrient availability in the soil (Steiner et al., 2008; Steiner et al., 2009) resulting in low quality tubers.

Site variability, depth to water table, and variability of stem cuttings used for planting material all impacted the overall CSC and tuber HCN response to added fertilizer (see Chapter 1 and/or Appendix II).

CONCLUSIONS AND RECOMMENDATIONS

From the quality parameters analysis and their respective results, CSC estimation is influenced by addition of fertilizer, sample size, and method or estimation procedure. Addition of 60 kg N per ha-90 kg P per ha-150 kg K per ha (treatment 13) and 60 kg N per ha-0 kg P per ha-0 kg K per ha (treatment 2) yielded the highest and the lowest CSC, respectively. CSC estimated using estimation equations I, II, and III did not differ significantly; however, all equations (I, II, and III) underestimated the actual CSC compared to the Megazyme total starch procedure. On the other hand, it was observed that all these equations (I, II, and III) may provide CSC estimates that approximate that obtained from Megazyme total starch procedure if a sample size of 3 kg is used instead of that of 5 kg. Furthermore, cassava HCN has been found not to affected or influenced by fertilizer addition. This suggests that cassava HCN is more related to the type of cultivar (bitter or sweet variety) and physiology of the crop itself rather than the nutrient poor conditions under which the crop is grown. Therefore it is recommend that low HCN cassava varieties should be developed and the methods used in lowering cassava HCN should be used more efficiently for minimizing the risks of human exposure to cassava HCN. It is also clear from this data that the Correlation Equations (I, II, and III) used in quick commercial CSC estimation deserve further review. Fertilizer combination 60 kg N per ha-90 kg P per ha-150 kg K per ha is, therefore, the suggested for high starch production at Milha-14.

CHAPTER III: EFFECT OF NITROGEN (N), PHOSPHOROUS (P), AND POTASSIUM (K) FERTILIZER RATES, AND CONTRASTING SOIL TYPES AND TILLAGE PRACTICES ON MAIZE GRAIN YIELD IN LESOTHO

ABSTRACT

Lesotho routinely faces chronic food shortages due in part to a decreased soil fertility and dearth of sustainable farming practices. Lesotho is the only country in southern Africa reported to have produced less food in 2009 as compared to 2008 with a 54 percent decrease in food production over the last decade. To address this issue, field studies were conducted over the 2012/2013 agricultural year to investigate the effect of different Nitrogen (N), Phosphorus (P), and Potassium (K) fertilizer rates, contrasting soil types and tillage practices on maize (*Zea mays*) grain yield in Mohale's Hoek District, Maphutseng. Results show that the vertisol and inceptisol of Maphutseng respond to N fertilizer with very low P and no K response. The results also suggest that an application of 30 kg of P (P_2O_5) per ha is required for high grain yields in inceptisol maize system, and confirm that the benefits of not tilling the soil are not immediate. Economically optimum nitrogen rate (EONR) was estimated for both soil types and tillage practices assuming typical corn and fertilizer prices as of 2012/2013 cropping season. N was applied as limestone ammonium nitrate (LAN). The EONRs were estimated at 222 kg of N per ha with a predicted maize grain yield of 8.17 tons per ha for no-till vertisol maize system, 182 kg of N per ha with a predicted maize grain yield of 4.92 tons per ha for no-till inceptisol maize system, and 123 kg of N per ha with a predicted maize grain yield of 7.47 tons per ha for till vertisol maize system. However, if other production factors were assumed constant, farmers in Lesotho (a country where access to fertilizer is still very low with an average fertilizer use < 20 kg per ha) would need to significantly increase their fertilizer rates to meet their food needs.

INTRODUCTION

The Kingdom of Lesotho is a low income, food deficit country with about 86 percent of its resident population living on subsistence farming (FAO, 2013). Presently less than a quarter of the country's total food demand is produced internally and as a result the Basotho depend on food assistance and rely on imports, mainly from South Africa to meet their food needs (CIA, 2013). Maize (*Zea mays*) is a major food crop (FAO, 2010) and forms an important part of the Basotho diet, making up about 54 percent of their average daily calorie intake. Nevertheless, maize imports have increased considerably in recent years with an approximate 11 percent increase reported from 2011 to 2013 marketing year (FAO, 2013).

Maize is still widely grown throughout the country and occupies about 60 per cent of the total crop land, but the major producing areas are the fertile lowlands that cover the western parts of the country (FAO, 2010). Maize is mainly grown for subsistence by small scale resource poor farmers with the use of simple technologies and tools such as a hand hoe. Maize is planted between late November and early December at the onset of the rains and harvested sometime between the first and second quarter of the following year (MAFS and MFDP, 2011).

The major factors limiting food production and maize production in particular are land degradation and erratic rainfall. The latter has also been reported in neighboring countries in southern Africa, with excessive and heavier rains becoming even more frequent in recent years (MAFS and MFDP, 2011), a trend some attributed to climate change. Heavy and excessive rains contribute to surface soil erosion, a decline in soil fertility, and consequently low agricultural yields. According to the Ministry of Agriculture and Food Security (MAFS) and Ministry of Finance and Development Planning (MFDP) of Lesotho, the total arable land decreased approximately 20.1 percent from 1999/2000 to 2009/2010 due mainly to an increased frequency of heavy rains coupled with a very fragmented soil cover and an aggressive collection of wood for home stove use.

From 1999-2009 the overall maize production decreased approximately 54 percent (FAO, 2013).

The Government of Lesotho has taken positive steps in designing and implementing policies to address extreme food insecurity by improving farmers' access to fertilizer and seed. However, maize yields are still very low and typically do not exceed 1 ton per ha (~10 to 20 percent of typical yields across the border in South Africa). These yields are also attributed to poor weed, pest and nutrient management practices, low plant population, inefficient fertilizer and water use, continuous maize-monocropping, and intensive tillage. Conversely, despite the prevailing low yields, the "Agricultural Situation Report of Lesotho 2010-2011" pointed out that the country has experienced an increase of 46.3 percent in maize production in 2009/2010. This increase was attributed mainly to an increase in land area planted to maize from 137,585 ha in 2001/2002 to 151,717 ha in equal period, 2009/2010 (MAFS and MFDP, 2011). This increase in arable land area coupled with combined interventions from the government of Lesotho, donor agencies and NGOs helped support smallholder farmers by increasing agriculture productivity and ensuring food security through provision of seed voucher and subsidies for agricultural inputs (FANRPAN, 2009). Despite the increased maize production, the overall economic performance of Lesotho's agricultural sector has witnessed a decreasing trend over the last decade. Agricultural sector's gross domestic product moved from 11.2 percent in year 2000 to 7.8 percent in year 2009, with horticulture witnessing the greatest decrease from 4.7 percent to 1.8 percent (MAFS and MFDP, 2011).

This study came about as an initiative led by the Government of Lesotho and The University of Tennessee with funding from USAID (SANREM CRSP) to investigate strategies that could be used to sustainably increase maize yields in Lesotho. The study examined the effect of different nitrogen (N), phosphorus (P) and potassium (K) fertilizer rates, and contrasting soil types and tillage practices on maize grain yield over 2012/2013 cropping season.

The component residues play an important role in Basotho's culture and have a high economic value. Residues are widely used for construction, grazing and other purposes (FAO, 2010) thus leaving most farmland soils completely exposed. As Derpsch et al. (2006) pointed out, residues also serve as storage of nutrients in tropical regions due to the low cation exchange capacity of tropical soils, and thus residues could be used to increase the efficiency of mineral fertilizers. Thierfelder et al. (2012) reported significant yield benefits from a combination of reduced tillage, permanent soil cover, crop rotation plus fertilizer over conventional tillage. The study was conducted for 7 cropping seasons. Initially, significant differences were hard to detect, but they became more evident after an average of a 4 year period. These results suggest that there is a higher buildup of organic matter over time and more nutrients are made available to plants and fertilization rates can be reduced whereas under conventional tillage there is a need to continuously apply fertilizer for maintaining the sustainability of the system. In another study, an assessment of the merits of the long-term rain-fed maize-legume cropping systems under conservation agriculture in Mozambique, Dias and Nyagumbo (2012) reported significant yield benefits from incorporating fertilizer together with cover crop, residues, and reduced tillage into maize production in their first year of study. This suggests that if a high management level and the key components towards sustainability are integrated, the benefits of this combination of different components can be immediate.

Bloem et al. (2009) collected data from various farmer demonstration plots at Belvedere, Dumbarton and Lusikisiki in South Africa. The analysis showed that incorporation of other components into maize production by either planting maize after or in combination with a legume resulted in fodder and grain yield benefits as applying high N fertilizer rates (54 kg at planting and 54 kg N as top dressing per ha). Benefits of incorporating these practices into maize production were also reported in Zimbabwe. Mapfumo et al. (2001) obtained a 22 percent increase in maize yield from a field where pigeon-pea (*Cajanus cajan*) was previously

cultivated. These increases in yield registered in Zimbabwe and South-Africa also show that there is potential to increase the agricultural productivity of the old and degraded soils of Lesotho. This can be achieved through implementation of combined approaches without discarding the use of legumes which can sometimes help address low soil fertility issues and provide smallholder farmers an alternative to the currently unaffordable synthetic fertilizers. The findings above are consistent with the FAO's (2010) research's findings in Lesotho, according to which highly significant advantages were obtained from incorporating a reduced tillage practice consisting of a planting basins system, locally known as the Likoti-system, along with the components fertilizer and crop residues into maize production. Among others, the advantages were (1) improved input use efficiency and (2) increased agricultural productivity and (3) output stability. The same study also pointed that tilling the soil causes severe stress to the soil and decreases its productivity, thus increasing farmers' dependence on fertilizer inputs which could be decreased over time if reduced tillage practices were adopted. Despite its very well-known advantages (FAO, 2010), digging planting basins is not an easy task especially if the soil is heavily compacted. Investigating the effect of contrasting soil types, alternative tillage systems and fertilization rates in Lesotho is therefore important to improve the current maize yields and reduce Lesotho's dependence on imports of such a major staple.

MATERIALS AND METHODS

Field experiments were conducted in the southwest lowlands of Mohale's Hoek District (latitude: 30^{o}8'60S and longitude: 27^{o}28'0E), Maphutseng, to assess the effect of different N, P and K fertilizer rates on maize grain yield under rain fed conditions. The experimental site is located at an elevation of 1553 meters above sea level, and receives an average low and high annual temperature of 8.9^{o}C and 22.8^{o}C, respectively, and rainfall of 811 mm (MAFS and MFDP, 2011). The experiments consisted of N, P, and K studies, and were

conducted on two contrasting soil types, namely vertisol and inceptisol. The former one belongs to the soil series Phechela, taxonomic classification Typic Pelluderts (Phechela fine montmorillonite mesic typic Pelluderts), and the later to the soil series Matela, taxonomic classification Dystic Eutrochrepts. Each soil type was planted to maize as sole crop. Planting was completed under different tillage systems (till and no-till) in combination with different N, P, and K fertilizer rates. Limestone ammonium nitrate (LAN) was used as N source, P_2O_5 as P source, and KCl as K source.

Agronomic information for each experiment or study and fertilizer rates are presented in Table 3. Fertilizer was broadcast over the row immediately following planting and the treatments were laid out in randomized complete block design (RCBD) with four replicates each. Each plot had 5 rows of maize and was seeded at a rate to provide a plant density of 44,444 plants per ha at a row by plant spacing of 90 cm by 25 cm.

After reaching physiological maturity, maize was allowed to dry for approximately 3 to 4 weeks and then grain yield was determined by manually harvesting the three center plot rows at the end of the cropping season and then converted to the equivalent yield per hectare. Statistical analyses of maize grain yield were performed using SAS mixed model procedures (SAS Ins., 1999). Means were compared using LSD and differences with probabilities less than P = 0.05 were considered as significant.

Economically optimum analysis (EOA): Economically optimum nitrogen rate(s) (EONR) - the point where maximum crop yield response is achieved with the minimum N fertilizer application (Sawyer et a., 2006) – was(were) estimated with SAS by fitting a response/regression model using crop yield as the response variable (Y), and fertilizer rate as the predictor variable (N). Three response models (quadratic, quadratic-plateau, and square root) were fit to the data (Appendix III) for each N-study (Table 4).

The quadratic model is defined by Equation IV:

$$Yj\ (N) = \beta_0 + \beta_1 N + \beta_2 N^2$$

where Yj is maize grain yield in tons per ha for a given treatment (fertilizer rate) within j study, and N is the rate of N-fertilizer applied as LAN in kg per ha. The coefficients β_0, β_1, and β_2 are the intercept, linear, and quadratic coefficients, respectively.

The quadratic-plateau model is defined by Equation V:

$$Yj\ (N) = \begin{cases} \beta_0 + \beta_1 N_1 + \beta_2 N_1^2, & N_1 < N_0 \\ \beta_0 + \beta_1 N_0 + \beta_2 N_0^2, & N_1 \geq N_0 \end{cases}$$

where Yj is maize grain yield in tons per ha for a given treatment (fertilizer rate) within j study, and N is the rate of N-fertilizer applied as LAN in kg per ha. The coefficients β_0, β_1, and β_2 are the intercept, linear, and quadratic coefficients, respectively, and N_0 is the critical rate of N fertilizer in kg per ha applied as LAN which occurs at the intersection of the quadratic response and plateau lines.

The square-root model is defined by Equation VI:

$$Yj\ (N) = \beta_0 + \beta_1 N + \beta_2 N^{1/2}$$

where Yj is maize grain yield in tons per ha for a given treatment (fertilizer rate) within j study, and N is the rate of N-fertilizer applied as LAN in kg per ha. The coefficients β_0, β_1, and β_2 are the intercept, linear, and quadratic coefficients, respectively.

After fitting the models to the data, the residual R-Square (RRS) was estimated for each model by study and the best fit was determined by choosing the model with the highest RRS (Table 4).

