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Studies of the growth and mineral nutrition of cassava (*Manihot esculenta* Crantz) grown as an industrial crop

by

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DECLARATION

I, Zethu Sifundo Isiphile Thabethe declare that this dissertation, which I hereby submit for the degree of MSc (Agric) Agronomy at the University of Pretoria is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE:

DATE: 2 December 2019

DEDICATION

To my late:

Mother Thulisile C. Masilela

Grandmother Elizabeth B. Malinga

Grandfather Humphrey Masilela

Grandfather Andrias S. Ginindza

Ngiyabonga kakhulu ngekungikhulisa ngibe ngulomuntfu lenginguye namuhla. Inzima leniyidlalile emphilweni yami yinkhulu kakhulu, angiyuze ngiyi khohlwe nanini nanini. Ngiyetsemba nitawuchubeka ningikhanyisela etindleleni tami niphindze nichubeke ningivikele kuko konkhe lokubi.

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ABSTRACT

Cassava (*Manihot esculenta* Crantz) is a substantial contributor to the food and industrial crops sectors in most African, Asian and Latin American countries. However, cassava production in Africa has been threatened by the shortage of improved cultivars and a decrease in soil fertility linked with continuous cultivation, while inadequately applying macronutrients; nitrogen (N), phosphorus (P) and potassium (K). The objectives of this study were to: (i) Assess the growth and yield performance of two local cassava cultivars (P4/10 and MSAF-1) in Mbombela, Mpumalanga, South Africa (SA), (ii) Examine the effects of different combinations of NPK on cassava growth and yield, and (iii) Evaluate the utility of SPAD-meter for assessing N status in cassava plants. The P4/10 and MSAF-1 cultivars growth and yield parameters were evaluated in a field experiment. MSAF-2 cultivar was planted in a greenhouse to optimize N and K applied at 0, 100, 150 and 200 kg ha^{-1} and P at 0, 15, 20 and 30 kg ha^{-1}. MSAF-2 was also planted in a greenhouse to assess N status of the plants fertilized at N rates of 0, 100, 150 and 200 kg ha^{-1}. SPAD-meter readings collected from five different leaf positions (Lf_1 – Lf_5) located at the top of the main stem. The results showed that MSAF-1 growth and yield parameters were significantly higher ($p < 0.05$) than those of P4/10 over time. The differences between the parameters were attributed to genotypic variation since the cultivars were grown under the same conditions. The three-way interaction (N × P × K) had a significant effect ($p < 0.05$) on the growth and yield over time. Both growth and yield parameters increased with increase in NPK application rates. Growth parameters were promoted by the different NPK combinations, but the best combination for cassava output was 200 kg ha^{-1} N, 30 kg ha^{-1} P and 150 kg ha^{-1} K. SPAD readings were found to be significantly influenced ($p < 0.05$) by N application rates and leaf position over time. The N application rates and leaf N concentration levels at 98 days after planting (DAT) were positively correlated with the lower leaves (Lf_4 and Lf_5) together with Lf_3, but negatively correlated with uppermost leaves (Lf_1 and Lf_2). However, the lower leaves readings were almost similar but higher than Lf_3 and therefore their average was used to assess nitrogen sufficiency index (NSI). The highest mean NSI values were obtained when 200 kg ha^{-1} N was applied (NSI = 1.04) compared to 0.99 and 0.88 when 100 and 0 kg ha^{-1} N was applied.

Key-words: P4/10, MSAF-1, MSAF-2, nitrogen, phosphorus, potassium, SPAD-meter readings, nitrogen sufficiency index, South Africa

CHAPTER 1

GENERAL INTRODUCTION

1.1 BACKGROUND AND PROBLEM STATEMENT

Cassava (*Manihot esculenta*) is among the crops which were sidestepped by 'Green evolution' in the 1960's. El-Sharkawy (2006) stated that this was because the international agricultural research center's only focused on the improvement of major cereal crops particularly; wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.) and maize (*Zea mays* L.). Cassava research has since been given a chance by the establishment of Consultative Group on International Agricultural Research (CGIAR) in 1971 in collaboration with the International Institute of Tropical Agriculture (IITA) (El-Sharkawy 2006). Currently, the crop is extensively cultivated in Asia, Latin America and Africa for its storage roots as a food source (Howeler 2012). This crop is considered as a basic crop for over half a billion human population worldwide (Ogola and Mathews 2011). It is an important industrial crop used in the production of pharmaceuticals, alcohol, confectioneries and glucose (Kanju et al. 2019). In African countries, cassava plays a major part in food security, income generation and employment for small-holder farmers (Uwah et al. 2013a). The leaves and tender shoots of the shrub can be consumed as vegetables in most parts of Africa (Akinpelu et al. 2011). Latin Americans and Asians, use the crop to produce ethanol which is later converted into fuel and alcohol (Leong 2016). In several areas of South Africa (SA), cassava is sold in retail markets as fresh roots and flour.

Empirical evidence gained over the years of cassava cultivation has shown that this crop is inherently drought tolerant and can survive in places and conditions under which other important crops may fail to perform well (Hershey 1984, Howeler 2000, El-Sharkawy 2007). The crop adapt to water stress by maintaining reasonable photosynthetic rates and reducing transpiration losses (El-Sharkawy 2003, 2007). The leaves partially closes stomata in response to both soil water and atmospheric stress (El-Sharkawy and De Tafur 2007). Furthermore, cassava leaves fold in order to reduce leaf temperature during water stress conditions (Alves and Setter 2004, Ogola and Mathews 2011). Moreover, during water stress conditions the total leaf area (LA) is reduced but the plant is capable of recovering from that by producing new leaves thus regaining LA leading to higher rates of photosynthesis (El-Sharkawy 1993, Alves

and Setter 2000, 2004). All these characteristics offer cassava relative dominance in marginal environments where other crops fail (Howeler 2002).

According to Ezui (2017), cassava can adapt in soils with pH levels below seven since the crop can tolerate acidic soils. Generally, cassava is widely cultivated in areas with low or without the application of fertilizers, without pests and diseases control and in areas with zero irrigation (Howeler 2012, Leong 2016). The crop undergoes multiple growing seasons since cultivars harvesting periods range from 6 – 30 months after planting (MAP) (Howeler 2012). The long growing cycle of some cultivars can expose them to a wide range of environmental, climatic and biological stresses (Ogola and Mathews 2011). Pests and diseases find these cassava cultivars as potential host, more so when the crop is planted in high densities as a monocrop (Uzokwe et al. 2016). According to Ogola and Mathews (2011), cassava growth is inhibited by cold due to a substantial reduction in photosynthetic rate.

Adequate fertilization coupled with good soil fertility have been reported to increase the yield potential of cassava (Macalou 2018). According to Howeler (2012) the major nutrients needed by the crop to obtain maximum yields are N and K. Adequate levels of K in the soil have been reported to increase the absorption of N by cassava plants, however excess amounts of N and K can lead to aboveground growth on the account of below ground growth (Howeler 2002, Macalou 2018). The continuous growth of the crop without practicing crop rotation results in fast depletion of major nutrients, especially N, P and K thus fertilizer addition is required to give acceptable and stable yields (Howeler 2014).

The worldwide production of cassava in 2009 was reported to be 241 million tons, with Africa as the leading producer (Ogola and Mathews 2011). However, the production of cassava in SA is insignificant. Therefore, evaluation of yield maximization strategies for this crop need to be documented in SA. Currently in the country, cassava is produced particularly by smallholder farmers in the Limpopo, KwaZulu-Natal and Mpumalanga provinces of SA (Ogola and Mathews 2011).

1.2 JUSTIFICATION OF THE STUDY

In order to meet the rising demand for cassava in the developing industrial crops sector in SA, appropriate agronomic information on cultivars and NPK fertilization is necessary and should be made available. Optimization and developing fertilizer recommendations together with evaluating adaptability of cultivars will contribute in enhancing cassava productivity thus increasing raw material for cassava products and food security especially for smallholder

farmers in SA. In addition, studying the above aspects will help in organizing cost-effective production strategies.

1.3 RESEARCH HYPOTHESES AND OBJECTIVES

The study focus was to evaluate some of the agronomic aspects for cassava production in SA. The three main factors that were investigated included cultivars adaptability, optimization of NPK and leaf N assessment. It was therefore, hypothesized that;

1. The environmental conditions in Mpumalanga will enhance growth and improve the yield of cassava.
2. The combination effects of NPK will improve cassava growth and yield better than the individual elements.
3. SPAD-meter readings are a good indicator of N status in cassava leaves.

The study intended to test the above hypotheses through the below objectives;

1. To assess the growth and yield performance of two local cassava cultivars in Mbombela, Mpumalanga, SA.
2. To examine the effects of different combinations of NPK on cassava growth and yield.
3. To evaluate the utility of SPAD-meter for assessing N status in cassava plants.

1.4 DISSERTATION LAYOUT

The study is presented in six chapters. Chapter 1 is a review of the cassava plant, uses and challenges facing its production. The origin, distribution, botany, environmental and nutritional requirements of the crop are reviewed in Chapter 2. Chapter 3 is focused on the field evaluation of growth and yield parameters for two local cultivars of cassava in Mbombela, Mpumalanga, SA. Results of a greenhouse experiment conducted to evaluate the growth and yield responses of cassava to different NPK combinations are presented in Chapter 4. Chapter 5 was also based on another greenhouse experiment to investigate the use of SPAD-502 chlorophyll meter as a method of assessing leaf nitrogen in cassava. Finally, Chapter 6 provides the general conclusions, recommendations and areas of future research.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The region of domestication for cassava (*Manihot esculenta* Crantz) is not clear but the current assent is that it is somewhere in South or Central America (Howeler 2012). Most indigenous relatives of cassava are found across southern parts of Brazil (Nassar and Ortiz 2007, Lebot 2009). Akinpelu et al. (2011), stated that cassava has been cultivated for over 4000 years by native Indian in Latin America. According to Balagopalan (2018), cassava was introduced to tropical zones of Africa by Portuguese who colonized South Americans in 1500 A.D, between the 16th and 17th centuries. These Portuguese conveyed cassava from South American regions to Africa and Asia. In Africa, cassava was firstly introduced in West Africa through the Gulf of Benin in the 16th and 17th centuries followed by East Africa in the 18th century through the island of Reunion, Madagascar and Zanzibar (Olsen and Schaal 1999, Howeler 2012). Widespread cultivation of cassava in Africa, was observed after the second half of the 18th century (Howeler 2012).