Table 3. Agronomic data for N, P and K studies in Maphutseng, Mohale's Hoek, Lesotho, 2012/13 cropping season

Experimental Studies	Source	Fertilizer rates (kg ha^{-1})	Dates		
			Planting	Fertilizer application	Harvesting
N	LAN	0, 50, 100, 150, 200	11/30/12	12/04/12	7/1/13
P	SSP	0, 30, 60, 90, 120	11/30/12	12/04/12	7/2/13
K	KCl	0, 20, 40, 60, 80	11/30/12	12/04/12	7/2/13

RESULTS AND DISCUSSION

Yield response: Maize grain yields in N study were affected by both soil type and N (LAN) fertilizer rates. In vertisol, grain yields ranged from 4.6 to 8.2 tons per ha while in inceptisol grain yields were relatively lower ranging from approximately 1.0 to 5.4 tons per ha (Figures 8.1 and 8.2). These results indicated that the yields did not increase significantly as N fertilizer rates were increased from 50 to 100 and 150 to 200 kg per ha in either soil types (Figures 8.1, 8.2, and 8.3). Thus suggesting that high maize grain yields could be maintained without any yield penalty by reducing N fertilization rates from 200 to 150 kg per ha in both soil types (vertisol and inceptisol). This 25 percent reduction translates to spend approximately less $25 on fertilizer assuming that a 50 kg bag of LAN costs 270 Maloti and $1 = 10.93 Maloti), and an opportunity to improve N use efficiency and cause less potential damage to the environment. The results of this study also showed that when fertilizer was omitted, the yields in inceptisol were slightly less than a quarter of those of vertisol, thus suggesting that the former is deprived of nutrients and may fail to sustain food production in the medium to long term (Figure 8.1 vs 8.2).

Grain yields did not differ siginificantly as N fertilization rate was increased from 0 to 50 kg per ha in no-till vertisol (Figure 8.1) compared to no-till inceptisol (Figure 8.2) and till vertisol (Figure 8.3). However, the highest grain yield

increases were observed in no-till inceptisol, with an increase in yield estimated at 1.8 (>150%) and 2.1 (>50%) tons per ha as N fertilization rates were increased from 0 to 50 and 100 to 150 kg per ha (Figure 8.3), respectively, thus suggesting that the red soil is more responsive to N fertilizer.

In the P study, maize grain yields were affected by both soil type and fertilizer rates, with soil type having a more significant impact. The results showed that vertisol had relatively higher grain yields as compared to inceptisol (Figures 9.1 and 9.2). These results indicated that applying 30, 60, 90 and 120 kg of P_2O_5 per ha did not significantly increase maize grain yields in vertisol as compared to not applying or applying zero kg of P_2O_5 per ha. Whereas in inceptisol, maize grain yields increased over 25 percent by applying 30 kg of P_2O_5 per ha as compared to not applying or applying zero kg of P_2O_5 per ha, and then the yield leveled off as the 30 kg rate was increased by 100, 150 and 200 percent. This result could be explained by a relatively higher content of organic matter present in vertisol. According to Abunyewa (2004), this unpronounced response to P (P_2O_5) fertilization could also be due to several other factors including high P sorption capacity, soil moisture conditions, and slow P release in vertisols. The results of the study suggest that P is not a limiting nutrient to maize grain production in vertisol at Maphusteng but it may limit maize grain production in inceptisol.

Unlike what was observed in N and P studies, no response to K (K_2O) was observed in the K study. Maize grain yields were only affected by soil type ($p<0.05$). However, a similar trend in yield was observed across both soil types (Figures 9.5 and 9.6). This suggests that applying K fertilizer has no effect on maize grain yields in both vertisol and inceptisol of Maputseng. However, soil type may affect yield to a certain extent, and more studies need to be conducted to verify whether K should be incorporated into the local fertilizer recommendation for maize or not.

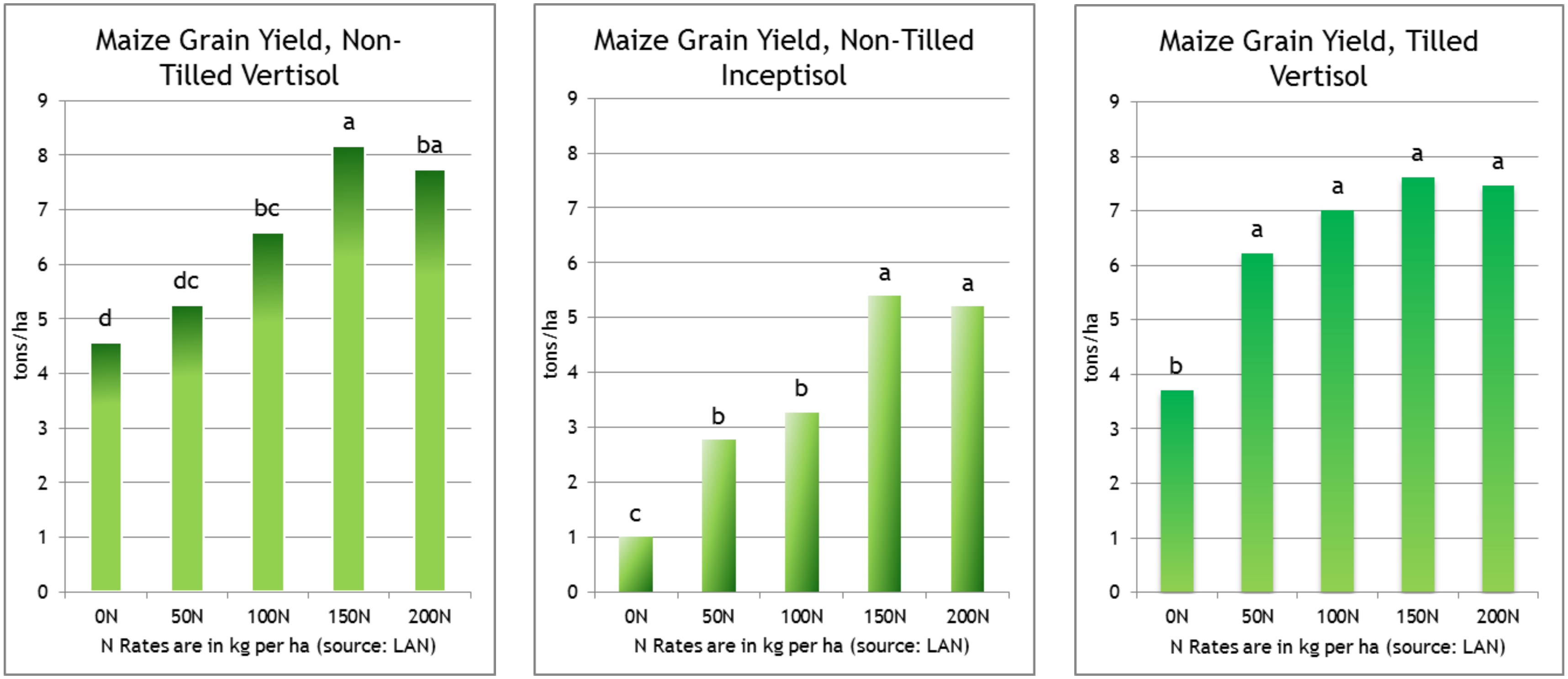
Overall, vertisol had relatively higher yields than inceptisol. This was observed across all N, P, and K studies (Figures 8.1-8.3, and 9.1-9.4). The yields

in vertisol ranged from approximately 4.5 tons per ha to slightly greater than 8.5 tons per ha, whereas in incetisol, the yields ranged from 1.0 ton per ha to approximately 6.5 tons per ha. Part of this can be attributed to the degree of weathering of these soils. Unlike vertisols, inceptisols are rather old and nutrient-poor and as a result inceptisols cannot sustain high crop yields unless their poor fertility and acidity are corrected (FAO, 2010). This agrees with the present experimental results. Taking the N study for instance, a side by side comparison between Figures 8.1 and 8.2 indicates that it took a rate of 150 kg of N applied per ha of inceptisol to get almost the same yield benefits as that obtained at an N application rate of 50 kg per ha of vertisol. Moreover, it was observed that significantly higher yield benefits were obtained at relatively higher N fertilizer rates (Figures 8.1 and 8.2) and this was somehow affected by the tillage component. For instance, a side by side comparison between Figures 8.1 and 8.3 indicates that it took double of the amount of N fertilizer applied under tilled plots of vertisol (50 kg per ha) to get the same or approximately the same yield benefits under non-tilled plots of the same soil type (100 kg per ha). According to Derpsch et al. (2006), tilling the soil may benefit the crop in the short-term; however, it leads to a decline in soil fertility in the long term, which is due to soil erosion, loss of soil organic matter, leaching of soil nutrients and deprivation of soil physical properties.

Despite the very well-known negative impacts of tillage on soil physical, chemical and biological properties in the long-term, some of which aforementioned, the yield benefits of no-till over tillage practices were not clearly evident in this study. However, this can be attributed to time. As Thierfelder et al. (2012) have highlighted, it takes at least 4 to 5 years before yield benefits of incorporating no-till or reduced tillage practices along with permanent soil cover and crop rotation into maize production become evident. Therefore, the benefits of incorporating one or just a portion of these components per se, e.g. no-till, would take even much longer to be seen. This agrees with Thierfelder and Wall

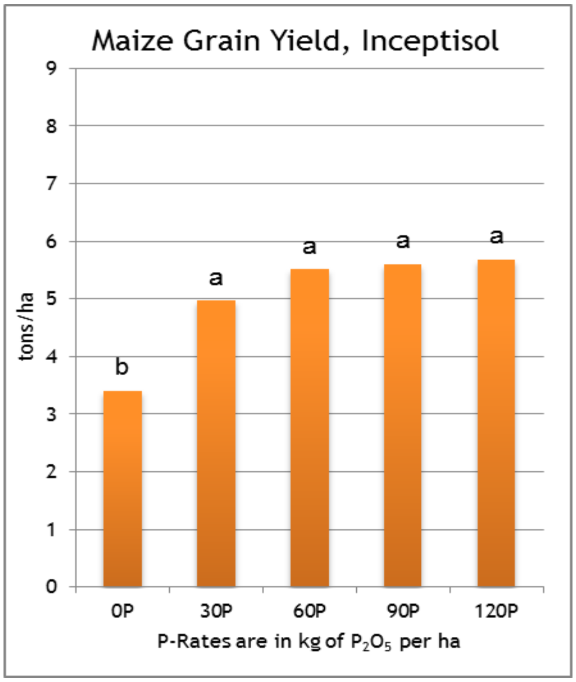
(2012) who observed that significant benefits in maize yield cannot be expected immediately if soil moisture is not a major limiting factor.

Similar to what was observed in the P study (vertisol, Figure 9.2), no response to K fertilization was observed in both soil types (vertisol and inceptisol, Figures 9.3 and 9.4, respectively). This suggests that like P in vertisol, K is not a limiting or a major limiting nutrient to maize production in both vertisol and inceptisol of Maphutseng, Lesotho. This is in agreement with the type of parent material of most soils in the lowlands and Senqu valley of Lesotho. According to Schmitz and Rooyani (1987), most of these soils are derived from the basaltic rocks, which upon weathering release the feldspars - with potassium-feldspar being the major component - thus serving as a major source of K. However, although both P and K may not be limiting in these soils (vertisol, and vertisol and inceptisol, respectively), their application is required to maintain soil fertility and high maize grain yields in the long term.

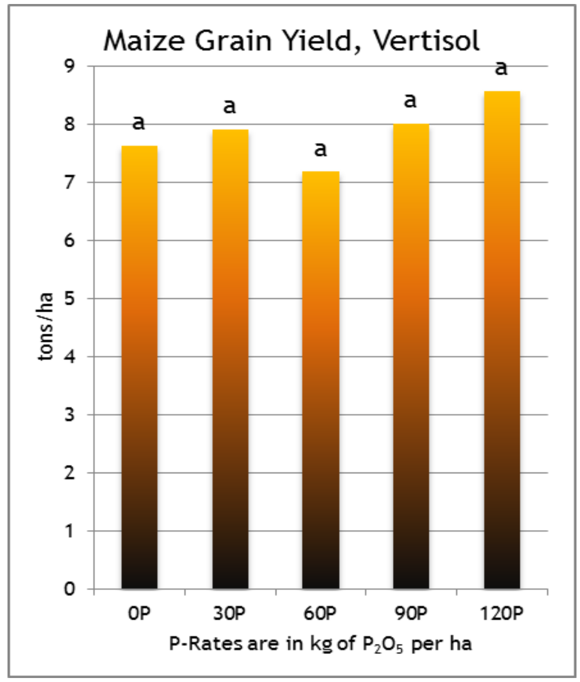


(8.1) (8.2) (8.3)

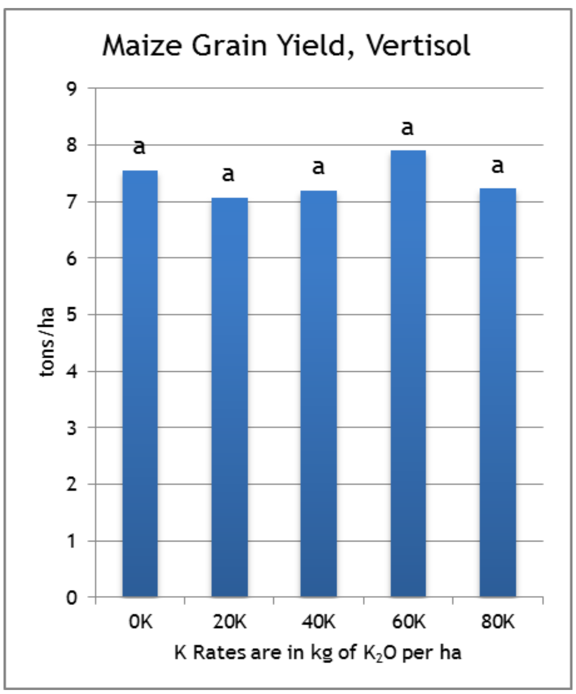
Figure 8. Maize grain yield response to various N fertilizer rates, soil type and tillage systems in southern lowlands of Mohale's Hoek District, Lesotho



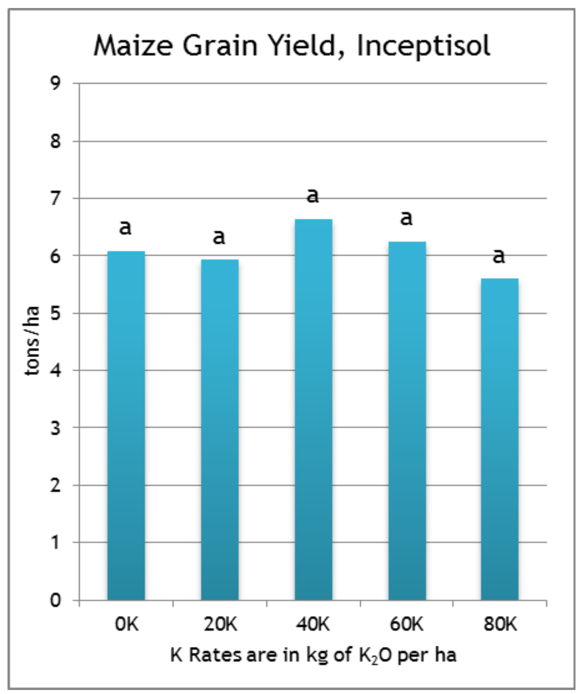
(9.1)



(9.2)



(9.3)



(9.4)

Figure 9. Maize grain yield response to various P and K fertilizer rates, soil type, and tillage system in southern lowlands of Mohale's Hoek District, Lesotho

Economically optimum: Table 4. shows a summary of the economically optimum analysis (EOA). Of the three models (quadratic, quadratic-plateau, and square root) fitted to the data, only the quadratic and quadratic-plateau were used to estimate both the biologically optimum (BO) and economically optimum (EO) nitrogen fertilizer rates, yields and profits for N studies. The models were chosen based on their R^2 values. Models with the highest R^2 values represented the best fit to the data. N studies 1: No-Till + Vertisol and 2: NoTill + Inceptisol used the quadratic model (R^2 = 0.71), and N study 3: Till + Vertisol used the quadratic-plateau model (R^2 = 0.70). BONR, BOY, and BOP ranged from 134 to 264 kg per ha, 4.98 to 8.28 tons per ha, and $1,477.00 to $2,598.00, respectively, whereas EONR, EOY, and EOP ranged from 123 to 222 kg per ha, 4.92 to 8.17 tons per ha, and $1,499.00 to $2,636.00, respectively.

Average BONR and EONR for all studies were 202 and 175.7 kg per ha, respectively. Unlike the average BONR, the average EONR for all studies was about 24.3 kg of N per ha less than the highest N fertilizer rate tested (applied) in the field (200 kg per ha) which translates to a loss of approximately 12.15 percent of the 200 kg of N fertilizer applied as LAN per ha to the environment. The lowest EONR was found in N-study 3 (Till + Vertisol) with 123 kg of N per ha, while the highest EONR was found in N-study 1 (No-Till + Vertisol) with 222 kg of N per ha. The latter also had the highest EOP with $2,636.00. N-study 2 (No-Till + Inceptisol) and 3 (Till + Vertisol) had EOP's of $1,499.00 and $2,551.00, respectively (Table 4). N-study 2 (No-Till + Inceptisol) had relatively higher EONR than N-study 1 (No-Till + Vertisol) but lower EOY (Figure 11) and consequently lower EOP (Figure 12). This suggests that the relationship between maize grain yield and N fertilization is not linear.

Figure 10 shows the relationship between EONR and its respective predicted yield or yield at EONR for each N study (1, 2, and 3). From this scatter plots, it is clear that unlike N-study 2 (No-Till + Inceptisol) and 3 (Till + Vertisol), N-study 1 (No-Till + Vertisol) has an EONR estimate which is beyond the highest N fertilizer rate (200 kg per ha) tested applied (tested) in the field. It is also clear that the type of

relationship between EONR and the expected yield at a given EONR in N-study 3 (Till + Vertisol) follows the typical maize yield response to N curve.

Table 4. Summary of economically optimum analysis

	N-Study		
	1: NoTill+Vertisol	2: NoTill+Inceptisol	3: Till+Vertisol
Model*	Quadratic	Quadratic	Quadratic-Plateau
R^2	0.71	0.71	0.70
β_0	4.32950	0.95400	3.77038
(t value)	*8.68*	*4.33*	*7.4*
β_1	0.02988	0.03872	0.05554
(t value)	*2.94*	*3.90*	*3.50*
β_2	-0.00006	-0.00009	-0.00021
(t value)	*-1.34*	*-1.73*	*-1.92*
Biological Optimum			
N in kg per ha	**264**	**208**	**134**
(t value)	*2.35*	*2.93*	*3.81*
Yield in tons per ha	**8.28**	**4.98**	**7.49**
(t value)	*10.56*	*7.32*	*18.34*
Profit in USD	**2,598.00**	**1,477.00**	**2,541.00**
(t value)	*20.88*	*8.89*	*22.44*
Economically Optimal			
N in kg per ha	**222**	**182**	**123**
(t value)	*2.73*	*3.23*	*4.15*
Yield in tons per ha	**8.17**	**4.92**	**7.47**
(t value)	*11.39*	*7.49*	*18.64*
Profit in USD	**2,636.00**	**1,499.00**	**2,551.00**
(t value)	*18.89*	*8.80*	*22.28*

*****Response/regression model that best fits the data for each study

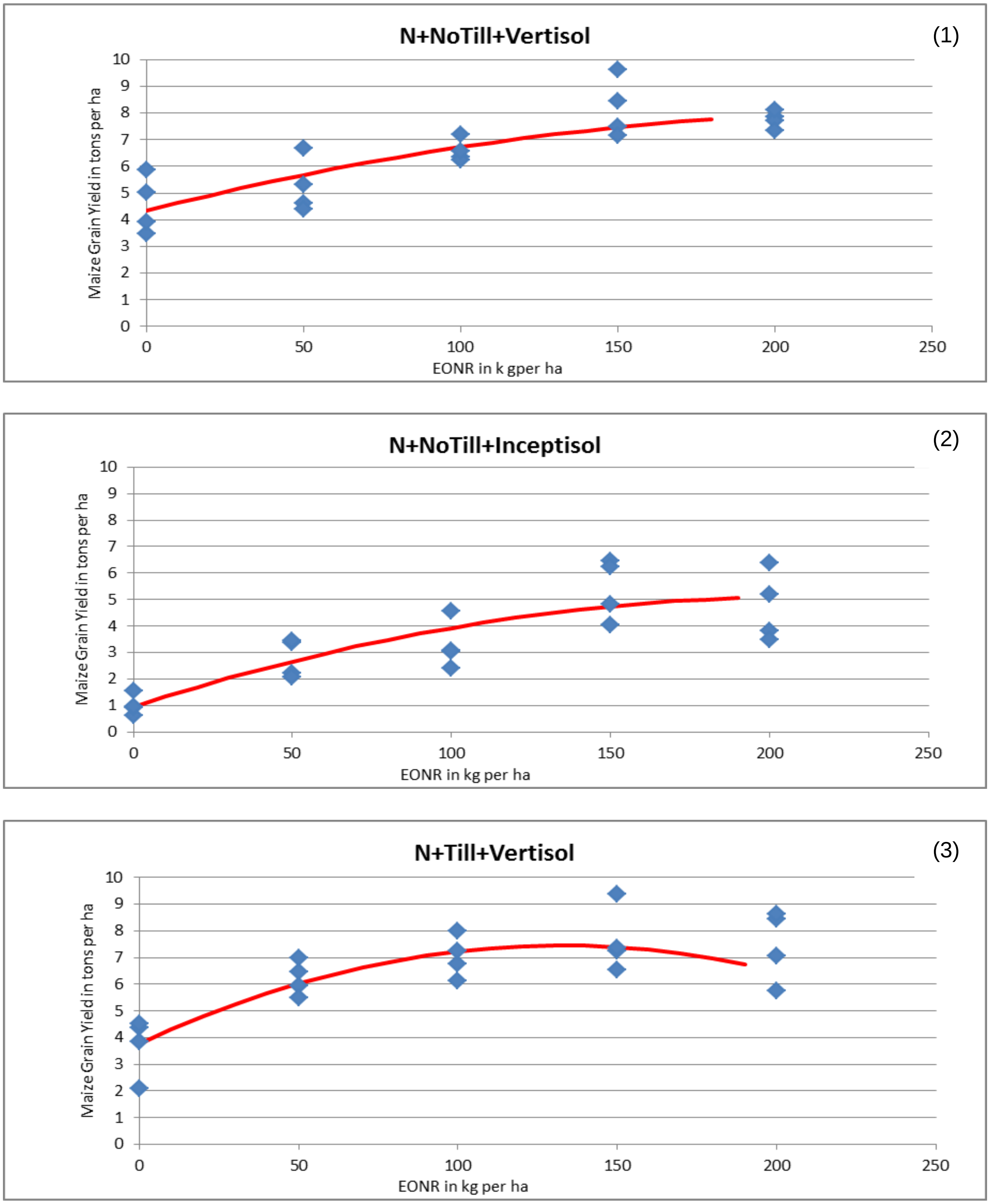


Figure 10. Relationship between economically optimum N rate (EONR) and its respective predicted yield for each N study

Figure 11. shows the relationship between EONR and predicted yield at EONR (EOY) by N study. N-study 1 had both the highest EONR and EOY. N-study 3 had the lowest EONR but had higher EOY than N-study 2. This is partly due to its relatively higher BOY which is likely associated with the type of soil. Owing to its inherent characteristics, vertisols are more likely to sustain relatively higher yields and increase maize's N use efficiency in short to middle term than inceptisols.

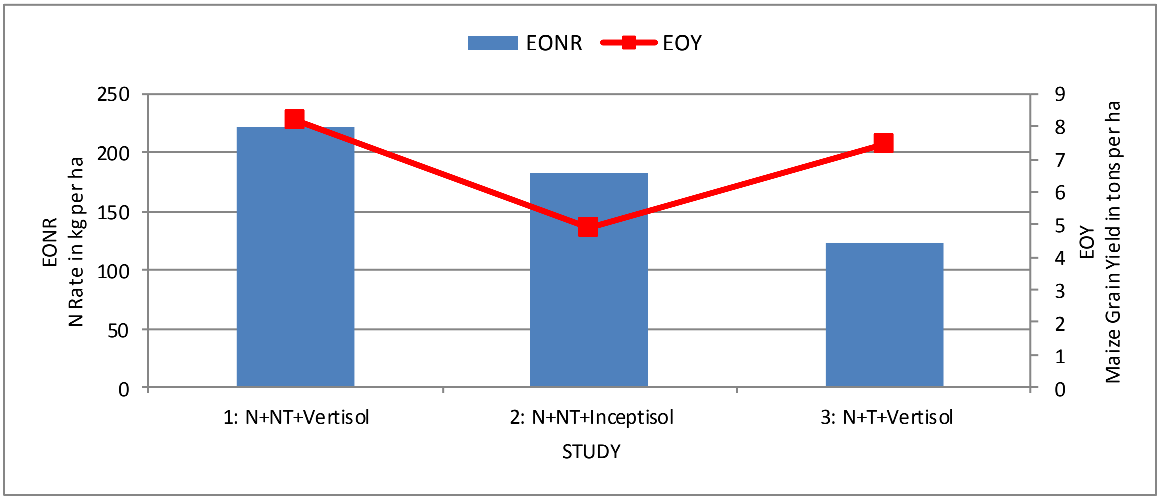


Figure 11. Economically optimum yield (EOY) and N rate (EONR) by N study

Figure 12 shows the relationship between economical optimum and biological optimum yield, N fertilizer rate, and profit. Minor differences were found between BOY and EOY (N-study 1), and BOP and EOP (N-study 3). However, the differences between BONR and EONR in each N-study were relatively much clearer (N-study 2). Although N-study 3 had a relatively lower BONR and EONR than N-studies 1 and 2, it had a BOP and an EOP about 40 percent higher than those achieved in N-study 2, and almost only 3.2 percent less than those achieved in N-study 1. This is likely due to its high BOY and EOY which is partly associated with the type of soil and the short term benefits of tilling it.

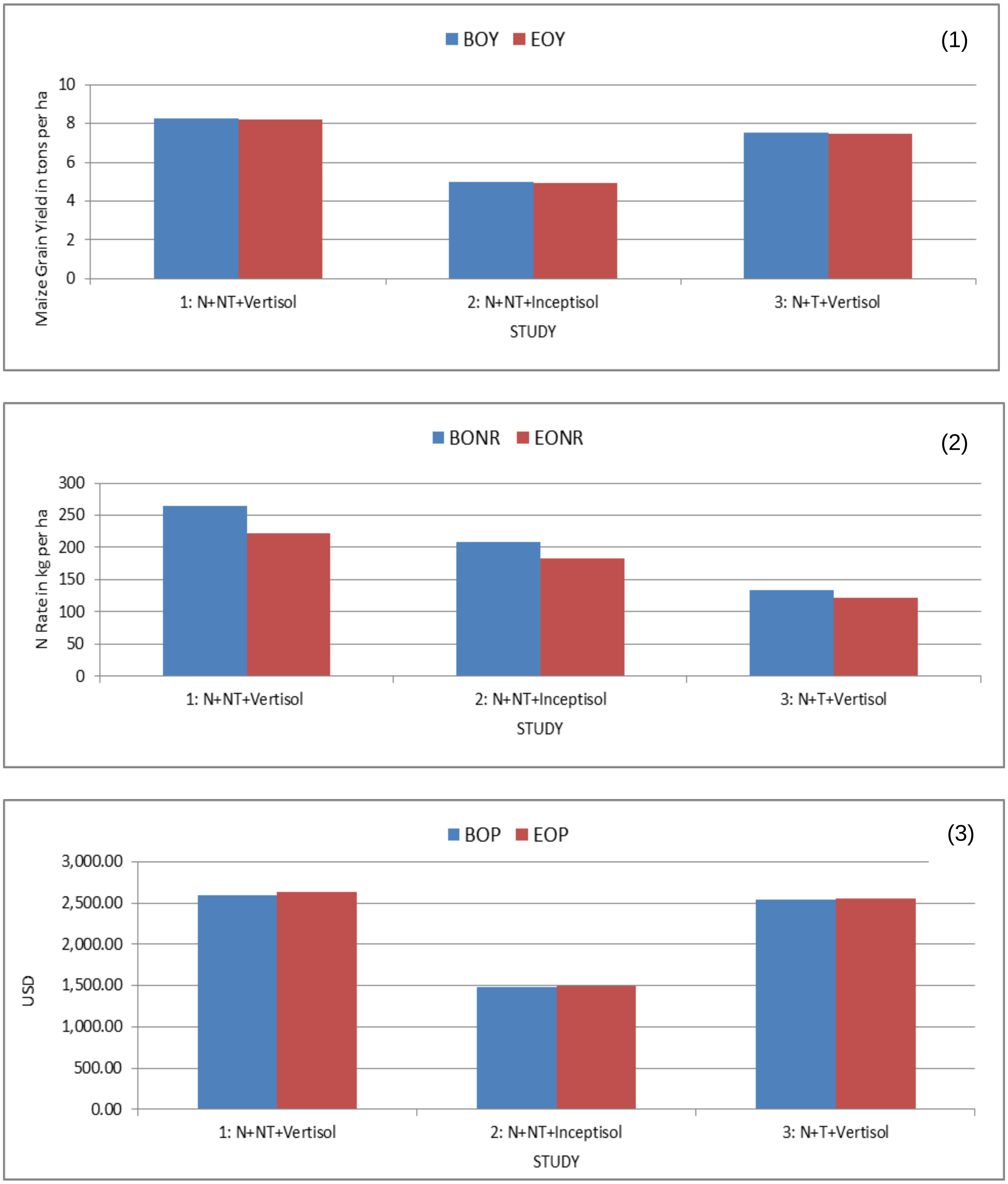


Figure 12. Relationship between economical optimum and biological optimum yield, N and profit