In Southern Africa, cassava was first introduced in Mozambique by the Portuguese during the 17th century (Mabasa 2008). Tsonga people used to consume cassava as food, and later spread the crop into the Kingdom of Swaziland and then to the Mpumalanga province of South Africa (SA) (Ogola and Mathews 2011). The crop was further spread southwards into Northern KwaZulu-Natal province of SA (Woodward et al. 1997). In Zimbabwe and Malawi, cassava was introduced through the trading paths of the Portuguese on the east coast of Africa from Mozambique. Haggblade and Zulu (2003) stated that in Zambia, the crop was introduced through the Congo basin on the last half of the 16th century.

A lot of research on cassava has been done in Asia, Latin America, the West and Eastern parts of Africa but not much research has been done in Southern African countries (Howeler 2012). Research work done in Asia has shown that cassava is a multi-purpose crop and more attention should be given to this crop. In West Africa, it was reported that, sub-optimal management of nutrients and water contributed to yield losses (Ezui 2017). The ability of the crop to produce reasonable yields on soils with poor fertility levels has led to the misconception that this crop does not need or even respond to fertilization (Biratu et al. 2018). Due to this, soil fertility is a major factor reducing cassava yields (Ezui et al. 2018).

The total global production of cassava has been growing tremendously over the past years. The total worldwide production of fresh storage roots was reported to be 277 million metric tons (MT) in 2013 (Ezui 2017). The production increased by 12.5% between 1900 and 1988. Moreover, statistics showed 25% increase between 2002 and 2008 (Sarfo 2016). In 2002, the total production was approximately 184 million MT then increased up to 230 million MT in 2008. The largest production came from Africa with 99.1 MT, followed by Asia with 51.5 MT then Latin America and the Caribbean with 33.2 MT (Sarfo 2016). The world's largest producer of the crop is Nigeria with a total production of over 45 million MT. However, dried cassava is largely exported by Thailand. Howeler (2012) reported that in 2005; Thailand, Vietnam, Indonesia and Costa Rica exported; 77, 13.6, 5.8 and 2.1%, respectively. Howeler (2012) also reported that, 12.5 t ha^{-1} was the average yield worldwide in 2010. India has the most productive farms of cassava, with an average yield 34.8 t ha^{-1} countrywide (Howeler 2000). Cassava is grown as a secondary crop in South Africa by smallholders and is utilized for the production of starch (commercial and food grade starch). Currently, 20 000 tons of its starch are produced commercially.

2.1.1 Cassava potential in Southern Africa

The Limpopo, Kwazulu-Natal and Mpumalanga are the provinces in which cassava is largely grown in SA (Ogola and Mathews 2011, Mkruqulwa et al. 2017). The crop is used in the production of starch products at Dendron in Limpopo province by a factory called Cassava Starch Manufacturing (CSM) Company (Mabasa 2008). The starch produced in the factory is largely utilized in the textile, paper, food and cardboard industries. The firm is cultivating cassava for raw materials in about 2000 hectares of land. However, this is not enough thus the firm get more raw materials from contracting small-scale farmers. Currently in the Mpumalanga province, commercial farms are planning on constructing a second factory for cassava in SA at Barberton.

In Mozambique, the crop is cultivated in the northern part of the country where it is consumed as a staple crop in Nampula, Zambezi and Cabo Delgado provinces (Sseruwagi et al. 2004). The crop was introduced together with sweet potato (*Ipomoea batatas* L.) in regions that are drought susceptible by the government of Mozambique (Swap et al. 2003). Most Southern African countries had limited large-scale production of cassava due to the taste preference for maize (*Zea mays* L.) and also the post-colonial government policies favored maize over cassava (Mabasa 2008). Consequently, maize has been cultivated in areas that are

not even environmentally suitable to it and where the performance of cassava would be far better. Due to climate change since the 1990's, maize production has decreased as conditions are becoming more unsuitable. Efforts on promoting cassava cultivation have been observed in Zambia and Malawi. The annual production of cassava in these countries has increased by approximately 8%, which has been reported to be the fastest increase rate in Africa and worldwide (Haggblade and Zulu 2003). Lack of proper information about fertilizers has contributed in poor productivity in Southern African countries in particular. The typical yields of cassava do not exceed 10.5 t ha^{-1} in Mozambique and Lesotho (Ogola and Mathews 2011). As a result, the Southern African region is amongst the most food insecure and vulnerable regions in the world.

In the sequence to meet the demand of food by the ever rising population, the first step is to increase agricultural productivity. Farmers can intensify crop production by; converting more land to the production of crops, shortening fallow periods and refraining from non-suitable tillage and mixed farming systems (Henao and Baanante 2006). In addition, farmers need to use fertilizer information based on research recommendations. Fertilizer; price, availability, soil fertility status, application rates and time of application are some of the factors influencing fertilizer use. Therefore, ways in which fertilizers can be incorporated into agricultural systems to potentially increase cassava storage roots yield should be investigated. Since, this crop has the potential of improving subsistence farming as it can provide opportunities for poor farmers to develop a cash crop. It is important that intensive agricultural strategies are adopted in order to improve cassava production.

2.2 BOTANY AND PHYSIOLOGY

Cassava is a shrubby perennial that grows from 1 – 5 m in plant height (Howeler 2012). This crop is classified under the Euphorbiaceae family which also consist of commercially cultivated crops like, rubber (*Havea bransiliensis* L.) and castor bean (*Ricinus communis* L.). The Genus '*Manihot*' is made up of about 100 species but *Manihot esculenta* Crantz. is the only species in the world largely cultivated (Alves 2002). This crop can be propagated using sexual seeds or stem cuttings. However, plants from sexual seeds take longer time to establish and they are even less vigorous and smaller than plants from stem cuttings (Ewa 2018). Plants propagated from stem cuttings can begin adventitious rooting and sprouting at seven days after planting (DAP) in favorable conditions (El-Sharkawy 2003).

Cassava is classified under monoecious species since it has both the male and female flowers in one plant (El-Sharkawy 2003). The inflorescence is either configured from the upper part of the plant leaf apex or terminal bud of the stem (Alves 2002). The female flower is located at the bottom part of the inflorescence and it usually begin unbolting between 10 and 14 days prior to the male flower in one branch (El-Sharkawy 2003). The opening of a male flower from a different branch or on a different plant of the same genotype can result to self-fertilization of the female flower through insect cross-pollination (Alves 2002, Sarfo 2016). The female flower is double the size of the male flower (Alves 2002).

Generally, this crop is exposed to alternating vegetative growth periods as a result of its perennial nature (Howeler 2012). It develops a majority of its leaves and stems from 30 – 180 DAP and therefore, maximum canopy size is reached at 180 DAP (Howeler 2012). The rate of leaf senescence increases during 180 – 300 DAP. The abscission period occurs at 210 DAP resulting to stem lignification. The growth cycle of cassava is completed at 360 DAP (Alves and Setter 2004). Some cassava cultivars do not develop branches while others develop branches with a minimum height of 20 cm. The leaves are unevenly divided into 3 – 9 lobes. Each leaf is attached on the stem through a petiole which has a light greenish to red color (El-Sharkawy 2003).

Cassava roots are anatomically not tuberous, but are true roots and hence they cannot be used for propagation (El-Sharkawy 2003). Mature storage roots have three different tissues; periderm, cortex and parenchyma. The edible tissue of the root is called parenchyma and it is made up of about 85% of the total weight which consists of xylem vascular bundles that are distributed radially in a matrix with cells containing starch (Alves 2002). The cortex make up 11 – 20% of the total storage roots weight and the periderm which is the outermost tissue of the roots, only make up 3% of the total root weight (Alves 2002, El-Sharkawy 2003). Cassava rooting system is sparsely oriented, and thus most of its roots are found in the topsoil and a very few descend beyond two meters (m) (Sriroth et al. 2001). The average length of economic roots can be 15 – 30 cm and their width is 5 – 10 cm (Howeler 2012). According to Alves (2002), initiation of economic roots begins at 60 – 90 DAP and maximum dry matter (DM) accumulation occurs from 180 – 300 DAP in the storage roots.

2.2.1 Photosynthesis and dry matter partitioning

Cassava has an unusual photosynthetic pathway as it is characterized by both C3 and C4 photosynthesis pathways (Palta 1983, Gleadow et al. 2009, Jansson et al. 2009). Cassava

is a C3 species but performs like a C4 species, hence it has elevated carbohydrates productivity (El-Sharkawy and De Tafur 2010). This crop has a high photosynthetic capacity under both stressful and favorable conditions. The anatomy of a cassava leaf has bundle sheaths with thin cell walls but not as well-formed as in a C4 plant Kranz anatomy (El-Sharkawy 2007). In addition, cassava has a low photorespiration under high leaf temperatures and photon flux densities (PFD) (El-Sharkawy and De Tafur 2007). The chloroplasts have close physical association with peroxisomes of the mesophyll cells, bundle-sheath and several mitochondria (El-Sharkawy and De Tafur 2010). The incorporation of carbon into C4 acids, has a high percentage even when exposed in two to five seconds of carbon dioxide (CO_2) under irradiation (El-Sharkawy and De Tafur 2007). Cassava has the ability to reprocess CO_2 in the amphistomatous palisade cell leaves at fluctuating temperatures and PFD when the stomata is closed (Rosenthal et al. 2012). This crop has elevated phosphoenolpyruvate carboxylase (PEPC) activities that support internal CO_2 recycling which help in utilizing the extra photon energy, while avoiding photo-inhibition of photosynthetic apparatus and leaf damage (Setter and Fregene 2007). The ratio of intercellular to ambient CO_2 concentration (Ci/Ca) of this C3 species is same to the amount obtained in C4 species, which is lesser than amounts obtained in other C3 plant species (El-Sharkawy and De Tafur 2007).

Canopy photosynthetic carbon absorption over the whole plant respiration influences the conversion efficiency of cassava (Liu et al. 2011). The conversion efficiency ranges from 0.69 – 0.94 g MJ^{-1}, which corresponds to the transduction energy intercepted by photosynthetic active radiation (PAR) (El-Sharkawy and De Tafur 2010). These values of cassava are less than the theoretical values of a C3 species (Hsiao 1973). According to El-Sharkawy et al. (1990), both the aboveground growth and storage roots growth are positively correlated to the rates of photosynthesis. Under field conditions, maximum rates of photosynthesis for cassava range from 20 – 35 µmol CO_2 m^{-1} s^{-1} (El-Sharkawy et al. 1990) and from 13 – 24 µmol CO_2 m^{-1} s^{-1} in growth chambers or greenhouse conditions (Edwards et al. 1990). This crop exhibits a high CO_2 compensation point ranging from 49 – 68 µl I^{-1} (Aslam et al. 1977). Cassava grown under field conditions require an optimum temperature of 35 °C for photosynthesis with a plateau varying between 25 and 35 °C (El-Sharkawy et al. 1990). The crop can absorb light between 1800 – 2000 µmol PAR m^{-1} s^{-1} (El-Sharkawy and De Tafur 2007).