CONCLUSIONS AND RECOMMENDATIONS

The most important difference across all studies was due to soil type, followed by fertilizer rate and then tillage. Vertisol had relatively higher grain yields across all studies, N, P and K, thus suggesting that overall, vertisol was more efficient in providing nutrients to the crop as compared with inceptisol. Maize grain yields were also affected by fertilizer rates with N rates having the greatest impact as compared to those of P and K which were mostly insignificant. This suggests that unlike P and K, N is indeed the major limiting nutrient to maize production in Maphutseng even though it is a well-known fact that most African soils are poor in P. The highest yield increase was obtained by applying 150 kg of N (LAN source) per ha in both tillage practices (till vs no till) and soil types (vertisol vs inceptisol), thus suggesting that applying 200 kg of N per ha (the highest fertilizer tested) under similar conditions is not as cost effective. Unlike non-tilled vertisol and inceptisol, applying 50 kg of N per ha under tilled vertisol (Figure 8) resulted in yield benefits statistically insignificant as compared to applying 100, 150 or 200 kg per ha of N (LAN source). From an agronomic perspective, looking at the yield response curves, it is suggested that 150 kg per ha could be the recommended N fertilizer rate for both the inceptisol and vertisol no-till maize systems, and 50 kg per ha the recommended N fertilizer rate for the vertisol till maize system both using LAN as N source; and 30 kg per ha could be the recommended P (P_2O_5) rate for high grain yields in inceptisol maize systems of Maphutseng. On the other hand, results from an economically optimum perspective (analysis) suggest that relatively higher N fertilizer rates are needed to achieve EOYs and EOPs. 222 kg per ha, 182 kg per ha, and 123 kg per ha are the estimated EONRs for no-till vertisol maize system with yield predicted at 8.17 tons per ha, no-till inceptisol maize system with yield predicted at 4.92 tons per ha, and till vertisol maize system with yield predicted at 7.47 tons per ha, respectively. However, it is evident from our research and the scientific literature

that these benefits may be temporary if an integrated nutrient management approach is not adopted.

CONCLUSIONS AND RECOMMENDATIONS

- From our studies, it is evident that there is potential to increase productivity of the agricultural systems in SA towards meeting the growing demand for food with the use of fertilizer.
- Combined application of 60 kg N-60 kg P-0 kg K per ha is suggested for high cassava tuber yields at Milha-14; 60 kg N-90 kg P-150 kg K kg per ha is suggested for high cassava starch content; 150 kg N per ha, 50 kg N per ha, and 30 kg P (P_2O_5) per ha are suggested for high maize grain yields in both vertisol and inceptisol no-till maize systems, vertisol till maize system using LAN as N source, and inceptisol maize system, respectively. On the other hand, EOA suggests that 222 kg per ha, 182 kg per ha, and 123 kg per ha are recommended for EOYs and EOPs in no-till vertisol, no-till inceptisol, and till vertisol maize systems, respectively. However, further research is needed to verify if these fertilizer rates can sustain high yields and quality in the long term.

LIST OF REFERENCES

Abunyewa, A., Asiedu, E. K. and Ahenkorah, Y. 2004. Phertilizer Phosphorus Fractions and their Availability to Maize on Different Landforms on a vertisol in the Coastal Savanna Zone of Ghana. West African Journal of Applied Ecology, vol. 5. p. 63-73.

Agbaje G. O. and Akinlosotu A. 2004. Influence of NPK on tuber yield of early and late-planted cassava in a forest alfisol of south western Nigeria. African Journal of Biotechnology. Vol. 3. No. 19. p. 548-550.

Benesi, IRM. 2005. Characterisation of Malawian cassava germplasm for diversity, starch extraction and its native and modified properties. University of the Free State, Ph.D. Thesis, Accessed 3 June 2014, available at http://etd.uovs.ac.za/ETD-db/theses/available/etd-07042006-090839/unrestricted/BENESIIRM.pdf

Bloem, J. E., Trytsman, G. and Smith, E. J. 2009. Biological nitrogen fixation in resource poor agriculture South Africa. Vol 48. South Africa.

Braidotti, G. 2011. Cassava, cyanide and konzo disease. Focus on NGOs, accessed on 19 Dezember 2013, available at: http://aciar.gov.au/files/node/13748/cassava_cyanide_and_konzo_disease__75809.pdf

Caribbean Agricultural Research and Development Institute (CARDI). 1992. Commercial Cassava Production. Factsheet. Frances Chandler. Order no.: CP-F/ 16-89.

Central Tuber Crops Research Institute (CTCRI). 1983a. Two Decades of Research. Central Tuber Crops Research Institute, Thiruvananthapuram.

Centro Internacional de Agricultura Tropical (CIAT). 1992. Cassava Breeding, Agronomy and Utilization Research in Asia. Proc. Third Regional Workshop held in Malang, Indonesia, Oct 22-27, 1990. R. H. Howeler (Ed.). Bangkok, Thailand. 444p.

CIA World Factbook. 2013. Index Mundi. Lesotho Economy Profile, February 21st 2013 Update. p. 1. Available at: http://www.indexmundi.com/lesotho/economy_profile.html

de Bruijn, G. H. 1973. The cyanogenic character of cassava (Manihot esculenta). In Chronic cassava toxicity: proceedings of an interdisciplinary workshop, London, England, 29-30 January 1973. mt. Develop. Res. CentreMonogr. IDRC-OLOe. p. 43-48.

Derpsch, R., Florentín, M. and Moriya, K. 2006. The Laws of Diminishing Yields in the Tropics. USDA Forest Service Proceedings RMRS-P-42CD.

Dias, D. and Nyagumbo, I. 2012. An assessment of the merits of the rain-fed maize-legume cropping systems under conservation agriculture In Mozambique. Poster presented at Indian Agronomy Conference, New Dehli, November 2012.

Dias, P. 2012. Analysis of incentives and disincentives for cassava in Mozambique. Technical notes series, MAFAP, FAO, Rome. Accessed 19 June 2014, available at: http://www.fao.org/fileadmin/templates/mafap/documents/technical_notes/MOZAMBIQUE/MOZAMBIQUE_Technical_Note_CASSAVA_EN_Oct2012.pdf

Donovan, C. and Tostão, E. 2010. Staple Food Prices in Mozambiuqe. Maputo, Mozambique. p 4-6.

Duluora, J. O. 2012. Effects of rainfall, temperature variation and fertilizer application on cassava yield in Anambra state from 1977 to 2006. NNAMDI AZIKIWE UNIVERSITY, MS Thesis, accessed June 4 2014, available at: http://naulibrary.org/dglibrary/admin/book_directory/Thesis/11008.pdf

EC-FAO Food Security Information for Action Programme. 2007. Sub-Sector Strategic Study on Cassava: Cassava Development Strategy for Mozambique (2008-2012). Volume 1. Via delle Terme di Caracalla, Rome, Italy, Available at: http://www.foodsec.org/

Eke-Okoro, O. N., Okereke, O.U. and Okele, J. E. 1999. Effects of weather change and planting set on growth and productivity of cassava in southeastern Nigeria. African Journal of Root and Tuber Crops. (ISTRC-AB) 3(2): 34-38.

El-Sharkawy, M. A. 2004. Cassava biology and physiology. Plant Molecular Biology 56: 481-501, Kluwer Academic Publishers, Netherlands.

Ezui, K. S., Mando A., Franke , A. C., Sogbedji, J., Ahiabor, B. D. K., Tetteh, F. M., Janssen, B. H. and Giller, K. E. 2012. Improving fertilizer use efficiency in cassava production system of West Africa. Agro Environ. 12424-13019-1-PB

FAO. 2006. Starch Market adds value to cassava: cassava-producing countries should convert more of this relatively low cost row material into high value starch for domestic and international markets. Agriculture, Biodiversity, Nutrition and consumer protection department. Vialle delle Terme di Caracalla, 00100 Rome, Italy. Available at www.fao.org/ag/magazine/pdf/0610-1.pdf

FAO. 2010. Integrated Crop Management. Conservation Agriculture and Sustainable Crop Intensification in Lesotho. Vol. 10. ISSN1020-4555. Rome.

FAO. 2011. Food Outlook: Global Market Analysis. Available at: www.fao.org/docrep/014/al981e/al981e00.pdf

FAO. 2013. Save and Grow: Cassava. A Guide to Sustainable Production Intensification, Rome. E-ISBN 978-92-5-107642-2 (PDF), available at http://www.fao.org/docrep/018/i3278e/i3278e.pdf

FAO. 2013. Bioenergy and food security projects (BEFS), country brief, Lesotho. p. 5. Available at: www.fao.org/bioenergy/foodsecurity/befs

FAO-Mozambique. 2010. Initiatives to counter soaring food prices. November 2010. Accessed 19 June 2014, available at: file:///C:/Users/icuvaca/Downloads/fao%20mozambique%20programs%20%20english%20nov%202010.pdf

Fermont, A. M. 2009. Cassava and Soil Fertility in Intensifying Smallholder Farming Systems of East Africa. Wagening University, PhD Thesis, Accessed 2 June 2014, available at: edepot.wur.nl/7784

Food Agriculture and Natural Resource Policy Analysis Network (FANRPAN). 2009. Agricultural Input Subsidy Program. Node Training and Common Vision Workshop, April 1st – 2nd, 2009, Pretoria, South Africa.

Gardner, F. P., Pearce, R. B., and Mitchell, R. L. 1985. Physiology of Crop Plants. Iowa State University Press.

Gomes, J. de Cerqueira and Howeler, R. H. 1980. Cassava production in low fertility soils: Cassava cultural practices. Proceedings of a workshop held in Salvador, Bahia, Brazil. 1821 March 1980. 93-102 (En. 10 tabs). EMBRAPA/CNPME, Cruz das Almas Bahia, Brazil.

Gwarizimba, V. 2009. Cotton and cassava seed systems: Malawi, Mozambique and Zambia. FAO. All Agricultural Commodities Programme. Zimbabwe. p. 7, 11, 28.

Henao, J. and Baanante, C. 2006. Agricultural Production and Soil Nutrient Mining in Africa. Implication for Resource Conservation and Policy Development Summary. Accessed 9 June 2014, available at: http://www.eurekalert.org/africasoil/report/Soil_Nutrient_Mining_in_Africa_Report_Final.pdf

Hillocks, R. J., Thresh J. M., and Bellotti, A. C. 2002. Cassava: Biology, Production and Utilization. Chapter 1: The origins and taxonomy of cassava. CABI Publishing. New York, USA. ISBN 0851995241. p. 1-11.

Hillocks, R. J., Thresh, J. M., Tomas, J., Botao, M., Macia, R., and Zavier, R. 2002. Cassava brown streak disease in northern Mozambique. International Journal of Pest Management, 48:3, 178-181, DOI: 10.1080/09670870110087376, available at: http://dx.doi.org/10.1080/09670870110087376

Howeler, R. H. 1981. Mineral Nutrition and Fertilization of Cassava (Manihoc esculenta Crantz). (CIAT SERIES). 52p.

Howeler, R. H. 2001. Nutrient inputs and losses in cassava based cropping systems: Examples of Vietnam and Thailand. CIAT Regional Cassava Office, Department of Agriculture, Chatuchak, Bangkok 10900. Presented at: International Workshop on Nutrient Balances for Sustainable Agricultural Production and Natural Resources Management in Southeast Asia. Bangkok, Thailand, 20-22 February. p. 4-5.

Howeler, R. H. and Cadavid, L. F. 1990. Short-and long term fertility trials in Colombia to determine the nutrient requirements of cassava. Fertilizer Research 26; 61-80, 1990. Kluwer Academic Publishers. Netherlands.

Howeler, R. H., Watananonta, W. and Ngoan, T. N. 2005. Working with Farmers: The Key to Achievong Adoption of More Sustainable Cassava Production Practices on Sloping Land in Asia. Paper presented at UPWARD Network Meeting, held in Hanoi, Vietanam. January 19-21, 2005.

International Starch Institute (ISI). 1999. ISI 13-2e Determination of starch in tubers by underwater weight. Science Park Aarhus, Denmark.

James, B., Yaninek, J., Tumanteh, A., Maroya, N., Dixon, A., Salawu, R. and Kwarteng, J. 2000. Starting a Cassava Farm. IPM Field Guide for Extension

Agents. ISBN 978-131-173-8, Nigeria, accessed June 4 2014, available at: http://www.infonet-biovision.org/res/res/files/1855.Starting.pdf

Kamaraj, S., Jagadeeswaran, R., Murugappan, V. and Rao, N. T. 2008. Balanced Fertilisation for Cassava. Better Crops – India. p. 8-9.

Khanthavong, P., Phattarakul, N., Jamjod, S., Aye, T. M, and Rerkasem, B. 2012. Effect of Stake Priming with Complete Nutrient Solution on Cassava Root and Starch Yield. CMU. J. Nat. Sci. Special Issue on Agricultural and Natural Resources. 11(1): 75

Krochmal, A. and Samuels, G. 1966. The influence of NPK levels on the growth and tuber development of cassava in tanks. Journal Ceiba. Vol. 16. No. 2. p. 35-43. Kentucky.