During plant growth, carbohydrates from metabolic processes are distributed from the leaves (source) to the sinks which include the storage roots, growing leaves and stems (Alves 2002, El-Sharkawy 2003) . Cassava translocates more DM to the growing leaves from planting

up until 60 – 75 DAP (Benesi et al. 2004, Leong 2016). About 50 – 60% of the total DM is rapidly accumulated in the storage roots from 75 – 120 DAP (Lahai and Ekanayake 2009). The aboveground growth and below ground growth have been positively correlated during the cassava growth cycle when DM distribution is constant (Veltkamp 1985, Figueiredo et al. 2017).

According to Alves (2002), uneven distribution of accumulated DM occurs between three and five months after planting (MAP). Thus, the harvest index (HI) per plant is also increased during this period. Harvest index is used to measure the amount of DM accumulated in the economically important part of the plant. Cultivars have significant differences in HI values and thus, HI can also be utilized as a selective measure for cassava cultivars with higher yields (Alves 2002). Harvest index values between 10 and 12 MAP can range from 0.49 – 0.77 (Alves 2002, Singh et al. 2017). At high latitude, cassava has maximum DM accumulation from four to seven MAP (Howeler 2012). In more tropical regions, maximum DM accumulation occurs from three to five MAP (Chipeta et al. 2016).

Dry matter accumulation is not constant since it is highly dependent on the availability of photo-assimilates from the source and the sink storage capacity (Zhou et al. 2017). The sink capacity is determined by the total number of economic roots and their mean mass (Ihemere et al. 2006). The demand for photo-assimilates from the source to the storage roots increases photosynthetic activity (Alves 2002, El-Sharkawy 2003). Photosynthetic rate has a strong positive relationship with total biomass yield (Lenis et al. 2006). In order for plants to reach maximum production, there should be a balance between the source and sink. Ramanujam and Ghosh (1990) study concluded that, storage roots growth is independent of shoots growth rate. When the source size is increased it will influence the DM production, as an increase of the leaf area index (LAI) from 3.0 – 6.0 reduces the economic yield growth and net assimilation rate (NAR) (Lenis et al. 2006). There is a strong positive correlation that exists between the starch content and storage roots dry matter (Hayford Mathew 2009). Storage roots DM may explain 40% in the variation of cassava starch content (Baafi and Safo-Kantanka 2008). According to Baafi (2005), starch quality depends on the swelling power, water binding and solubility capacity.

2.2.2 Leaf area development

Plant growth and yield are usually analyzed based on LAI and NAR. Cassava leaf area (LA) and economic root yield have a strong positive relationship (Sinha and Nair 1971, Lenis

et al. 2006). This relationship indicates that LA is a major determinant of the rate of plant growth and bulking rate of storage roots. The crop LA is dependent on the number of branches, leaf formation rate per branch, leaf duration (LAD) and the size of the leaves. Leaf area is influenced by environmental conditions and genotypic formation (Lian and Cock 1979, Lenis et al. 2006). It takes about 10 – 12 days, under normal circumstances for a cassava leaf to reach its full size (Mitprasat et al. 2011). The cassava leaf life can be influenced by temperature, cultivar shade level and water availability (Irikura et al. 1979, El-Sharkawy 2006). Cassava leaf life is 60 – 120 days or 40 – 210 days under normal conditions (El-Sharkawy and De Tafur 2007). Maximum leaf size is achieved at three to four MAP but maximum LA is reached from 4 – 5 MAP (Lian and Cock 1979, El-Sharkawy 2006). Plants with less number of branches have larger leaves (El-Sharkawy 2006). Leaf formation is reduced as the plant ages and during low temperatures (Irikura et al. 1979, Mitprasat et al. 2011).

Cassava LAI is positively related to the canopy height (El-Sharkawy et al. 1998, El-Sharkawy 2003) and to root bulking rate (Lian and Cock 1979, El-Sharkawy 2006). In order to reach optimum root bulking rate, the optimum LAI value should be 3.0 – 3.5 (El-Sharkawy 2006). Values of about 1.0 are obtained from 60 – 80 DAP since initial LA development is sluggish (Alves and Setter 2000, El-Sharkawy 2006). The maximum LAI of 3.0 is obtained between 120 and 150 DAP since canopy development is around 90% during this period and hence the plant is able to absorb more photosynthetic light (Veltkamp 1985, Alves and Setter 2000). Leaf abscission begins when LAI reach 5.0 – 6.0 (Keating et al. 1982, Alves and Setter 2000, Hillocks et al. 2002). Leaf area index is affected by branch formation stage, as high values of LAI are obtained in early branching plants (El-Sharkawy et al. 1998). Biomass yield of aboveground plant parts and root yield vary amongst cassava cultivars. When 5% of LA is reached, the transition of cell division to cell expansion begins (Takami 1981, Alves 2002).

2.3 ENVIRONMENTAL REQUIREMENTS

Cassava can be grown under varying environmental and climatic conditions between latitude 30°N (north) and 30°S (south) (Alves 2002, Papong and Malakul 2010). Areas in which this crop is grown should be 2000 – 3000 m above sea level (Sarfo 2016). Maximum economic root production can be obtained in lowland areas of the tropics with an average altitude below 150 m but some cultivars do well in up to 1500 m altitudes (Howeler 2000).

The crop can grow in areas receiving an annual rainfall ranging from 500 – 5000 mm (Akinpelu et al. 2011). However, cassava grows best in warm humid climatic conditions with

well annual distribution of rainfall (1000 – 2000 mm) (Alves 2002). This crop can survive in areas receiving low rainfall or where rainfall distribution is uneven as it is a drought tolerant. During dry periods, the plant undergoes a period of dormancy lasting for maximum of two to three months and when rains begin, growth resumes (El-Sharkawy 2003, 2006).

Storage roots development is promoted in well drained, deep, friable sandy loam to loamy soils. Cassava can also survive in a broad range of heavy soil types (Howeler 2012). However, when cultivated on sandy soils, organic matter should be added to a depth 30 – 40 cm to improve drainage and increase clay content up to 18% since the crop is saline intolerant. This plant can also tolerate varying degrees of temperature, photoperiods and solar radiation (Alves 2002).

2.3.1 Soil characteristics

Cassava yield response in the soil is linked with total N, exchangeable K, available P, soil organic carbon (SOC) and the total bases. The critical soil nutrients for cassava are shown in Table 2.1. The crop can tolerate acidic soils with a low pH and exchangeable aluminium content (Howeler 2002). Therefore cassava does not need large quantities of lime for acidic soils, (Howeler et al. 2013). However, a balanced addition of macronutrients, micronutrients and secondary nutrients is required to obtain maximum yields (Howeler 2008).

Howeler (2002) reported that cassava response to the addition of calcium (Ca), magnesium (Mg) and sulphur (S) was significant. Calcium promotes the regulation and supply of water, while Mg is an important component of chlorophyll used in photosynthesis. Significant responses of cassava to Mg and Ca were found on sandy loam soils (Howeler and Cadavid 1990) and significant response to Mg were found on highly acidic soils (Howeler 1998). Sulphur is an important element of certain amino acids and is necessary in protein production. The crop is highly responsive to S applied from 20 – 40 kg ha^{-1}. Generally, S content is low in tropical soils thus cassava may respond to S application in tropical regions (Pypers et al. 2011). During the early stages of growth, cassava is sensitive to zinc (Zn) deficiency (Howeler 2002). Therefore, applying Zn at the same time with NPK can increase cassava yields significantly up to 12% in field experiments (Howeler 2012).

Table 2.1: Soil chemical characteristics approximate classification in relation to cassava nutritional requirements (Howeler 2000).

Soil parameter	Very low	Low	Medium	High	Very high
pH	<3.5	3.5 – 4.5	4.5 – 7	7 – 8	>8
OM	<1.0	1.0 – 2.0	2.0 – 4.0	>4.0	-
Al-saturation (%)	-	-	<75	75 – 85	>85
Na-saturation (%)	-	-	<2	2 – 10	>10
B (µg g^{-1})	<0.2	0.2 – 04	0.5 – 1.0	1 – 2	>2
Cu (µg g^{-1})	<0.1	0.1 – 03	0.3 – 1.0	1 – 5	>5
Fe (µg g^{-1})	<1	1 – 10	10 – 100	>100	-
Mn (µg g^{-1})	<5	5 – 10	10 – 100	100 – 250	>250
P (µg g^{-1})	<2	2 – 4	4 – 15	>15	-
S (µg g^{-1})	<20	20 – 40	40 – 70	>70	-
Zn (µg g^{-1})	<0.5	0.5 – 1.0	1.0 – 5.0	5 – 50	>50
Ca (me $100g^{-1}$)	<0.25	0.25 – 1.0	1.0 – 5.0	>5.0	-
K (me $100g^{-1}$)	<0.10	0.10 – 0.15	0.15 – 0.25	>0.25	-
Mg (me $100g^{-1}$)	<0.2	0.2 – 0.4	0.4 – 1.0	>1.0	-
Salinity (mS cm^{-1})	-	-	<0.5	0.5 – 1.0	>1.0

2.3.2 Temperature

Generally, temperature in cassava affects plant growth especially during sprouting and in the formation of leaves and storage roots (Hillocks et al. 2002). Cassava growth is favorable in temperatures that range from 25 – 29 °C but the crop can survive in a broad range of temperatures (16 – 38 °C) (Lenis et al. 2006). Temperatures below 16 °C delay stem cutting sprouting, and decreases the rate of storage roots and leaf production (Cock and Rosas 1975, Alves 2002). Sprouting is promoted in temperatures ranging between 16 and 30°C but inhibited by temperatures greater than 37 °C (Keating and Evenson 1979, El-Sharkawy 2006). Temperatures ranging from 15 – 24 °C promote leaf life to 200 days, meanwhile temperatures beyond 24 °C decrease leaf life up to 120 days (Splittstoesser and Tunya 1992). A summary of temperature ranges and their effects on physiological development of cassava is shown in Table 2.2. Photosynthesis is promoted between 30 and 40 °C (El-Sharkawy et al. 1992, El-Sharkawy 2006). Cultivars growing in cool temperatures had lower photosynthetic activities than those growing from warm temperatures (Alves 2002).

Table 2.2: Temperature effects on cassava growth and development (Alves 2002).

Air temperature (°C)	Physiological effects
< 15	Plant growth inhibited.
16 – 30	Transpiration rate increases linearly and declines.
16 – 38	Cassava can grow.
< 17	Leaf production, total and root dry weight are reduced.
< 17 or > 37	Spouting impaired.
20 – 24	Increase in leaf production and size.
25 – 29	Optimum plant growth.
25 – 30	Highest rates of photosynthesis in green house experiments.
28	Leaves shed faster and number of branches are reduced.
28.5 – 30	Optimum sprouting.
30 – 40	Maximum photosynthesis rates in field experiments.

2.3.3 Photoperiod and solar radiation

Tuberization, dry matter partitioning and flowering of cassava are affected by day length duration (El-Sharkawy 2006). Storage roots development is promoted by short days but inhibited by long days, while shoot development is promoted by long day but slowed down by short days, without influencing total dry weight (DW) (El-Sharkawy 2003). The significant increases in LA per plant, number of living leaves per apex, plant height and number of apices per plant increase the aboveground DW under long days (Veltkamp 1985, Alves 2002). Storage roots yield reduction is likely caused by the changes in DM distribution patterns rather than a delay in the initiation of storage roots (Keating et al. 1982, Alves 2002).

The most common cropping system of producing cassava is intercropping. Africans and Latin American usually intercrop cassava with legumes (*Phaseolus vulgaris* L.) and maize (Ramanujam and Ghosh 1990). Generally, these crops establish faster than cassava (Alves 2002). Perennial crops can also be intercropped with cassava for instance, coconut trees.

In order for cassava to have efficient photosynthesis it requires high solar radiation. Therefore, it is necessary to know about the effects of shading during crop growth and development (El-Sharkawy et al. 1992). Shading reduce NAR and economic roots production per stool. Okoli and Wilson (1986) conducted an experiment where cassava was submitted to six different degrees of shades and the results showed that shading delayed the rate of bulking in storage roots. As a results yields were decreased by 43, 56, 59, 69 and 80% at 20, 40, 50, 60 and 70% shading, respectively. Under field conditions, shading tend to increase plant height, LA per unit weight but shortens leaf life under severe shading (Ramanujam and Jos 1984). Shading levels less than 75% have been reported to have a very low effect on leaf life, but shades levels from 90 – 100% lead to leaf abscission within 10 days.

However, Aresta and Fukai (1984) reported that shoot growth rate decreased by 32% under 68% shade. In addition, 22% shade reduced fibrous roots elongation by 53% and storage roots were reduced by 36% without altering shoot growth. This results show that shoots are stronger sinks than roots (Alves 2002). Light intensity can re-arrange chloroplast thus affecting the relationship of optical/absolute chlorophyll (Nauš et al. 2010). Shade species have the greatest mean maximum change of the chloroplast with light transmission percentages ranging from low to high acclimation of 6.3% for leaves growing under shade and 2.1% for leaves oriented towards the sun (Alves 2002).

2.3.4 Water

Plant elongation and cell division results in plant growth. In order for growth to occur a certain limit of turgor is essential and therefore, water is necessary for plant growth (El-Sharkawy 1993). When plants are water stressed, polyribosome activity and cell elongation are reduced at a high rate. In addition, cell division is reduced and also protein metabolism processes are decreased in case of water stress (Alves and Setter 2000, 2004). Consequently, DM production and plant size are reduced as a result of metabolic, physiological and morphological changes caused by water stress.

Cassava yields are decreased by prolonged periods of drought even though cassava is a drought tolerant crop (Alves and Setter 2004). Water deficit duration affect storage roots yield depending on the sensitivity of a growth stage (Alves 2002). The water deficit most crucial period starts from one to five MAP, which corresponds to root initiation and tuberization stages. Water deficit duration of two months during these periods can decrease storage root yield by 32 – 60% (El-Sharkawy 1993).

This crop can survive without soil moisture for a period between 12 and 24 weeks. According to El-Sharkawy (2006), water deficit in cassava can be divided into three distinct stages; early stage that occurs between eight and 24 weeks after planting (WAP), mid-season stress beginning from 16 – 32 WAP and lastly the terminal stress which occurs at 24 – 48 WAP. Timely planting is important especially to small-scale farmers without supplementary irrigation. Therefore, farmers need to plant at the correct time in order to avoid water deficit particularly in the early stages of cassava growth and development.

2.4 NUTRITIONAL REQUIREMENTS

The production of cassava has increased more than triple times over the past four decades and it is now cultivated in approximately 12 million hectares (Hillocks et al. 2002). In Africa, the average cassava output has been gradually growing from 6 to 10 t ha^{-1} (Legg et al. 2006). The average African farmer output is currently about 20% below the world average 12 t ha^{-1} due to zero or low fertilizer application.

According to Howeler (2002), cassava is more responsive to N followed by K then P. Howeler (2017), reported that cassava require 135 kg ha^{-1} N, 15 kg ha^{-1} P and 124 kg ha^{-1} K determined by the fertility of the soil status and desired yield levels. High storage roots output of 40 t ha^{-1} is achieved when sufficient amounts (100 kg N + 22 kg P + 83 kg K) are added every year (Howeler 2012). However, when zero fertilizer is applied, cassava yields can decline significantly, from 30 t ha^{-1} in the first year and to around 7 t ha^{-1} after six years. The NPK fertilizer application of 100:50:100 can yield 92, 184 and 192 kg ha^{-1} for N, P and K are respectively added (Howeler and Cadavid 1990). Meanwhile, fertilizer application of 60:16:138 yielded 23, 88 and 10 kg ha^{-1} for N, P and K applied, respectively.

Some of the soluble sources fertilizers for N, P and K used in cassava include limestone ammonium nitrate (LAN), urea, single and triple super phosphate, diammonium phosphate ($(NH_4)2HPO_4$), potassium sulphate (K_2SO_4) and potassium chloride (KCl) (Howeler 2012). These fertilizers can be added at planting or one MAP, when the roots have established (Fermont et al. 2009). However, P should be applied at or within a few days after planting (DAP). Nitrogen and K can be best applied in two equal doses, 50% at planting and the other 50% when cassava plants have established, at two to three MAP (Howeler 2012).

Nitrogen, P and K decrease in the soil during the growth cycle of cassava (Howeler 2002) due to plant absorption, N and K leaching and P fixation. Howeler (2012), observed that fertilized cassava accumulated 198 kg ha^{-1} N, 30 kg ha^{-1} P and 183 kg ha^{-1} K. Meanwhile, unfertilized cassava accumulated 123 kg ha^{-1} N, 16 kg ha^{-1} P and 92 kg ha^{-1} K. Cassava plants absorption of N is much higher, followed by K then P, Mg and S at a much lower rate (Howeler 2012). However, only 23% of N is found in the storage roots at harvest which is much lower than the percentages for P (47%) and K (54%). In addition, Howeler (2012) also reported that the aboveground growth become dominant sinks especially for N, S, Mg and Ca after 360 DAP, while the storage roots become dominant sink for P and K. According to Uwah et al. (2013a), stem diameter, plant height, number of branches and leaves significantly increased with NPK application. This increase is linked to the role of these nutrients in promoting plant growth

characters through increased photosynthesis and cell multiplication. Significant differences in storage roots starch content were observed among various cassava cultivars over varying fertilizer rates (Baafi 2005).

Nitrogen and K are responsible for root initiation, increasing storage roots number and size (Howeler 2000). This is also in alliance with Howeler (1998) report stating that cassava yield increased due to N and K application. Makinde and Agboola (2001) reported that plants high number of branches are necessary to increase photosynthesis since more leaves are exposed to the sunlight, thus, increasing DM partitioning and accumulation in the storage roots. Howeler (2002), also reported that early tuberization at about 20 DAP is achieved when either K is applied or the combination of N and K is applied. The single fertilizer application of N or P can decrease storage root output when cassava is cultivated without crop rotation. It has been reported that storage roots yield increase at high P fertilization but decrease at high N fertilization (Howeler 2002).

Studies conducted to compare cassava with other crops on nutrient removal, have shown that N and P removal ha^{-1} by the crops storage roots is lower relative to most crops (Howeler 2002, 2012, Leong 2016, Ezui 2017). While K removal was found to be substantially higher in cases when higher cassava yields of 36 t ha^{-1} were obtained. According to Putthacharoen et al. (1998), K removal in cassava is similar to other crops when cassava yields are moderate (11 t ha^{-1}). According to Howeler (2012), fertilized plants removed about 33 kg ha^{-1} N, 11 kg ha^{-1} P and 66 kg ha^{-1} K after harvesting storage roots. While, unfertilized plants removed about 14 kg ha^{-1} N, 4 kg ha^{-1} P and 25 kg ha^{-1} N.

Total quantities of nutrients removed by fertilized plants at root harvest is 34% N, 55% P and 56% K. According to Howeler (2017), the early growth stages for cassava require N, P and K applied at levels between 500 and 800 kg ha^{-1} using compound fertilizers like 15-15-15 or 16-16-16 NPK. The NPK balance need to be modified with a compound fertilizer containing large amounts of N and K, but low in P and such fertilizer combination can be about 2:1:3, or 2:1:2 NPK (Nguyen and Pham 2001). Howeler (2012) reported that the soil properties change during the growth and development cycle of the crop and these changes include: a slight increase in Al-saturation, soil pH, exchangeable Ca and Al. While, Mg is slightly decreased, and little changes occur in the total inorganic and organic N.

2.4.1 Soil fertility status in South Africa

South Africa is poorly endowed with agricultural resources, and much of the country is considered marginal and susceptible to degradation (Laker 2004). Soil organic matter (SOM) is naturally very low in South Africa, and it is estimated that 60% of the soils contain less than 0.5% SOM (Du Preez et al. 2011). Soil organic matter, or its indicator element soil organic carbon (SOC), are indicative of healthy, productive soils, while low SOM or SOC are typically associated with poor soil structure, soil crusting, low water infiltration and poor nutrient status (Fey and Mills 2003). Carbon (C) is furthermore linked to climate change and agricultural production directly contributes to climate change by emitting greenhouse gases (Powlson et al. 2016). However, agricultural soils not only contribute to greenhouse gas emissions, but are also the largest terrestrial sink of C with a high C sequestration and mitigation potential to reduce the impact of climate change (McCarthy et al. 2001).