Kusanga, S. An assessment of the potential effects of climate induced sea level rise on land uses and land cover in Beira, Mozambique. Accessed June 5 2014, available at: http://www.planet-ction.org/automne_modules_files/polyProjects/public/r9594_93_kusangaya_cc_sea_level_rise_beira_planet_action.pdf

Lambri, M., Fumi, M. D., Roda, A., and De Faveri, D. M. 2013. Improved processing methods to reduce the total cyanide content of cassava roots from Burundi. Afr. J. Biotechnol. 12(19): 2685-2691.

Li K., Zhu W., Zeng K., Zhang Z., Ye J., Ou W., Rehman S., Heuer B. and Chen S. 2010. Proteome characterization of cassava (ManihotesculentaCrantz) somatic embryos, plantlets and tuberous roots. Proteome Science, 8:10. doi: 10.1186/1477-5956-8-10. p. 1-9. Available: http://www.proteomesci.com/content/8/1/10.

Malavota E., Graner E. A., Coury T., M. O. C. Brasil SOBRo, and Pacheco J. A. C. 1954. Studies on the mineral nutrition of cassava (Manihot utilissima

Pohl). Escolar Superior de Agricultura “Luis de Queiroz”, University of São Paulo, Piracicaba, São Paulo, Brazil. p. 81-82.

Mapfumo, P., Champel, B. M., Mpepereki, S. and Mafongoya P. 2001. Legumes in soil fertility management: the case of pigeon-pea in smallholder farming systems of Zimbabwe. University of Zimbabwe, Department of soil science and agricultural engineering, Pleasant, Harare.

Maria, R. 2004. Soil nutrient status, spatial variability of soil chemical properties and fertilization requirements in Cabo Delgado, Nampula and Manica provinces of Mozambique. University of Hawai’I, M.S Thesis, USA. 3923. p. 12-28.

Maria, R. M. and Yost R. 2006. A survey of soil fertility status of four agro-ecological zones of Mozambique. Soil Science. U.S.A. Vol. 171. No. 11. 0038-075X/06/17111. p. 902-914.

Mariscal, A.M. 1984. Major constraint of cassava production in the Philipines. Philippians Root Crops Research and Training Centre, Visca, Baybay layte Philippians. Radix: 6(1): 13-14 (En. 11 ref.).

Megazyme International Ireland (MII). 2011. Megazyme Total Starch Assay Procedure (Amyloglucodsidase/α-Amylase Method). AOAC Method 996.11 and AACC Method 76.13 (and improvements). K-TSTA 07/11.

Ministry of Agriculture and Fisherie (MAF). 1996. Agroecological Zones and Production Systems. Working Document 2/b, Program of Investiment in Agricultural Extension, Process of the Formulation of Proagrii. Maputo, Mozambique; Ministry of Agriculture and Fisheries.

Ministry of Agriculture and Food Security (MAFS) and Ministry of Finance and Development Planning (MFDP) of Lesotho. 2011. Lesotho agricultural situation report 2010-2011. Final Draft. p. 5, 8, 20. Maseru, Lesotho.

Nkamilo, G. S. and Jeremiah, S. C. 2005. Current status of cassava improvement in Tanzania. African Crop Science Conference Proceedings, vol. 7. Pp. 1311-1314. Accessed 19 June 2014, available at: http://www.acss.ws/upload/xml/research/699.pdf

Mole, P. N. 2006. Smallholder agricultural intensification in Africa. Mozambique micro-study report – AFRINT. Maputo. p. 2-4. Available at: blog.sam.lu.se/afrint/pdf/mozmicro.pdf/

Moraghan, J. and Horsager, K. 1991. Influence of nitrogen fertilizer on sugarbeet production in a wet year. North Dakota State University, Sugarbeet Research and Extension Reports, vol. 22, p. 72-83, accessed June 4 2014, available at: http://www.sbreb.org/research/soil/soil91/91p72.htm

Msuya, N., Masanja, E. and Temu, A. K. 2011. Environmental Burden of Cahrcoal Production and Use in Dar es Salaam, Tanzania. Journal of Environmental Protection 2011, 2, 1364-1369

Nambisan, B. 2011. Strategies for elimination of cyanogens from cassava for reducing toxicity and improving food safety. Food Chem. Toxicol. 49: 690-693.

Nwosu, L. A. and Onofeghara, F. A. 1991. A comparison of cyanide accumulation, leaf retention and Linamarase activity of cassava varieties during water stress. Tropical Root Crops in a Developing Economy: Proceeding of the ninth Symposium of the International Society for Tropical Root Crops held in Accra, Ghana. October 20-26 1991. 187-193(En. 13 ref, 4 tabs)

Promar Consulting. 2011. SUBSISTENCE AGRICULTURE STUDY. The Cassava Industries in Mozambique and Tanzania: production, processing, distribution and consumption of cassava and its related policy challenges. p.79-81. Available at: http://www.apip-apec.com/ja/good-

practices/files/The_Cassava_Industries_in_Mozambique_and_Tanzania-2011.pdf

Sarkiyayi, S. and Agar, T. M. 2010. Comparative analysis on the nutritional and anti-nutritional contents of the sweet and bitter cassava varieties. Adv. J. Food Sci. Technol. 2: 328-334.

Sawyer, J., Nafziger, E., Randall, G., Bundy, L., Rehm, G. and Joern, B. 2006. Concepts and Rationale for Regional Nitrogen Rate Guidelines for Corn. Iowa State University, University Extension, Pm 2015. April 2006.

Saxena, S. 2013. Cleanstar Mozambique: A commercial case study of sustainable food and biofuel production with smallholder farmers. Presented at the "IFAD-ICRAF Biofuel Program" side event, Bonn, Germany, 5 June 2013.

Schmitz, G. and Rooyani, F. 1987. Lesotho Geology, Geomorphology, Soils. National University of Lesotho. PN-ABK-98176638. p. 169.

Speijers, G. Cyanogenic Glycosides (WHO Food Addetives Series 30). Accessed May 30 2014, available at: www.inchem.org/documents/jecfa/jecmono/v30je18.htm

Steiner, C., Garcia, M. and Zech, W. 2009. Effects of Charcoal as Slow Release Nutrient Carrier on N-P-K Dynamics and Soil Microbial Population: Pot Experiments with Ferrasol Subtrate. WI Woods et al. (eds.), Amazonian Dark Earths: Wim Sombroek's cisio, Springer Science + Business Media B.V. 2009, 325-338

Steiner, C., Glaser, B., Teixeira, W. G., Lehmann, J., Blum, W. E. H.and Zech, W. 2008. Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. J. Plant Nutr. Soil Sci. 171, 893-899

Sungzikaw, S. 2008. Measurements of Starch Content in Cassava. Presnted at Workshop on Metrology in Food Safety, Agricultural Products and Products Safety, Hangzhou, PR China, June 2-6, 2008.

Thierfelder C. and Wall P. C. 2010. Rotation in conservation agriculture systems of Zambia: Effects on soil quality and water relations. Mount Pleasant, Harare, Zimbabwe.

Thierfelder C. and Wall P. C. 2012. Effects of conservation agriculture on soil quality and productivity in contrasting agro-ecological environments of Zimbabwe. British Society of Soil Science, Soil Use and Management, 28, 209-220.

Thierfelder, C. and Eash, N. Unpublished paper. Conservation Agriculture in Southern Africa.

Thierfelder, Christian., Chisui John L., Gama Mpatso, Cheesman Stephanie, Jere Zwide D., Bunderstone W. Trent, Eash Neal and Rusinamhodzi Leonard. 2012. Maize-based conservation agriculture systems in Malawi: Long-term trends in productivity. Eslevier. Field crops research 142(2013) 45-47.

Tisdale, S. L., Nelson, W. L. and Beaton, J. D. 1985. Soil Fertility and Fertilizers. Fourth Edition. Macmillan Publishing Company. USA, New York. p. 112-249.

Toro, J. C. and Atlaa, C. B. 1980. Agronomic practices for cassava production: a Literature Review. Cassava cultural practices. Proceedings of the workshop held in Salvador Bahia, Brazil, March 18-21 1980. 13-28.(En 2 tabs). Cassava program, CIAT, Cali Colombia.

APPENDICES

APPENDIX I: CASSAVA TUBER YIELD DATA

1. CASSAVA TUBER YILED

Rep	Fertilizer Rate (Treatment)			Treatment ID	NoObs	Tuber Weight in g	Yield Estimate in tons per ha
	N	P	K				
1	0	0	0	1	1	1050	10.5
1	0	0	0	1	2	1180	11.8
1	0	0	0	1	3	1060	10.6
1	0	0	0	1	4	105	1.05
1	60	0	0	2	1	840	8.4
1	60	0	0	2	2	80	0.8
1	60	0	0	2	3	1140	11.4
1	60	0	0	2	4	530	5.3
1	0	60	0	3	1	350	3.5
1	0	60	0	3	2	1695	16.95
1	0	60	0	3	3	240	2.4
1	0	60	0	3	4	145	1.45
1	0	0	150	4	1	1425	14.25
1	0	0	150	4	2	590	5.9
1	0	0	150	4	3	2160	21.6
1	0	0	150	4	4	2690	26.9
1	0	60	150	5	1	2975	29.75
1	0	60	150	5	2	6350	63.5
1	0	60	150	5	3	3375	33.75
1	0	60	150	5	4	3860	38.6
1	25	60	150	6	1	2700	27
1	25	60	150	6	2	3675	36.75
1	25	60	150	6	3	3305	33.05
1	25	60	150	6	4	2215	22.15
1	50	60	150	7	1	2235	22.35
1	50	60	150	7	2	840	8.4
1	50	60	150	7	3	1895	18.95
1	50	60	150	7	4	1830	18.3
1	75	60	150	8	1	2630	26.3
1	75	60	150	8	2	740	7.4
1	75	60	150	8	3	680	6.8
1	75	60	150	8	4	1350	13.5
1	100	60	150	9	1	1735	17.35
1	100	60	150	9	2	1485	14.85

1	100	60	150	9	3	1510	15.1
1	100	60	150	9	4	360	3.6
1	60	0	150	10	1	2860	28.6
1	60	0	150	10	2	635	6.35
1	60	0	150	10	3	1175	11.75
1	60	0	150	10	4	30	0.3
1	60	30	150	11	1	2.295	0.02295
1	60	30	150	11	2	1360	13.6
1	60	30	150	11	3	2610	26.1
1	60	30	150	11	4	1955	19.55
1	60	60	150	12	1	830	8.3
1	60	60	150	12	2	2700	27
1	60	60	150	12	3	620	6.2
1	60	60	150	12	4	585	5.85
1	60	90	150	13	1	870	8.7
1	60	90	150	13	2	2830	28.3
1	60	90	150	13	3	1665	16.65
1	60	90	150	13	4	1985	19.85
1	60	60	0	14	1	710	7.1
1	60	60	0	14	2	1415	14.15
1	60	60	0	14	3	4860	48.6
1	60	60	0	14	4	3755	37.55
1	60	60	30	15	1	2190	21.9
1	60	60	30	15	2	1290	12.9
1	60	60	30	15	3	1120	11.2
1	60	60	30	15	4	430	4.3
1	60	60	60	16	1	1380	13.8
1	60	60	60	16	2	245	2.45
1	60	60	60	16	3	1515	15.15
1	60	60	60	16	4	735	7.35
1	60	60	90	17	1	1975	19.75
1	60	60	90	17	2	970	9.7
1	60	60	90	17	3	3170	31.7
1	60	60	90	17	4	2950	29.5
1	60	60	120	18	1	1390	13.9
1	60	60	120	18	2	1580	15.8
1	60	60	120	18	3	1065	10.65
1	60	60	120	18	4	210	2.1
1	60	60	150	19	1	2075	20.75

1	60	60	150	19	2	3870	38.7
1	60	60	150	19	3	1825	18.25
1	60	60	150	19	4	835	8.35
1	60	60	180	20	1	1295	12.95
1	60	60	180	20	2	2195	21.95
1	60	60	180	20	3	1840	18.4
1	60	60	180	20	4	4500	45
2	0	0	0	1	1	430	4.3
2	0	0	0	1	2	2460	24.6
2	0	0	0	1	3	1070	10.7
2	0	0	0	1	4	3460	34.6
2	60	0	0	2	1	170	1.7
2	60	0	0	2	2	135	1.35
2	60	0	0	2	3	3840	38.4
2	60	0	0	2	4	175	1.75
2	0	60	0	3	1	2425	24.25
2	0	60	0	3	2	1395	13.95
2	0	60	0	3	3	1300	13
2	0	60	0	3	4	1340	13.4
2	0	0	150	4	1	1090	10.9
2	0	0	150	4	2	410	4.1
2	0	0	150	4	3	5310	53.1
2	0	0	150	4	4	3350	33.5
2	0	60	150	5	1	4700	47
2	0	60	150	5	2	995	9.95
2	0	60	150	5	3	720	7.2
2	0	60	150	5	4	1235	12.35
2	25	60	150	6	1	1285	12.85
2	25	60	150	6	2	65	0.65
2	25	60	150	6	3	2890	28.9
2	25	60	150	6	4	620	6.2
2	50	60	150	7	1	4405	44.05
2	50	60	150	7	2	3075	30.75
2	50	60	150	7	3	3595	35.95
2	50	60	150	7	4	1570	15.7
2	75	60	150	8	1	780	7.8
2	75	60	150	8	2	310	3.1
2	75	60	150	8	3	2865	28.65
2	75	60	150	8	4	3220	32.2

2	100	60	150	9	1	1130	11.3
2	100	60	150	9	2	30	0.3
2	100	60	150	9	3	4325	43.25
2	100	60	150	9	4	85	0.85
2	60	0	150	10	1	1240	12.4
2	60	0	150	10	2	685	6.85
2	60	0	150	10	3	2510	25.1
2	60	0	150	10	4	3370	33.7
2	60	30	150	11	1	645	6.45
2	60	30	150	11	2	1100	11
2	60	30	150	11	3	3550	35.5
2	60	30	150	11	4	1335	13.35
2	60	60	150	12	1	3035	30.35
2	60	60	150	12	2	795	7.95
2	60	60	150	12	3	1325	13.25
2	60	60	150	12	4	775	7.75
2	60	90	150	13	1	2045	20.45
2	60	90	150	13	2	4615	46.15
2	60	90	150	13	3	1720	17.2
2	60	90	150	13	4	3775	37.75
2	60	60	0	14	1	2720	27.2
2	60	60	0	14	2	1960	19.6
2	60	60	0	14	3	1885	18.85
2	60	60	0	14	4	3225	32.25
2	60	60	30	15	1	40	0.4
2	60	60	30	15	2	570	5.7
2	60	60	30	15	3	2940	29.4
2	60	60	30	15	4	1320	13.2
2	60	60	60	16	1	2460	24.6
2	60	60	60	16	2	3320	33.2
2	60	60	60	16	3	610	6.1
2	60	60	60	16	4	4295	42.95
2	60	60	90	17	1	1090	10.9
2	60	60	90	17	2	1375	13.75
2	60	60	90	17	3	4525	45.25
2	60	60	90	17	4	3085	30.85
2	60	60	120	18	1	225	2.25
2	60	60	120	18	2	95	0.95
2	60	60	120	18	3	2155	21.55

2	60	60	120	18	4	1785	17.85
2	60	60	150	19	1	720	7.2
2	60	60	150	19	2	1825	18.25
2	60	60	150	19	3	2175	21.75
2	60	60	150	19	4	340	3.4
2	60	60	180	20	1	2490	24.9
2	60	60	180	20	2	535	5.35
2	60	60	180	20	3	1755	17.55
2	60	60	180	20	4	1930	19.3
3	0	0	0	1	1	875	8.75
3	0	0	0	1	2	1630	16.3
3	0	0	0	1	3	2160	21.6
3	0	0	0	1	4	225	2.25
3	60	0	0	2	1	1025	10.25
3	60	0	0	2	2	1465	14.65
3	60	0	0	2	3	600	6
3	60	0	0	2	4	255	2.55
3	0	60	0	3	1	1545	15.45
3	0	60	0	3	2	2723	27.23
3	0	60	0	3	3	200	2
3	0	60	0	3	4	4705	47.05
3	0	0	150	4	1	1950	19.5
3	0	0	150	4	2	240	2.4
3	0	0	150	4	3	5550	55.5
3	0	0	150	4	4	1780	17.8
3	0	60	150	5	1	705	7.05
3	0	60	150	5	2	1440	14.4
3	0	60	150	5	3	1175	11.75
3	0	60	150	5	4	240	2.4
3	25	60	150	6	1	1235	12.35
3	25	60	150	6	2	10035	100.35
3	25	60	150	6	3	4655	46.55
3	25	60	150	6	4	1045	10.45
3	50	60	150	7	1	1350	13.5
3	50	60	150	7	2	540	5.4
3	50	60	150	7	3	3725	37.25
3	50	60	150	7	4	1600	16
3	75	60	150	8	1	290	2.9
3	75	60	150	8	2	360	3.6

3	75	60	150	8	3	3080	30.8
3	75	60	150	8	4	525	5.25
3	100	60	150	9	1	755	7.55
3	100	60	150	9	2	4405	44.05
3	100	60	150	9	3	4765	47.65
3	100	60	150	9	4	1990	19.9
3	60	0	150	10	1	1460	14.6
3	60	0	150	10	2	5820	58.2
3	60	0	150	10	3	1705	17.05
3	60	0	150	10	4	570	5.7
3	60	30	150	11	1	690	6.9
3	60	30	150	11	2	180	1.8
3	60	30	150	11	3	3810	38.1
3	60	30	150	11	4	3305	33.05
3	60	60	150	12	1	1510	15.1
3	60	60	150	12	2	930	9.3
3	60	60	150	12	3	3100	31
3	60	60	150	12	4	680	6.8
3	60	90	150	13	1	1390	13.9
3	60	90	150	13	2	1345	13.45
3	60	90	150	13	3	2195	21.95
3	60	90	150	13	4	2320	23.2
3	60	60	0	14	1	905	9.05
3	60	60	0	14	2	5045	50.45
3	60	60	0	14	3	3285	32.85
3	60	60	0	14	4	5915	59.15
3	60	60	30	15	1	1375	13.75
3	60	60	30	15	2	460	4.6
3	60	60	30	15	3	3510	35.1
3	60	60	30	15	4	980	9.8
3	60	60	60	16	1	2165	21.65
3	60	60	60	16	2	3630	36.3
3	60	60	60	16	3	1575	15.75
3	60	60	60	16	4	5210	52.1
3	60	60	90	17	1	970	9.7
3	60	60	90	17	2	965	9.65
3	60	60	90	17	3	1005	10.05
3	60	60	90	17	4	595	5.95
3	60	60	120	18	1	2970	29.7

3	60	60	120	18	2	965	9.65
3	60	60	120	18	3	1210	12.1
3	60	60	120	18	4	3120	31.2
3	60	60	150	19	1	630	6.3
3	60	60	150	19	2	3385	33.85
3	60	60	150	19	3	2265	22.65
3	60	60	150	19	4	1100	11
3	60	60	180	20	1	1305	13.05
3	60	60	180	20	2	2865	28.65
3	60	60	180	20	3	6030	60.3
3	60	60	180	20	4	3535	35.35
4	0	0	0	1	1	1235	12.35
4	0	0	0	1	2	7125	71.25
4	0	0	0	1	3	1540	15.4
4	0	0	0	1	4	4595	45.95
4	60	0	0	2	1	0	0
4	60	0	0	2	2	0	0
4	60	0	0	2	3	0	0
4	60	0	0	2	4	0	0
4	0	60	0	3	1	5215	52.15
4	0	60	0	3	2	2570	25.7
4	0	60	0	3	3	365	3.65
4	0	60	0	3	4	550	5.5
4	0	0	150	4	1	3495	34.95
4	0	0	150	4	2	3045	30.45
4	0	0	150	4	3	1935	19.35
4	0	0	150	4	4	1730	17.3
4	0	60	150	5	1	6145	61.45
4	0	60	150	5	2	545	5.45
4	0	60	150	5	3	5835	58.35
4	0	60	150	5	4	580	5.8
4	25	60	150	6	1	920	9.2
4	25	60	150	6	2	1815	18.15
4	25	60	150	6	3	3710	37.1
4	25	60	150	6	4	1425	14.25
4	50	60	150	7	1	1960	19.6
4	50	60	150	7	2	4750	47.5
4	50	60	150	7	3	265	2.65
4	50	60	150	7	4	4785	47.85

4	75	60	150	8	1	2345	23.45
4	75	60	150	8	2	1660	16.6
4	75	60	150	8	3	100	1
4	75	60	150	8	4	60	0.6
4	100	60	150	9	1	1485	14.85
4	100	60	150	9	2	4945	49.45
4	100	60	150	9	3	680	6.8
4	100	60	150	9	4	3325	33.25
4	60	0	150	10	1	0	0
4	60	0	150	10	2	0	0
4	60	0	150	10	3	0	0
4	60	0	150	10	4	0	0
4	60	30	150	11	1	0	0
4	60	30	150	11	2	0	0
4	60	30	150	11	3	0	0
4	60	30	150	11	4	0	0
4	60	60	150	12	1	1000	10
4	60	60	150	12	2	2275	22.75
4	60	60	150	12	3	930	9.3
4	60	60	150	12	4	620	6.2
4	60	90	150	13	1	2240	22.4
4	60	90	150	13	2	3375	33.75
4	60	90	150	13	3	2220	22.2
4	60	90	150	13	4	645	6.45
4	60	60	0	14	1	3075	30.75
4	60	60	0	14	2	1805	18.05
4	60	60	0	14	3	1435	14.35
4	60	60	0	14	4	1960	19.6
4	60	60	30	15	1	1660	16.6
4	60	60	30	15	2	3410	34.1
4	60	60	30	15	3	1630	16.3
4	60	60	30	15	4	2340	23.4
4	60	60	60	16	1	1185	11.85
4	60	60	60	16	2	2555	25.55
4	60	60	60	16	3	150	1.5
4	60	60	60	16	4	1850	18.5
4	60	60	90	17	1	1665	16.65
4	60	60	90	17	2	6370	63.7
4	60	60	90	17	3	1080	10.8

4	60	60	90	17	4	2615	26.15
4	60	60	120	18	1	5410	54.1
4	60	60	120	18	2	3680	36.8
4	60	60	120	18	3	3270	32.7
4	60	60	120	18	4	4285	42.85
4	60	60	150	19	1	2875	28.75
4	60	60	150	19	2	3255	32.55
4	60	60	150	19	3	1475	14.75
4	60	60	150	19	4	45	0.45
4	60	60	180	20	1	2565	25.65
4	60	60	180	20	2	3850	38.5
4	60	60	180	20	3	2330	23.3
4	60	60	180	20	4	1095	10.95

APPENDIX II: CASSAVA STARCH AND HCN DATA

1. CASSAVA SPECIFIC GRAVITY OF 3 AND 5 KG SAMPLES

Rep	Fertilizer Rate			Treatment ID	Wo (~3kg)	Wu (~3kg)	Wo (~5kg)	Wu (~5kg)	To	Tu	BC	SG = Wo/[Wo - (Wu + BC)]	
	N	P	K									~3Kg sample	~5Kg sample
1	0	0	0	1	2.99	0.7	0	0	0.38	0.33	0.05	1.334821429	0
1	60	0	0	2	2.3	0.56	0	0	0.38	0.33	0.05	1.360946746	0
1	0	60	0	3	2.19	0.59	0	0	0.38	0.33	0.05	1.412903226	0
1	0	0	150	4	3.01	0.41	5.18	0.72	0.38	0.33	0.05	1.180392157	1.174603175
1	0	60	150	5	3.05	0.7	5	0.98	0.38	0.33	0.05	1.326086957	1.259445844
1	25	60	150	6	3.09	0.71	5.01	0.98	0.38	0.33	0.05	1.326180258	1.25879397
1	50	60	150	7	3.08	0.42	5.15	0.75	0.38	0.33	0.05	1.180076628	1.183908046
1	75	60	150	8	3.04	0.71	0	0	0.38	0.33	0.05	1.333333333	0
1	100	60	150	9	3.9	0.54	0	0	0.38	0.33	0.05	1.178247734	0
1	60	0	150	10	3.27	0.72	0	0	0.38	0.33	0.05	1.308	0
1	60	30	150	11	3.05	0.67	5.05	0.99	0.38	0.33	0.05	1.309012876	1.259351621
1	60	60	150	12	3.05	0.7	0	0	0.38	0.33	0.05	1.326086957	0
1	60	90	150	13	3.08	0.7	5.01	0.96	0.38	0.33	0.05	1.321888412	1.2525
1	60	60	0	14	3.57	0.78	5.35	0.102	0.38	0.33	0.05	1.302919708	1.029242016
1	60	60	30	15	3.6	0.74	0	0	0.38	0.33	0.05	1.28113879	0
1	60	60	60	16	2.9	0.68	0	0	0.38	0.33	0.05	1.33640553	0
1	60	60	90	17	3.06	0.71	5.04	0.97	0.38	0.33	0.05	1.330434783	1.253731343
1	60	60	120	18	3.24	0.44	0	0	0.38	0.33	0.05	1.178181818	0
1	60	60	150	19	3.18	0.68	5.03	0.94	0.38	0.33	0.05	1.297959184	1.245049505
1	60	60	180	20	3.03	0.42	5.08	0.7	0.38	0.33	0.05	1.18359375	1.173210162
2	0	0	0	1	3.57	0.77	5.44	1.03	0.38	0.33	0.05	1.298181818	1.247706422
2	60	0	0	2	3.74	0.7	0	0	0.38	0.33	0.05	1.25083612	0

2	0	60	0	3	3.85	0.81	5.41	1.03	0.38	0.33	0.05	1.287625418	1.249422633
2	0	0	150	4	3.04	0.7	5.04	0.98	0.38	0.33	0.05	1.327510917	1.256857855
2	0	60	150	5	3.59	0.7	5.35	1.02	0.38	0.33	0.05	1.264084507	1.25
2	25	60	150	6	3.01	0.72	0	0	0.38	0.33	0.05	1.34375	0
2	50	60	150	7	3.21	0.5	5.15	0.78	0.38	0.33	0.05	1.206766917	1.19212963
2	75	60	150	8	3.39	0.65	5.36	0.85	0.38	0.33	0.05	1.260223048	1.201793722
2	100	60	150	9	3.26	0.7	5	0.85	0.38	0.33	0.05	1.298804781	1.219512195
2	60	0	150	10	3.9	0.81	5.45	1.02	0.38	0.33	0.05	1.282894737	1.244292237
2	60	30	150	11	3.02	0.7	5	0.85	0.38	0.33	0.05	1.330396476	1.219512195
2	60	60	150	12	3.87	0.84	0	0	0.38	0.33	0.05	1.298657718	0
2	60	90	150	13	3.15	0.7	5.01	0.93	0.38	0.33	0.05	1.3125	1.243176179
2	60	60	0	14	3.78	0.8	5.44	1.01	0.38	0.33	0.05	1.290102389	1.242009132
2	60	60	30	15	3.41	0.88	0	0	0.38	0.33	0.05	1.375	0
2	60	60	60	16	3.95	0.84	5.38	1.02	0.38	0.33	0.05	1.290849673	1.248259861
2	60	60	90	17	3.49	0.78	5.44	1.06	0.38	0.33	0.05	1.312030075	1.256351039
2	60	60	120	18	3.03	0.72	3.75	0.82	0.38	0.33	0.05	1.340707965	1.302083333
2	60	60	150	19	3.6	0.81	0	0	0.38	0.33	0.05	1.313868613	0
2	60	60	180	20	4.18	0.89	0	0	0.38	0.33	0.05	1.290123457	0
3	0	0	0	1	4.18	0.87	0	0	0.38	0.33	0.05	1.282208589	0
3	60	0	0	2	2.97	0.68	0	0	0.38	0.33	0.05	1.325892857	0
3	0	60	0	3	3.82	0.83	5.48	1.07	0.38	0.33	0.05	1.299319728	1.256880734
3	0	0	150	4	3.86	0.82	0	0	0.38	0.33	0.05	1.2909699	0
3	0	60	150	5	3.14	0.71	0	0	0.38	0.33	0.05	1.319327731	0
3	25	60	150	6	3.57	0.76	5.67	1.02	0.38	0.33	0.05	1.293478261	1.232608696
3	50	60	150	7	3.9	0.83	5.42	1.02	0.38	0.33	0.05	1.291390728	1.245977011
3	75	60	150	8	3.74	0.78	5.35	1	0.38	0.33	0.05	1.285223368	1.244186047
3	100	60	150	9	3.34	0.71	5.45	0.98	0.38	0.33	0.05	1.294573643	1.233031674
3	60	0	150	10	3.45	0.73	5.51	1.02	0.38	0.33	0.05	1.292134831	1.240990991