2.4.2 Nutrient concentration in plant tissues

The most important step in identifying the best way to apply appropriate fertilizers is to correctly diagnose plant nutritional problems (Howeler 2002). In most instances, the blade of the youngest fully developed leaf (YFDL) collected at three to four MAP is the best tissue indicator for cassava plants nutritional problems. Leaf samples can be delayed if the three to four MAP period occurs during a long and severe drought season. Samples can be taken at about two to three MAP after the drought season (Howeler 2002). Nutrient concentration in the YFDL can be compared using the critical nutrient concentration values shown in Table 2.3.

Table 2.3: Cassava nutrient concentration on the blades of the youngest fully developed leaf (YFDL) at 3 – 4 MAP according to various nutrition states of the plant (Howeler 2002)

	Nutritional states					
Nutrient	Very deficient	Deficient	Low	Sufficient	High	Toxic
B (µg g^{-1})	<7	7 – 15	15 – 18	18 – 28	28 – 64	>64
Cu (µg g^{-1})	<1.5	1.5 – 4.8	4.8 – 6.0	6 – 10	10 – 15	>15
Fe (µg g^{-1})	<100	100 – 110	110 – 120	120 – 140	140 – 200	>200
Mn (µg g^{-1})	<30	30 – 40	40 – 50	50 – 150	150 – 250	>250
Zn (µg g^{-1})	<25	25 – 32	32 – 35	35 – 57	57 – 120	>120
Ca (%)	<0.25	0.25 – 0.41	0.41 – 0.50	0.50 – 072	0.7 – 0.88	>0.88
K (%)	<0.85	0.85 – 1.26	1.26 – 1.42	1.42 – 1.88	1.88 – 2.40	>2.40
Mg (%)	<0.15	0.15 – 0.22	0.22 – 0.24	0.24 – 0.29	>0.29	-
N (%)	<4.0	4.1 – 4.8	4.8 – 5.1	5.1 – 5.8	>5.8	-
P (%)	<0.25	0.25 – 0.36	0.36 – 0.38	0.38 – 0.50	>0.50	-
S (%)	<0.20	0.20 – 0.27	0.2 – 0.30	0.30 – 0.36	>0.36	-

2.4.2 Effects of NPK in cassava production

2.4.2.1 Nitrogen

Remarkable cassava reactions to N-fertilization were found to be more in Asia than in Africa and Latin America (Hagens and Sittibusaya 1988). Under field conditions N can be lost by leaching and runoff (Howeler 2002). In addition, N can be lost due to a wide plant spacing in the long growing period of cassava (Sánchez et al. 2009). Uwah et al. (2013a) observed that N fertilization levels of 120 kg ha^{-1} N expanded cassava storage roots weight and yield by 36 – 48%. Nitrogen promotes plant photosynthesis since it increases leaf chlorophyll content. Nitrogen also takes a main role in the manufacturing of proteins and leading to an increase in plant yields (Aliyu et al. 2019). However, excess N fertilization enhances shoot growth at the expense of root bulking especially in very low pH soils. In addition, high application rates of N increase the concentration of N-containing compounds like Hydrogen cyanide (HCN) and protein thus decreasing storage roots starch quality (Howeler 2002).

In a study that was conducted by Wargiono et al. (1995), when cassava was intercropped with corn (*Zea mays* L.), a competition for the narrow N-availability in the soil was observed. The response of cassava to N-application exhibited a closely linear curve of up to 150 kg ha^{-1} N. According to Weite et al. (1998), N levels must not only be recommended according to the soil analysis but also according to the cultivars to be planted. Nitrogen deficiency symptoms in cassava include a decline in plant growth and homogenous leaf chlorosis, which begins with lower leaves and then spread all over the plant (Howeler 2002).

2.4.2.2 Phosphorus

Fungi and bacteria are the only microorganisms that can secrete phosphate outside their cell walls (Tabatabai 1994). Phosphorus uptake by plant roots is promoted by an essential group of microorganisms called vesicular-arbuscular mycorrhiza (VAM) (Mosse 1973). The VAM fungi is coupled with the colonization of the fine plant roots. The hyphae increase the root surface area in the soil in which P is absorbed. The hyphae is extended to a wider soil volume in which plant available P is found to absorbed by the roots (Sposito 2008). The VAM is most active in soils with low P. However, its efficiency is highly decreased in water deficits since it is a microorganism (Hue 1992). The class and quantity of clay minerals and aluminium ions present in the soil can also directly affect P fixation (Sposito 2008).

According to Pellet and El-Sharkawy (1993), low concentration of P in acidic soils usually limit cassava yield production. The response of cassava to P fertilization is influenced

by soil pH, soil texture, VAM infection, P fertilizer application method and crop variety (Howeler and Asher 1982). The ability of cassava to absorb P from the soil can be influenced by the production of organic acids and microbial phosphate enzymatic activity. The presence of high fibrous roots density and average shoot growth increase phosphorus use efficiency (PUE) (Leong 2016). The effectiveness of VAM is generally decreased by highly intensive use of fertilizers.

The lack of P in plants can lead to a reduction in cell formation and enlargement (Howeler 2002). Phosphorus deficient plants have uniform purple or yellow chlorosis on the lower leaves, stunted plant growth, short petioles, thin stems, low number of leaf lobes per leaf and narrow leaf lobes (Asher et al. 2002). In addition, some cultivars lower leaves change to yellow-orange or purplish/brown and become flaccid and necrotic (Howeler 2012). Leaves may eventually fall off as a result of P deficiency. According to Howeler and Asher (1982), cassava inoculated with endotrophic VAM in nutrient solution improved its growth significantly. Cassava fibrous roots with masses growing in and around of mycorrhizal hyphae greatly increase P absorption ability from the surrounding medium of the plant. Phosphorus is responsible is also for CO_2 assimilation and partitioning of photosynthates from the top to the storage roots (Howeler 2002). Cassava roots have an extensive relationship with mycorrhizal fungi in the soil. Cassava has a low requirement for P fertilization compared to less mycorrhizal dependent crops like beans and maize due to its mutual relationship with VAM (Howeler 2012).

2.4.2.3 Potassium

Potassium plays a major part in the metabolism of fats, carbohydrates and proteins (Howeler 2002). Potassium promotes photosynthesis and stimulates the redistribution of the assimilates to the storage roots thus resulting in low levels of carbohydrates in the aboveground biomass (Kasele et al. 1995). Storage roots starch content is increased by the application of K (Howeler 1998). Increases in starch content can be from 80 – 100 kg K ha^{-1} but at excessive rates of K, starch content then decreases (Obigbesan 1973, Howeler 2002). Ramanujam and Ghosh (1990) reported an increase in cassava plant growth parameters at high levels of K application.

Howeler (2012), examined the effect of applying K and reported that the application of K influenced the number of storage roots and the average storage root weight per plant. In addition, high application levels of K (200 kg ha^{-1}) can increase cassava storage roots yield

(Howeler 2002). In addition, high K fertilization has been reported to increase starch, DM content and reducing HCN content on cassava storage roots (Uwah et al. 2013a). Furthermore, increase in K fertilization has been reported to increase other starch quality parameters like pasting temperature, granule size, amylose content and viscosity (Howeler 2002). Potassium application response is often observed in low pH soils and cation exchange capacity (CEC) (Kang and Okeke 1983). According to Kasele et al. (1995), K application increased the storage cell size by accelerating the cambium activity.

The HCN content in the storage roots is decreased by adequate application of K (Kabeerathumma et al. 1988). Storage roots with low K have been found to have the highest levels of HCN (Howeler 2002). Potassium facilitates the stimulation of net photosynthetic rate and acceleration of partitioning of assimilates into the storage root (Howeler 2012).

Potassium deficiency is usually found in tropical soils characterized by low clay activity, for instance in the ultisols, inceptisols, alfisols, as well as the oxisols (Howeler 2002). When the crop is cultivated on the same piece of land year after year without addition of K fertilizers, K deficiency will become the main yield limiting factor. Potassium deficiency reduce cassava plant growth and this is portrayed by excessive branching which result in a prostate small plant type (Howeler 2002). Lack of K may cause chlorosis on upper leaves and the stems may be thick, thus, protruding short internodes. During severe K deficiency, lignification of cell walls may occur prematurely, hence, formation of very short internodes which results in a zig-zag growth pattern of the upper stems. Different cultivars of cassava exhibit various symptoms when subjected to K deficiency (Howeler 2002). Some cultivars have border necrosis, yellow and purple spotting of lower canopy leaves. Meanwhile, other cultivars may have upward curling of borders of the lower plant leaves which is a symptom also found in drought stress. Howeler (2002) observed that not applying K on cassava resulted in lower plant biomass, stunted plant growth, lower crop growth rate and extended stems with a greater number of leaves. Potassium deficiency results to excessive aboveground growth and low storage root yield.

In a study by Kabeerathumma et al. (1988), yields of cassava decreased from 22.4 – 6.3 t ha^{-1} after 10 years when the crop rotation was not practiced. This was due to the reduction in exchangeable K from 0.18 – 0.064 meq 100 g^{-1} of the soil. Long term trials have shown that cassava yields decreased approximately 3.5 times in 10 years without the application of K (Kabeerathumma et al. 1988).

2.4.3 Effects of nitrogen on chlorophyll

Chlorophyll content is an essential leaf component used as a measure for chloroplast development, leaf photosynthetic capacity, N status and RuBP carboxylase (Anand and Byju 2008). Leaf chlorophyll content and storage roots yield have been reported to be positively correlated. (Cock 1985, Anand and Byju 2008, Byju and Anand 2009). Leaf chlorophyll content varies with nutrient status. Cassava cultivars with high leaf chlorophyll content obtain high root storage yields (Sookchalearn and Abdullakasim 2017). Tivana (2012), reported that chlorophyll content in cassava leaves increases from planting up to 6 MAP and decreases up to 9 MAP then gradually increases at 12 MAP. Leaf chlorophyll content can be used for plant acclimation and tolerance to low temperature (Sookchalearn and Abdullakasim 2017). Chlorophyll content is decreased in low temperatures due to the results of photo-oxidation (Tivana 2012).

The accurate way to measure leaf chlorophyll concentration is extracting green pigment in a solvent then measure it by *in vitro* using a spectrophotometer (Parry et al. 2014). According to Parry et al. (2014), the method used for extracting chlorophyll coupled with the extraction solvent, spectrometric equation and resolution must correspond in order to obtain accurate chlorophyll by *in vitro*. Acetone is a largely used organic solvent for extracting chlorophyll (Parry et al. 2014). Complete extraction of chlorophyll using acetone requires grinding of the leaf tissue (Ritchie 2006). Chlorophyll a/b can be differentiated at *in vitro* (Parry et al. 2014). The disadvantages of using *in vitro* colorimetric methods in determining chlorophyll content is that they are destructive, time consuming and expensive (Parry et al. 2014).