3	60	30	150	11	3.51	0.76	5.35	1.01	0.38	0.33	0.05	1.3	1.247086247
3	60	60	150	12	3.66	0.81	0	0	0.38	0.33	0.05	1.307142857	0
3	60	90	150	13	3.37	0.74	5.33	1	0.38	0.33	0.05	1.30620155	1.245327103
3	60	60	0	14	3.53	0.72	5.41	0.98	0.38	0.33	0.05	1.278985507	1.235159817
3	60	60	30	15	3.48	0.76	5.36	1.01	0.38	0.33	0.05	1.303370787	1.246511628
3	60	60	60	16	3.74	0.8	5.38	1.04	0.38	0.33	0.05	1.294117647	1.254079254
3	60	60	90	17	2.98	0.69	0	0	0.38	0.33	0.05	1.330357143	0
3	60	60	120	18	3.35	0.75	5.41	1.04	0.38	0.33	0.05	1.31372549	1.252314815
3	60	60	150	19	3.66	0.81	5.46	1.04	0.38	0.33	0.05	1.307142857	1.249427918
3	60	60	180	20	3.61	0.77	5.41	1.02	0.38	0.33	0.05	1.29390681	1.246543779
4	0	0	0	1	3.97	0.86	5.37	1.04	0.38	0.33	0.05	1.297385621	1.254672897
4	60	0	0	2	0	0	0	0	0.38	0.33	0.05	0	0
4	0	60	0	3	3.89	0.79	5.41	0.98	0.38	0.33	0.05	1.275409836	1.235159817
4	0	0	150	4	3.58	0.76	5.37	1	0.38	0.33	0.05	1.292418773	1.243055556
4	0	60	150	5	3.63	0.73	5.5	0.98	0.38	0.33	0.05	1.273684211	1.230425056
4	25	60	150	6	3.53	0.77	5.49	1.03	0.38	0.33	0.05	1.302583026	1.244897959
4	50	60	150	7	3.64	0.75	5.41	0.99	0.38	0.33	0.05	1.281690141	1.23798627
4	75	60	150	8	3.61	0.72	0	0	0.38	0.33	0.05	1.271126761	0
4	100	60	150	9	3.8	0.77	5.34	0.98	0.38	0.33	0.05	1.275167785	1.238979118
4	60	0	150	10	0	0	0	0	0.38	0.33	0.05	0	0
4	60	30	150	11	0	0	0	0	0.38	0.33	0.05	0	0
4	60	60	150	12	3.95	0.76	0	0	0.38	0.33	0.05	1.257961783	0
4	60	90	150	13	3.78	0.79	5.38	0.98	0.38	0.33	0.05	1.285714286	1.236781609
4	60	60	0	14	3.86	0.78	5.38	1	0.38	0.33	0.05	1.273927393	1.242494226
4	60	60	30	15	3.81	0.83	5.47	1.06	0.38	0.33	0.05	1.300341297	1.254587156
4	60	60	60	16	4.04	0.81	0	0	0.38	0.33	0.05	1.270440252	0
4	60	60	90	17	3.68	0.8	5.4	1.03	0.38	0.33	0.05	1.300353357	1.25
4	60	60	120	18	3.54	0.78	5.38	1.02	0.38	0.33	0.05	1.306273063	1.248259861

4	60	60	150	19	3.64	0.78	5.36	1.01	0.38	0.33	0.05	1.295373665	1.246511628
4	60	60	180	20	3.83	0.83	5.43	1.03	0.38	0.33	0.05	1.298305085	1.248275862

2. CYANIDE (HCN) STANDARD SAMPLES

RUN/SET	Sample #	Sample ID	Concentration	WL490.0
1	1	Standard 0.1	0	0
1	2	Standard 0.2	0	0
1	3	Standard 5.1	5	0.1495
1	4	Standard 5.2	5	0.1416
1	5	Standard 10.1	10	0.2091
1	6	Standard 10.2	10	0.2094
1	7	Standard 25.1	25	0.5368
1	8	Standard 25.2	25	0.4987
1	9	Standard 50.1	50	1.0215
1	10	Standard 50.2	50	0.9927
1	11	Standard 100.1	100	1.82
1	12	Standard 100.2	100	1.9004
2	1	Standard 0.1	0	0
2	2	Standard 0.2	0	0
2	3	Standard 5.1	5	0.0277
2	4	Standard 5.2	5	0.0331
2	5	Standard 10.1	10	0.1046
2	6	Standard 10.2	10	0.1069
2	7	Standard 25.1	25	0.3366
2	8	Standard 25.2	25	0.4102
2	9	Standard 50.1	50	0.9072
2	10	Standard 50.2	50	0.8593
2	11	Standard 100.1	100	1.6979
2	12	Standard 100.2	100	1.5893
3	1	Standard 0.1	0	0
3	2	Standard 0.2	0	0
3	3	Standard 5.1	5	0.0787
3	4	Standard 5.2	5	0.0878
3	5	Standard 10.1	10	0.1931
3	6	Standard 10.2	10	0.1784
3	7	Standard 25.1	25	0.4352
3	8	Standard 25.2	25	0.4857
3	9	Standard 50.1	50	0.9945
3	10	Standard 50.2	50	0.9018
3	11	Standard 100.1	100	1.8469

3	12	Standard 100.2	100	1.6835
4	1	Standard 0.1	0	0
4	2	Standard 0.2	0	0
4	3	Standard 5.1	5	0.0945
4	4	Standard 5.2	5	0.1007
4	5	Standard 10.1	10	0.2424
4	6	Standard 10.2	10	0.1798
4	7	Standard 25.1	25	0.5014
4	8	Standard 25.2	25	0.4721
4	9	Standard 50.1	50	0.9836
4	10	Standard 50.2	50	0.9693
4	11	Standard 100.1	100	1.7901
4	12	Standard 100.2	100	1.8488
5	1	Standard 0.1	0	0
5	2	Standard 0.2	0	0
5	3	Standard 5.1	5	0.0562
5	4	Standard 5.2	5	0.0391
5	5	Standard 10.1	10	0.1322
5	6	Standard 10.2	10	0.1376
5	7	Standard 25.1	25	0.3888
5	8	Standard 25.2	25	0.4035
5	9	Standard 50.1	50	0.8893
5	10	Standard 50.2	50	0.9234
5	11	Standard 100.1	100	1.6429
5	12	Standard 100.2	100	1.7469
6	1	Standard 0.1	0	0
6	2	Standard 0.2	0	0
6	3	Standard 5.1	5	0.0755
6	4	Standard 5.2	5	0.0367
6	5	Standard 10.1	10	0.1378
6	6	Standard 10.2	10	0.1404
6	7	Standard 25.1	25	0.4134
6	8	Standard 25.2	25	0.4112
6	9	Standard 50.1	50	0.9641
6	10	Standard 50.2	50	0.9597
6	11	Standard 100.1	100	1.7559
6	12	Standard 100.2	100	1.7296

3. CYANIDE (HCN) UNKNOWN SAMPLES

Sample/ Extraction #	Fertilizer Rate (Treatment)	Sample ID	Rep	RUN/ SET	Sample weight (g)	Absorbance (490 nm)	HCN (µg/ml)	HCN (µg/g sample)	HCN (mg/100 g sample)
1	0N0P0K	A1.1	1	1	5.0633	1.4795	82.9157303	818.7914042	81.87914042
2	0N0P0K	A1.2	1	1	5.0633	1.44	80.6966292	796.8778189	79.68778189
3	60N0P0K	A2.1	1	1	5.0259	1.1302	63.2921348	629.659711	62.9659711
4	60N0P0K	A2.2	1	1	5.0259	1.1367	63.6573034	633.2925782	63.32925782
5	0N60P0K	A3.1	1	1	5.0633	1.3223	74.0842697	731.5808827	73.15808827
6	0N60P0K	A3.2	1	1	5.0633	1.3285	74.4325843	735.0204834	73.50204834
7	0N0P150K	A4.1	1	1	5.002	1.7934	100.550562	1005.103577	100.5103577
8	0N0P150K	A4.2	1	1	5.002	1.7169	96.252809	962.1432326	96.21432326
9	0N60P150K	A5.1	1	1	5.0185	1.6025	89.8258427	894.9471226	89.49471226
10	0N60P150K	A5.2	1	1	5.0185	1.7727	99.3876404	990.2126178	99.02126178
11	25N60P150K	A6.1	1	1	5.0373	1.909	107.044944	1062.523016	106.2523016
12	25N60P150K	A6.2	1	1	5.0373	1.862	104.404494	1036.314041	103.6314041
13	50N60P150K	A7.1	1	1	5.0114	2.1388	119.955056	1196.821808	119.6821808
14	50N60P150K	A7.2	1	1	5.0114	2.0723	116.219101	1159.547244	115.9547244
15	75N60P150K	A8.1	1	1	5.0173	1.6696	93.5955056	932.7278179	93.27278179
16	75N60P150K	A8.2	1	1	5.0173	1.7019	95.4101124	950.8113164	95.08113164
17	100N60P150K	9A.1	1	1	5.0339	1.7382	97.4494382	967.9318044	96.79318044
18	100N60P150K	9A.2	1	1	5.0339	1.6465	92.2977528	916.7618825	91.67618825
19	60N0P150K	A10.1	1	1	6.0672	1.3915	77.9719101	642.5691432	64.25691432
20	60N0P150K	A10.1	1	1	5.0672	1.3995	78.4213483	773.8134306	77.38134306
21	60N30P150K	A11.1	1	1	5.0161	1.4131	79.1853933	789.3123468	78.93123468
22	60N30P150K	A11.1	1	1	5.0161	1.4256	79.8876404	796.312279	79.6312279

23	60N60P150K	A12.1	1	1	5.0457	0.4502	25.0898876	248.6264308	24.86264308
24	60N60P150K	A12.1	1	1	5.0457	0.6033	33.6910112	333.8586444	33.38586444
25	60N90P150K	A13.1	1	1	5.0072	1.5638	87.6516854	875.2564846	87.52564846
26	60N90P150K	A13.2	1	1	5.0072	1.4328	80.2921348	801.7668041	80.17668041
27	60N60P0K	A14.1	1	1	5.084	1.6025	89.8258427	883.417021	88.3417021
28	60N60P0K	A14.2	1	1	5.084	1.5376	86.1797753	847.5587655	84.75587655
29	60N60P30K	A15.1	1	1	5.1656	1.6025	89.8258427	869.4618505	86.94618505
30	60N60P30K	A15.2	1	1	5.1656	1.6167	90.6235955	877.1836331	87.71836331
31	60N60P60K	A16.1	1	1	5.0784	0.9119	51.0280899	502.4032164	50.24032164
32	60N60P60K	A16.2	1	1	5.0784	1.0823	60.6011236	596.655675	59.6655675
33	60N60P90K	A17.1	1	2	5.003	1.2068	67.5955056	675.5497263	67.55497263
34	60N60P90K	A17.2	1	2	5.003	1.1796	66.0674157	660.2779905	66.02779905
35	60N60P120K	A18.1	1	2	5.0462	0.8487	47.4775281	470.4285214	47.04285214
36	60N60P120K	A18.2	1	2	5.0462	0.8154	45.6067416	451.8919343	45.18919343
37	60N60P150K	A19.1	1	2	5.0042	1.9644	110.157303	1100.648489	110.0648489
38	60N60P150K	A19.2	1	2	5.0042	2.0057	112.477528	1123.831263	112.3831263
39	60N60P180K	A20.1	1	2	5	1.6015	89.7696629	897.6966292	89.76966292
40	60N60P180K	A20.2	1	2	5	1.5737	88.2078652	882.0786517	88.20786517
41	0N0P0K	B1.1	2	2	5.0092	1.6797	94.1629213	939.8997979	93.98997979
42	0N0P0K	B1.2	2	2	5.0092	1.7484	98.0224719	978.4244182	97.84244182
43	60N0P0K	B2.1	2	2	5.0675	1.2158	68.1011236	671.9400453	67.19400453
44	60N0P0K	B2.2	2	2	5.0675	1.2909	72.3202247	713.5690648	71.35690648
45	0N60P0K	B3.1	2	2	5.0098	1.2847	71.9719101	718.3112111	71.83112111
46	0N60P0K	B3.2	2	2	5.0098	1.3004	72.8539326	727.114182	72.7114182
47	0N0P150K	B4.1	2	2	5.037	1.731	97.0449438	963.3208638	96.33208638
48	0N0P150K	B4.2	2	2	5.037	1.7368	97.3707865	966.5553555	96.65553555
49	0N60P150K	B5.1	2	2	5.0607	1.0931	61.2078652	604.7371428	60.47371428
50	0N60P150K	B5.2	2	2	5.0607	1.064	59.5730337	588.5849162	58.85849162

51	25N60P150K	B6.1	2	2	5.0748	0.4173	23.241573	228.9900393	22.89900393
52	25N60P150K	B6.2	2	2	5.0748	0.4079	22.7134831	223.7869783	22.37869783
53	50N60P150K	B7.1	2	2	5.0635	1.0271	57.5	567.7890787	56.77890787
54	50N60P150K	B7.2	2	2	5.0635	1.0434	58.4157303	576.8315428	57.68315428
55	75N60P150K	B8.1	2	2	5.007	1.9977	112.02809	1118.714698	111.8714698
56	75N60P150K	B8.2	2	2	5.007	1.8679	104.735955	1045.895297	104.5895297
57	100N60P150K	B9.1	2	2	5.0705	1.8798	105.404494	1039.389551	103.9389551
58	100N60P150K	B9.2	2	2	5.0705	1.9134	107.292135	1058.003499	105.8003499
59	60N0P150K	B10.1	2	2	5.1054	0.4292	23.9101124	234.1649269	23.41649269
60	60N0P150K	B10.2	2	2	5.1054	0.4418	24.6179775	241.0974412	24.10974412
61	60N30P150K	B11.1	2	2	5.036	1.3922	78.011236	774.5357025	77.45357025
62	60N30P150K	B11.2	2	2	5.036	1.3786	77.247191	766.949871	76.6949871
63	60N60P150K	B12.1	2	3	5.0275	1.6234	91	905.0223769	90.50223769
64	60N60P150K	B12.1	2	3	5.0275	1.629	91.3146067	908.1512356	90.81512356
65	60N90P150K	B13.1	2	3	5.0254	1.5322	85.8764045	854.4235732	85.44235732
66	60N90P150K	B13.2	2	3	5.0254	1.6025	89.8258427	893.7183378	89.37183378
67	60N60P0K	B14.1	2	3	5.0316	1.5848	88.8314607	882.735717	88.2735717
68	60N60P0K	B14.2	2	3	5.0316	1.5571	87.2752809	867.2716521	86.72716521
69	60N60P30K	B15.1	2	3	5.0138	1.5021	84.1853933	839.536811	83.9536811
70	60N60P30K	B15.2	2	3	5.0138	1.4594	81.7865169	815.6140737	81.56140737
71	60N60P60K	B16.1	2	3	5.0123	1.1721	65.6460674	654.8497438	65.48497438
72	60N60P60K	B16.2	2	3	5.0123	1.1065	61.9606742	618.0862494	61.80862494
73	60N60P90K	B17.1	2	3	5.0196	1.7396	97.5280899	971.4727258	97.14727258
74	60N60P90K	B17.2	2	3	5.0196	1.7499	98.1067416	977.2366481	97.72366481
75	60N60P120K	B18.1	2	3	5.0044	0.6591	36.8258427	367.9346445	36.79346445
76	60N60P120K	B18.2	2	3	5.0044	0.6521	36.4325843	364.0055178	36.40055178
77	60N60P150K	B19.1	2	3	5.0233	0.25	13.8426966	137.7848887	13.77848887
78	60N60P150K	B19.2	2	3	5.0233	0.2685	14.8820225	148.1299392	14.81299392

79	60N60P180K	B20.1	2	3	5.0561	1.4779	82.8258427	819.0684786	81.90684786
80	60N60P180K	B20.1	2	3	5.0561	1.526	85.5280899	845.7911225	84.57911225
81	0N0P0K	C1.1	3	3	5.0126	1.9898	111.58427	1113.037841	111.3037841
82	0N0P0K	C1.1	3	3	5.0126	1.9644	110.157303	1098.804048	109.8804048
83	60N0P0K	C2.1	3	3	5.0289	0.6824	38.1348315	379.1567884	37.91567884
84	60N0P0K	C2.1	3	3	5.0289	0.6868	38.3820225	381.6144929	38.16144929
85	0N60P0K	C3.1	3	3	5.008	0.3011	16.7134831	166.8678429	16.68678429
86	0N60P0K	C3.2	3	3	5.008	0.3063	17.005618	169.7845245	16.97845245
87	0N0P150K	C4.1	3	3	5.0241	1.92	107.662921	1071.464753	107.1464753
88	0N0P150K	C4.2	3	3	5.0241	1.8838	105.629213	1051.225229	105.1225229
89	0N60P150K	C5.1	3	3	5.0253	2.0111	112.780899	1122.131006	112.2131006
90	0N60P150K	C5.2	3	3	5.0243	2.057	115.359551	1148.016147	114.8016147
91	25N60P150K	C6.1	3	3	0	0	0	0	0
92	25N60P150K	C6.2	3	3	0	0	0	0	0
93	50N60P150K	C7.1	3	4	5.0618	0.9919	55.5224719	548.4459274	54.84459274
94	50N60P150K	C7.2	3	4	5.0618	0.9862	55.2022472	545.2827768	54.52827768
95	75N60P150K	C8.1	3	4	5.0501	0.2993	16.6123596	164.4755505	16.44755505
96	75N60P150K	C8.2	3	4	5.0501	0.3322	18.4606742	182.7753327	18.27753327
97	100N60P150K	C9.1	3	4	5.0731	0.808	45.1910112	445.3983879	44.53983879
98	100N60P150K	C9.2	3	4	5.0731	0.8172	45.7078652	450.492452	45.0492452
99	60N0P150K	C10.1	3	4	5.0088	1.7225	96.5674157	963.9775568	96.39775568
100	60N0P150K	C10.2	3	4	5.0088	1.7469	97.9382022	977.6613385	97.76613385
101	60N30P150K	C11.1	3	4	5.0249	1.1335	63.4775281	631.6297647	63.16297647
102	60N30P150K	C11.2	3	4	5.0249	1.0369	58.0505618	577.6290254	57.76290254
103	60N60P150K	C12.1	3	4	5.0146	1.1485	64.3202247	641.3295649	64.13295649
104	60N60P150K	C12.2	3	4	5.0146	1.121	62.7752809	625.9251077	62.59251077
105	60N90P150K	C13.1	3	4	5.0325	1.3331	74.6910112	742.0865498	74.20865498
106	60N90P150K	C13.2	3	4	5.0325	1.3623	76.3314607	758.3851036	75.83851036

107	60N60P0K	C14.1	3	4	5.009	1.5029	84.2303371	840.7899489	84.07899489
108	60N60P0K	C14.2	3	4	5.009	1.526	85.5280899	853.7441594	85.37441594
109	60N60P30K	C15.1	3	4	5.0105	0.2991	16.6011236	165.6633429	16.56633429
110	60N60P30K	C15.2	3	4	5.0105	0.308	17.1011236	170.6528649	17.06528649
111	60N60P60K	C16.1	3	4	5.0111	0.9305	52.0730337	519.5768764	51.95768764
112	60N60P60K	C16.2	3	4	5.0111	0.9249	51.758427	516.4377778	51.64377778
113	60N60P90K	C17.1	3	4	5.0233	1.3195	73.9269663	735.8406455	73.58406455
114	60N60P90K	C17.2	3	4	5.0233	1.2392	69.4157303	690.9375345	69.09375345
115	60N60P120K	C18.1	3	4	5.0871	1.836	102.94382	1011.81243	101.181243
116	60N60P120K	C18.2	3	4	5.0871	1.836	102.94382	1011.81243	101.181243
117	60N60P150K	C19.1	3	4	5.0006	0.3779	21.0280899	210.2556682	21.02556682
118	60N60P150K	C19.2	3	4	5.0006	0.3812	21.2134831	212.1093783	21.21093783
119	60N60P180K	C20.1	3	4	5.0072	0.9149	51.1966292	511.2301208	51.12301208
120	60N60P180K	C20.2	3	4	5.0072	0.832	46.5393258	464.7240558	46.47240558
121	0N0P0K	D1.1	4	4	5.0038	0.2935	16.2865169	162.741485	16.2741485
122	0N0P0K	D1.2	4	4	5.0038	0.3492	19.4157303	194.0098559	19.40098559
123	60N0P0K	D2.1	4	5	0	0	0	0	0
124	60N0P0K	D2.2	4	5	0	0	0	0	0
125	0N60P0K	D3.1	4	5	5.0005	0.4026	22.4157303	224.1348899	22.41348899
126	0N60P0K	D3.2	4	5	5.0005	0.3776	21.011236	210.0913504	21.00913504
127	0N0P150K	D4.1	4	5	5.0016	1.4096	78.988764	789.6349573	78.96349573
128	0N0P150K	D4.2	4	5	5.0016	1.4335	80.3314607	803.0576283	80.30576283
129	0N60P150K	D5.1	4	5	5.002	0.2836	15.7303371	157.2404746	15.72404746
130	0N60P150K	D5.2	4	5	5.002	0.276	15.3033708	152.9725189	15.29725189
131	25N60P150K	D6.1	4	5	5.0231	1.6658	93.3820225	929.5258155	92.95258155
132	25N60P150K	D6.2	4	5	5.0231	1.7211	96.488764	960.4503598	96.04503598
133	50N60P150K	D7.1	4	5	5.0485	0.9895	55.3876404	548.5554169	54.85554169
134	50N60P150K	D7.2	4	5	5.0485	0.9935	55.6123596	550.7810196	55.07810196

135	75N60P150K	D8.1	4	5	5.0261	0.6747	37.7022472	375.0646345	37.50646345
136	75N60P150K	D8.2	4	5	5.0261	0.7216	40.3370787	401.2761251	40.12761251
137	100N60P150K	D9.1	4	5	5.0153	0.5079	28.3314607	282.4503088	28.24503088
138	100N60P150K	D9.2	4	5	5.0153	0.484	26.988764	269.0643037	26.90643037
139	60N0P150K	D10.1	4	5	0	0	0	0	0
140	60N0P150K	D10.2	4	5	0	0	0	0	0
141	60N30P150K	D11.1	4	5	0	0	0	0	0
142	60N30P150K	D11.2	4	5	0	0	0	0	0
143	60N60P150K	D12.1	4	5	5.0045	1.1663	65.3202247	652.6148938	65.26148938
144	60N60P150K	D12.2	4	5	5.0045	1.2136	67.9775281	679.1640333	67.91640333
145	60N90P150K	D13.1	4	5	5.0053	1.0416	58.3146067	582.5285871	58.25285871
146	60N90P150K	D13.2	4	5	5.0053	1.0615	59.4325843	593.6965244	59.36965244
147	60N60P0K	D14.1	4	5	5.0304	0.3693	20.5449438	204.2078544	20.42078544
148	60N60P0K	D14.2	4	5	5.0404	0.4242	23.6292135	234.3981974	23.43981974
149	60N60P30K	D15.1	4	5	5.0007	0.307	17.0449438	170.4255786	17.04255786
150	60N60P30K	D15.2	4	5	5.0007	0.2668	14.7865169	147.8444703	14.78444703
151	60N60P60K	D16.1	4	5	5.0866	0.3252	18.0674157	177.5981572	17.75981572
152	60N60P60K	D16.2	4	5	5.0866	0.3604	20.0449438	197.0367615	19.70367615
153	60N60P90K	D17.1	4	5	5.0059	0.2709	15.0168539	149.9915493	14.99915493
154	60N60P90K	D17.2	4	5	5.0059	0.2774	15.3820225	153.6389308	15.36389308
155	60N60P120K	D18.1	4	6	5.012	0.4978	27.7640449	276.9757077	27.69757077
156	60N60P120K	D18.2	4	6	5.012	0.5554	31	309.2577813	30.92577813
157	60N60P150K	D19.1	4	6	5.0025	1.4866	83.3146067	832.7297026	83.27297026
158	60N60P150K	D19.2	4	6	5.0025	1.4732	82.5617978	825.2053748	82.52053748
159	60N60P180K	D20.1	4	6	5.0785	0.5445	30.3876404	299.1792896	29.91792896
160	60N60P180K	D20.2	4	6	5.0785	0.5094	28.4157303	279.764993	27.9764993

APPENDIX III: MAIZE GRAIN YIELD DATA

1. MAIZE GRAIN YIELD: N STUDIES DATA

N-Study								
No-Till + Vertisol			No-Till + Inceptisol			Till + Vertisol		
Rep	Fert. Rate	Yield	Rep	Fert. Rate	Yield	Rep	Fert. Rate	Yield
1	0	3.46	1	0	1.54	1	0	4.36
1	50	4.62	1	50	2.21	1	50	6.47
1	100	6.35	1	100	3.08	1	100	6.74
1	150	7.5	1	150	6.47	1	150	9.37
1	200	7.85	1	200	6.38	1	200	5.76
2	0	5.88	2	0	0.63	2	0	3.85
2	50	6.67	2	50	2.07	2	50	6.98
2	100	6.25	2	100	3.04	2	100	6.11
2	150	7.14	2	150	4.83	2	150	7.25
2	200	7.71	2	200	3.83	2	200	7.06
3	0	3.9	3	0	0.9	3	0	2.1
3	50	4.4	3	50	3.36	3	50	5.94
3	100	7.2	3	100	2.4	3	100	7.99
3	150	8.43	3	150	4.03	3	150	7.34
3	200	8.11	3	200	3.47	3	200	8.44
4	0	5.03	4	0	0.94	4	0	4.53
4	50	5.33	4	50	3.44	4	50	5.5
4	100	6.58	4	100	4.55	4	100	7.23
4	150	9.62	4	150	6.25	4	150	6.53
4	200	7.34	4	200	5.2	4	200	8.64

2. MAIZE GRAIN YIELD: P STUDIES DATA

P-Study					
Inceptisol			Vertisol		
Rep	Fert. Rate	Yield	Rep	Fert. Rate	Yield
1	0	3.55	1	0	9.12
1	30	4.33	1	30	8.02
1	60	4.83	1	60	7.15
1	90	5.67	1	90	8.01
1	120	6.03	1	120	8.87
2	0	3.06	2	0	5.86
2	30	4.41	2	30	8.74
2	60	5.69	2	60	6.16
2	90	4.01	2	90	7.13
2	120	5.37	2	120	7.94
3	0	2.7	3	0	7.39
3	30	3.58	3	30	7.52
3	60	4.08	3	60	9.35
3	90	4.48	3	90	9.18
3	120	3.46	3	120	8.03
4	0	4.34	4	0	8.15
4	30	7.57	4	30	7.35
4	60	7.44	4	60	6.07
4	90	8.22	4	90	7.71
4	120	7.85	4	120	9.46

3. MAIZE GRAIN YIELD: K STUDIES DATA

K-Study					
Vertisol			Inceptisol		
Rep	Fert. Rate	Yield	Rep	Fert. Rate	Yield
1	0	8.58	1	0	7.38
1	20	6.53	1	20	5.32
1	40	6.9	1	40	5.72
1	60	9.79	1	60	6.49
1	80	8.37	1	80	5.46
2	0	8.8	2	0	5
2	20	7.31	2	20	7.84
2	40	6.94	2	40	5.98
2	60	7.34	2	60	5.53
2	80	5.64	2	80	4.14
3	0	5.75	3	0	6.37
3	20	7.75	3	20	5.68
3	40	7.49	3	40	6.05
3	60	6.48	3	60	6.32
3	80	7.19	3	80	6.43
4	0	7.06	4	0	5.55
4	20	6.67	4	20	4.88
4	40	7.48	4	40	8.83
4	60	8	4	60	6.64
4	80	7.7	4	80	6.39

VITA

Ivan Bernardo Cuvaca was born in 1988. He received his B.S./HONORS in Agricultural Engineering from Instituto Superior Politécnico de Manica (Mozambique) in August 2010. He began his graduate studies at the University of Tennessee in August of 2012, resulting in the preceding thesis and his graduation from the Master of Science in Environmental and Soil Science program of the Biosystems Engineering and Soil Science department in August of 2014.