Leaf chlorophyll concentration can also be measured by *in vivo* using non-destructive spectroscopic techniques (Parry et al. 2014). Two methods used in vivo are; absorbance measurements at 676 nm and reflectance measurements which include the use of optical dual-wavelength chlorophyll meters (SPAD-502, CCM-200 and Dualex 4 Scientific). However, the reported relationship between chlorophyll concentration and optical or absolute meter values, varies widely and even within species. Optical chlorophyll meters are used to measure transmission of red wavelength at estimated levels of 650 nm and near infrared (NIR) wavelength at around 900 nm on the plant leaves (Parry et al. 2014). An increase in chlorophyll concentration will increase the absorption of the red wavelength. In addition, the sampling area is different between the optical equipment's. The CCM-200 samples 71 mm^2 while the Dualex 4 samples 20 mm^2 and the SPAD-502 samples 6 mm^2. Larger sampling areas have larger spatial mean and smaller sampling areas can measure narrow leaves.

According to Parry et al. (2014), chlorophyll a/b ratio is influenced by environment, cultivar, leaf growth phase and nutrient status. Walters (2005) reported that a reduction in leaf N content, increases chlorophyll a/b ratio. The C4 plants have higher chlorophyll a/b ratio than C3 plants. Chlorophyll ratio is not influenced by water deficit (Mafakheri et al. 2010). There ratio can be decreased during leaf senescence (Castro and Sanchez-Azofeifa 2008).

2.4.3.1 SPAD-meter

The acronym SPAD means soil-plant analyses development. The SPAD-meter is used to measure radiation between 940 and 650 nm (Parry et al. 2014). A complete equation (2.1) that converts measurements into a SPAD-value was derived by Nauš et al. (2010):

$$\text{SPAD} = k \times \log\left(\frac{\%\ \text{transmission 940 nm}}{\%\ \text{transmission 650 nm}}\right) + C \qquad (2.1)$$

Where C is the confidential offset value and k is the confidential slope coefficient. SPAD values are impossible to derive from transmission measurements because the offset and slope values are confidential. However, SPAD and CCI values are computed using transmission ratio of two nearly connected wavelengths (2.2):

$$\text{SPAD} \approx k \times \log\ (\text{CCI}) + \text{C} \qquad (2.2)$$

Where CCI represent chlorophyll content index. SPAD-values have no direct relationship with chlorophyll concentration (Cerovic et al. 2012). The NIR transmission to red wavelengths ratio determines SPAD-meter output (Parry et al. 2014). Transmission of radiation is closely related to the absorbance of leaf tissue but not linearly related to the amount of leaf tissue absorbance (Huheey et al. 2006). Absorbance occurs when the log of transmittance is negative. Both non-chlorophyll and chlorophyll compounds absorb NIR and red lights in the same way, thus red light transmission is also affected by non-chlorophyll compounds (Huheey et al. 2006). However, chlorophyll does not influence NIR transmission but non-chlorophyll compounds can be influenced.

The cell wall and the absolute amount of chlorophyll in leaves can be computed using the relationship derived by the Beer–Lambert law (2.3) if chlorophyll distribution in the leaves is assumed to be uniform.

$$CCI \approx \frac{\%\ \text{transmission NIR}}{\%\ \text{transmission RED}} \approx \frac{e^{-(\text{cell wall})}}{e^{-(\text{chlorophyll+cell wall})}} = \frac{e^{-(\text{chlorophyll+cell wall})}}{e^{-(\text{cell wall})}}$$

$$CCI = e^{(\text{chlorophyll+cell wall})} - e^{(\text{cell wall})}$$

$$\ln(CCI) = \ln\left[e^{(\text{chlorophyll+cell wall})}\right] - \ln\left[e^{(\text{cell wall})}\right]$$

$$\ln(CCI) = (\text{chlorophyll} + \text{cell wall}) - (\text{cell wall})$$

$$\text{SPAD} \approx \ln(CCI) = (\text{chlorophyll}) \qquad (2.3)$$

The equation shows that if chlorophyll distribution is uniform SPAD and the CCI readings would be closely related to the concentration of chlorophyll similar to the logarithmic function (Parry et al. 2014). However, chlorophyll distribution in the leaves is not uniform. These differences in the transmission measurements are called sieve and detour effects (Parry et al. 2014). Light transmission can be influenced by pigment spatial distribution and concentration in the leaves (Parry et al. 2014). Non-uniform chlorophyll distribution reduces light transmission when chlorophyll concentration is low but will increase light transmission when chlorophyll concentration is high (Parry et al. 2014). The distribution of chlorophyll in a leaf is affected by; organization of grana within chloroplasts, chloroplasts within cells, and cells within tissue layers (Hatfield et al. 2008).

The sieve effect occurs when light goes via leaf tissue but not absorbed. This effect is increased with an increase in non-uniformity of chloroplasts (Parry et al. 2014). The efficiency the absorption of red light increases with even distribution of chloroplast (Nauš et al. 2010). Optical path-length through the leaf positively affect light scattering or the detour effect by reducing light transmission. Leaf reflectance at the absorption of red light is lower than that at the absorption of NIR light (Nauš et al. 2010). The reference NIR wavelength is more pronounced due to the detour effects. In addition, transmission per unit chlorophyll is reduced by the detour effect (Uddling et al. 2007). The differences sieve and detour effects and chlorophyll distribution patterns cause differences in absolute chlorophyll relationships between species (Parry et al. 2014).

2.4.3.2 Nitrogen sufficiency index

The N sufficiency index (NSI) is calculated using SPAD readings means from optimum N application rate as the N-reference area. The use of the NSI requires an N-rich reference area which receives adequate N application to make sure that N is not a problem (Blackmer and Schepers 1994, Shanahan et al. 2008). The N-rich reference area allows SPAD readings to be normalized, therefore improving correlation by limiting the effects of environmental conditions (Shanahan et al. 2001). The NSI values are therefore calculated using the formula (2.4):

$$\text{Sufficiency index} = \frac{\text{Average SPAD reading of target}}{\text{Average SPAD reading of reference}} \qquad (2.4)$$

The NSI values can be calculated at 95% and 100%. Nitrogen deficiency corresponds to the critical sufficiency index of 95% which indicates that N fertilizers should be applied because yields might be reduced (Hussain et al. 2000, Varvel et al. 2007, Muchecheti et al. 2016). The NSI values at 100% can be used as a selection criteria to indicate whether N application rates are sufficient. The N application rates whose NSI values are less than 95% at least for two consecutive weeks are categorized as N deficient.

2.5 CONCLUSION

Cassava is traditionally considered a subsistence crop which is progressively becoming a commercial crop in Southern African countries. Generally, cassava is cultivated by poor farmers who live in marginal areas. Consequently, sustainable intensification in cassava production is relatively low since the crop can be produced in marginal areas, considered not suitable for cereals and many other crops cultivation. These unsustainable intensification will eventually lead to a decline in environmental quality and nutrient mining especially of N, P and K. This entails that application of fertilizers can be used to sustain environmental quality and agricultural productivity. However, increasing yields using fertilization have to work within the bounds of nature but not against them. In addition, efficient use of fertilizers should be based on the crop nutrient needs together with the soil chemical analysis, in order eliminate the risks of nutrient deficiency and toxicity. Therefore, optimum levels of inputs should established and recommended for farmers use to obtain maximal crop yields. In addition, it is also important to study the adaptability of cassava cultivars in several areas of SA.

CHAPTER 3

FIELD EVALUATION OF CASSAVA (*Manihot esculenta* Crantz) CULTIVARS FOR GROWTH AND YIELD IN MBOMBELA, MPUMALANGA, SOUTH AFRICA

ABSTRACT

Cassava (*Manihot esculenta* Crantz) is cultivated for food and industrial purposes. However, there is wide variation in its adaptability to environmental conditions. This study was conducted to assess the growth and yield performance of P4/10 and MSAF-1 in Mbombela, Mpumalanga, South Africa (SA). The two cultivars were evaluated in a three block RCBD with each cultivar replicated four times. Data was collected on plant height, stem diameter, number of branches and leaf area index (LAI) at five, eight, 10 and 15 months after planting (MAP). The leaf area duration (LAD) for each cultivar was calculated for the end of season. At harvest (15 MAP) the total biomass weight, dry matter yield, number of storage roots per stool and harvest index (HI) were recorded. MSAF-1 mean values of plant height (206.5 cm), stem diameters (59.0 mm), number of branches (39.5), LAI (4.0) were significantly higher ($p < 0.05$) than those for P4/10; 181.2 cm, 49.7 mm, 31.4, 2.2 at 15 MAP, respectively. MSAF-1 cultivar LAD value (893.44 days) was higher than for P4/10 (558.93 days). MSAF-1 mean values of the total fresh biomass (15.55 kg ha^{-1}), aboveground biomass dry matter yield (3.97 kg ha^{-1}), storage root dry matter yield (5.66 kg ha^{-1}), number of storage roots (13.6), HI (0.621) were higher than those for P4/10 whose respective means were 13.14 kg ha^{-1}, 2.79 kg ha^{-1}, 3.73 kg ha^{-1}, 10.0, 0.5 at 15 MAP. Significant differences in traits evaluated between cultivars were largely due to genotypic variability since the cultivars were grown and treated the same way. The taller cultivar (MSAF-1) was exposed to more sunlight and therefore positively associated with yield components since more photosynthetic radiation was intercepted compared to the short cultivar (P4/10). Results suggest that MSAF-1 performed better than P4/10 in the Mbombela conditions as it maintained a greener canopy.

Key words: P4/10, MSAF-1, leaf area index, harvest index, storage roots

3.1 INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is a shrub that is classified under the Euphorbiaceae family (Dalton et al. 2011). It is considered the main food source for over 500 million people globally (Okogbenin et al. 2006). The crop can be cultivated in a broad range of environmental conditions. However, the adaptability of most cultivars is limited and has shown large genotype by environment (G × E) interaction effects (Dixon et al. 2002). So, to achieve maximum productivity of a cultivar, environmental conditions need to be considered.

The crop is widely grown in tropical environments characterized by high temperatures and solar radiation intensity (El-Sharkawy and Cock 1990). It requires warm climatic conditions for optimal growth and productivity (Irikura et al. 1979). Net leaf photosynthesis rate is greatly reduced and growth becomes slower when cassava is grown under cool areas. (El-Sharkawy 2006, 2012). Positive correlations were observed between photosynthetic rates and crop growth rate (CGR) in tropical environments at low altitude with higher temperatures (Alves 2002). Maximum cassava productivity and growth also require high air humidity and sufficient rainfall (Cock and Rosas 1975).

Cassava can be harvested whenever economic yields are obtained since it has no definite maturity period (Chipeta et al. 2016) but there is a safe duration to harvest to avoid high cyanide content (HCN). Temperature changes influence the maximum accumulation of dry matter (DM) in the economic roots which takes place between 300 and 360 DAP in the tropics (Alves 2002). There are new cultivars with a maximum DM before 270 DAP. Most cassava is harvested at 360 DAP. Harvest index can be used as a standard measure for DM accumulation in the storage roots. Cassava cultivars HI were found to be significantly different after 10 – 12 MAP, indicating that HI can also be used to select cassava cultivars which could produce higher yields (Alves 2002, Kawano 2003). In addition, cultivars exhibiting high HI values between 6 and 9 MAP can be categorized under early maturing economic roots (Alves 2002).

The production of cassava is faced by a number of challenges that include pest and diseases (Uzokwe et al. 2016). The other constraints include; late maturing storage roots, early postharvest deterioration, and shortage of labour, land and capital. In addition, susceptible cultivars with insufficient quantities of good planting materials are frequently used by most farmers for continued low yields and pest and diseases (Aerni 2006).

More than 50% of the total world's annual output for cassava comes from Africa. However, cultivars grown in most African countries are low storage roots yielders (6.4 t ha^{-1})

and late maturers (harvested from 20 – 24 MAP) (IITA 2005). The world production of this crop in 2012 was estimated to be 250 million tons (FAO 2013). Nigeria, Congo, Indonesia and Thailand dominate 60% of the total cassava output in the world (Noerwijati and Budiono 2015). The increase in output, especially in Nigeria, was mainly attributed to the development and distribution of high yielding, pest and disease resistant cultivars accompanied by improved production technologies (Nhassico et al. 2008).

Even though Africa is the largest producer of cassava, SA is only realizing the potential of this crop now. The crop is largely grown in the Mpumalanga, KwaZulu-Natal and Limpopo provinces of SA (Ogola and Mathews 2011). In several areas of the country including Gauteng, cassava is sold in retail markets as fresh roots and flour. Therefore, in order to meet the increasing demand for cassava in an emerging cassava industrial sector in SA, it is necessary to provide basic agronomic information on cassava cultivars. The objective of this study was to assess the growth and yield performance of two local cassava cultivars in Mbombela, Mpumalanga, SA.

3.2 MATERIALS AND METHODS

3.2.1 Experimental site

The field experiment was conducted at the Agricultural Research Council-Institute for Tropical and Sub-tropical crops (ARC-ITSC) Friedenheim farm in Mbombela, Mpumalanga Province, SA. The field lies between latitude (DMS) – 25° 25’ 59 S and longitude - 30° 59’ 23 W. Mbombela receives about 667 mm of rain per year, with most of the rainfall occurring during the summer season (November – February). The average daily temperatures range from 21.4 °C (June) to 27.9 °C (January). The region is coldest in July as temperatures drop to 6.2 °C on average during the night.

3.2.2 Cultural practices

The experiment was established on the 21st of December, 2016 and terminated on the 25th of March 2018. The field was ploughed, harrowed and ridged. Irrigation was applied to field capacity (depending on rainfall) using a drip irrigation system. Soil samples were taken across the site in an organized systematic grid-diamond pattern using a soil auger and were analyzed for chemical and physical properties before the experiment was established. Soil pH was determined using electrometric method in distilled water at 1:1 soil to water ratio. The macro-Kjeldahl digestion method was used for total N determination. The pH 7 ammonium

acetate extraction method was used to determine Ca, K, Mg and Na (exchangeable cations) (Chapman 1965). The Olsen P extraction method was used for P in a bicarbonate extraction at pH 8.5, while carbon and aluminium were determined using diethylenetriamine pentaacetic acid (DTPA). The soil was made up of 89% sand, 4.8% clay and 6.2% silt and was slightly acidic with pH 6.84 as presented in Table 3.1.

Table 3.1: Physico-chemical properties of the soil of the experimental site at ARC-ITSC Friedenheim farm in Mbombela.

Properties		Units		Percentage (%)
Soil pH (soil: water)	6.84	-	-	-
Total carbon (%)	-	-	-	1.66
Elements		mg kg^{-1}	me (%)	
Al	-	0.0	-	-
Ca^{2+}	-	125	7.6	67.0
K^{+}	-	118	0.3	1.9
Mg^{2+}	-	31.2	7.6	27.9
N	-	1.3	-	-
Na^{+}	-	0	0.1	0.7
P	-	10.2	-	-
Sand	-	-	-	89
Silt	-	-	-	6.2
Clay	-	-	-	4.8

The two local cassava cultivars that were studied were P4/10 and *Manihot* South Africa (MSAF-1). Both cultivars produce relatively high storage roots yields and are pest and disease resistant based on earlier studies (Melis 1984). The planting material for both cultivars was obtained from the ARC Levubu, SA. For each cultivar 25 cm long stem cuttings with five nodes were planted. The cassava stem cuttings were inserted at about 45° on the crest of the ridges. Compound fertilizer (NPK 15:15:15) was applied at 150 kg ha^{-1} (Ogola and Mathews 2011), with 50% being applied at one MAP and the other 50% at three MAP. Weeding was manually done every two months using the hoe and hand pulling methods.

3.2.3 Treatments, measurements and data analysis

The two cultivars were arranged in a randomized complete block design (RCBD) with three blocks. Each of the blocks consisted of eight plots (each measuring 4.0 m × 6.0 m), allowing each cultivar to have four replicate plots in each block. Four rows were planted per

plot with an inter-row spacing of 1.0 m and an intra-row spacing of 1.0 m, giving a plot population of 24 plants corresponding to a plant density of 10 000 plants per hectare.

Data on plant height, stem diameter, number of branches per plant and leaf area index (LAI) was collected using four plants from the center of each plot. The leaf area duration (LAD) were collected at five, eight, 10 and 15 MAP. Plant height was measured from the soil surface to the tip of the main stem using a graduated stick. The stem diameter was measured using vernier calipers, while number of branches were counted. Leaf area index was measured using a LP-80 ceptometer (Meter Group, Inc. USA). Leaf area duration was calculated by the equation 3.1:

$$\text{LAD} = \left(\frac{LAI_1 + LAI_2}{2}\right) \times \text{Days} \qquad (3.1)$$

Where LAI_1 and LAI_2 are the LAI's between two growth stages, and days represent the days corresponding to LAI determination (Liu et al. 2005). At harvest (15 MAP) the average data of for plants per plot was recorded on fresh aboveground biomass, storage roots fresh weight and number of storage roots per plant. Fresh samples (1 kg) were dried for 72 hours at 60 ^{o}C for dry matter determination. The total plant fresh weight and fresh storage roots weight were used to calculate the harvest index (HI) using equation 3.2:

$$\text{Harvest index} = \frac{\text{Fresh storage roots weight}}{\text{Total plant fresh weight}} \qquad (3.2)$$

Growth and yield data for the two cultivars was subjected to analysis of variance for each sampling day using SAS 9.4 version 6.1.7061 for windows general linear procedures (Cary, NC, SAS Institute Inc., 2012). When the data for the two cultivars was significantly different, the means were compared by the Tukey test ($p < 0.05$). The rates of increase for plant height, stem diameter, number of branches and LAI were computed by regressing each parameter change over time. The b-values were used to depict the rate of change.

3.3 RESULTS AND DISCUSSIONS

3.3.1 Weather conditions

Monthly temperatures, rainfall, humidity and radiation taken from the ARC weather station, in Mbombela Experimental Farm are presented in Figure 3.1. Total rainfall for the

growing season was 1301.3 mm and it was abundantly distributed in the first three MAP. The highest total monthly rainfall (227.6 mm) was received in February and the lowest (0.25 mm) was in June 2017. Average daily temperatures ranged from 7.7 – 31.3 °C. The lowest mean monthly temperatures were obtained between June and August 2017. The highest total monthly radiation (22.8 MJ m^{-2}) was in January 2017, while the lowest (12.7 MJ m^{-2}) was in June 2017. Maximum humidity was maintained at about 90% throughout the experiment, but the minimum humidity was relatively lower between May and September 2017.

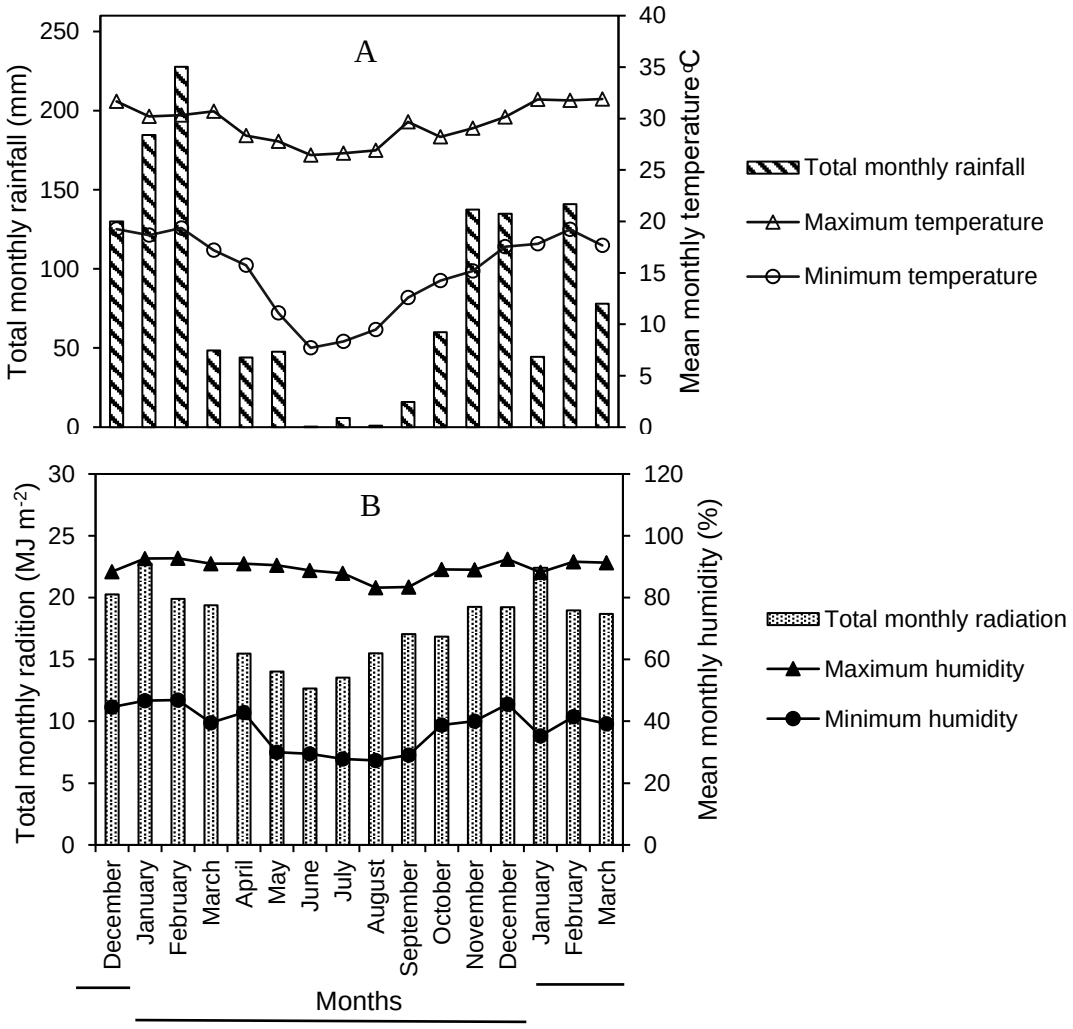

Figure 3.1: Monthly (a) rainfall, mean maximum and minimum temperature values and (b) radiation, mean maximum and minimum humidity values data recorded from December 2016 to March 2018 in Mbombela, Mpumalanga, SA.

Total rainfall for the growing season was ideal for cassava growth since can grow in regions receiving an annual rainfall ranging from 500 – 5000 mm (Akinpelu et al. 2011). Cassava is inherently a drought tolerant plant and therefore, the crop can survive in places where rainfall is low or unevenly distributed (Alves 2002). During dry periods, the plant undergoes a period of dormancy lasting for a maximum of 2 – 3 months and then growth resumes when it begins to rain (El-Sharkawy 2003, 2006). The temperatures were favourable since cassava can tolerate temperatures from 16 – 38 °C (Lenis et al. 2006). However, temperatures below 16 °C decrease cassava growth (Alves 2002). According to Irikura et al. (1979) temperatures from 20 – 24 °C increased LAI values, leaf size and leaf formation but temperatures above 24 °C decreased number of branches and leaf area. The total radiation and humidity for the growing season were also ideal for the growth of the crop. Leong (2016) reported that increased total biomass and storage roots is associated with high relative humidity of 70% than low humidity of 30%.

3.3.2 Plant height

Significant differences ($p < 0.05$) were observed in plant height from 5 – 15 MAP between cultivars (Figure 3.2). Plant height of MSAF-1 was significantly higher ($p < 0.05$) than P4/10 in all the sampling periods. Plant height for P4/10 was 99.4 cm at 5 MAP and 181.2 cm at 15 MAP, while the respective values for MSAF-1 were 118.8 and 206.5 cm.

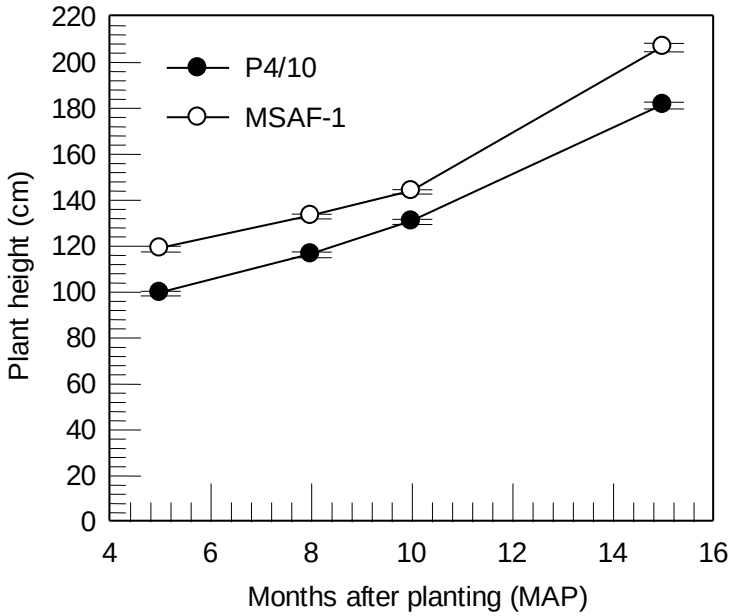

Figure 3.2: Changes in plant height for P4/10 and MSAF-1 from 5 – 15 months after planting (MAP) in Mbombela, Mpumalanga, SA. The bars denote standard deviation of mean.

The rate of increase in height for the two cultivars were generally different (Table 3.2). Plant height for P4/10 increased at a higher rate during periods 5 – 8 and 8 – 10 MAP than MSAF-1. After 10 MAP, height of MASF-1 increased at a higher rate than for P4/10. The rate of increase in height from 10 – 15 MAP was significantly higher ($p < 0.05$) than during the early growth for both cultivars. Cultivar P4/10 rate of increase in height was 5.61, 7.18 and 10.22 cm month^{-1} between 5 – 8, 8 – 10 and 10 – 15 MAP, respectively. The values for MSAF-1 cultivar were 4.73, 5.35 and 12.55 cm month^{-1} between 5 – 8, 8 – 10 and 10 – 15 MAP, respectively.

Table 3.2: Rates of increase in plant height from 5 – 15 months after planting (MAP) for two cassava cultivars at Mbombela, SA.

Plant height	Cultivars		LSD
	P4/10	MSAF-1	
At 15 MAP	181.2 b*	206.5 a	4.741
Mean rate of increase	7.668 a	7.511 a	0.913
Rate of increase by stage			
5 – 8	5.609 b#	4.727 b	
8 – 10	7.175 b	5.347 b	
10 – 15	10.219 a	12.548 a	
LSD	1.612	1.341	

* Mean maximum plant height and mean rate of increase in plant height for P4/10 and MSAF-1 followed by different letters differ significantly ($p < 0.05$) using the Turkey LSD test.

Rate of increase in plant height (cm month^{-1}) at different growth stages for each cultivar followed by different letters differ significantly ($p < 0.05$) using the Turkey LSD test.

Increases in plant height are consistent with the findings by Nweke (2004). Plant height is an important attribute for cassava yield. Tall cassava plants are exposed to more sunlight and therefore positively associated with yield components since they intercept more photosynthetic radiation than short plants (Pommel et al. 2002, Gyau and Jnr 2015). In the present study, MSAF-1 plants were more exposed to light than P4/10, resulting in higher yield parameters.

3.3.3 Stem diameter

There were significant cultivar differences ($p < 0.05$) in stem diameter between cultivars from 5 – 15 MAP. The stem diameters for the two cultivars increased as the plants aged (Figure 3.3). Cultivar MSAF-1, stem diameters were higher than for P4/10. Stem diameter for MSAF-1 was 20.9 mm at 5 MAP and 59.0 mm at 15 MAP, while the respective values for P4/10 were 16.8 and 49.7 mm.

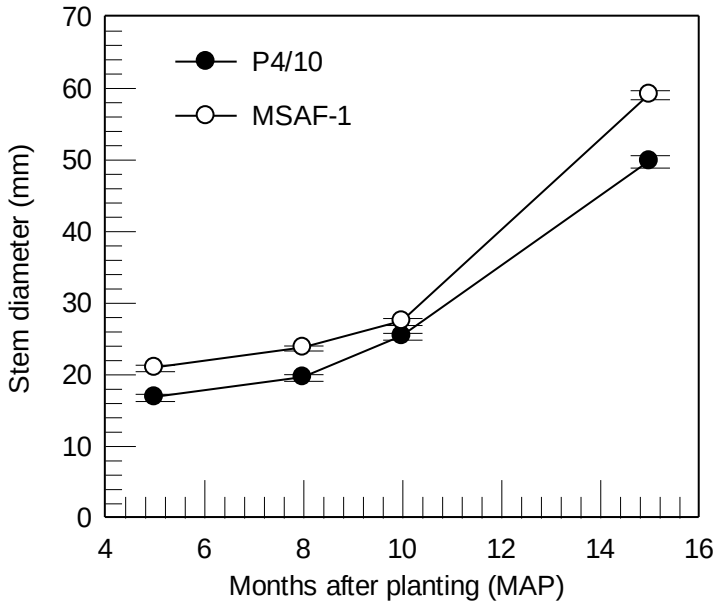

Figure 3.3: Changes in stem diameter for P4/10 and MSAF-1 from 5 – 15 months after planting (MAP) in Mbombela, Mpumalanga, SA. The bars denote standard deviation of mean.

Generally, the stem diameter for P4/10 cultivar increased at a higher rate than MSAF-1 between all the growth stages (Table 3.3). The rate of increase from 10 – 15 MAP was significantly higher compared to that from 5 – 18 and 8 – 10 MAP, for both cultivars. The P4/10 stem diameter increase rate was 0.93, 2.88 and 4.61 mm month^{-1} from 5 – 8, 8 – 10 and 10 – 15 MAP, respectively. The respective values for MSAF-1 were 0.93, 1.85 and 4.59 mm month^{-1}.

Table 3.3: Rates of increase in stem diameter from 5 – 15 months after planting (MAP) for two cassava cultivars at Mbombela, SA.

Stem diameter	Cultivars		LSD
	P4/10	MSAF-1	
At 15 MAP	49.7 a*	59.0 b	1.781
Mean rate of increase	2.458 b	2.806 a	0.345
Rate of increase by stage			
5 – 8	0.929 c[#]	0.928 c	
8 – 10	2.879 b	1.847 b	
10 – 15	4.609 a	4.598 a	
LSD	0.622	0.567	

* Mean maximum stem diameter and mean rate of increase in stem diameter for P4/10 and MSAF-1 followed by different letters differ significantly ($p < 0.05$) using the Turkey LSD test.
[#] Rate of increase in stem diameter (mm month^{-1}) at different growth stages for each cultivar followed by different letters differ significantly ($p < 0.05$) using the Turkey LSD test.

3.3.4 Number of branches

The number of branches for the two cultivars were significantly different ($p < 0.05$) from 5 – 15 MAP (Figure 3.4). Mean number of branches for MSAF-1 were significantly higher than those for P4/10. The number of branches for P4/10 were 7.9 at 5 MAP and 31.4 branches at 15 MAP. Meanwhile, MSAF-1 branches were 12.6 at 5 MAP and 39.5 branches at 15 MAP.

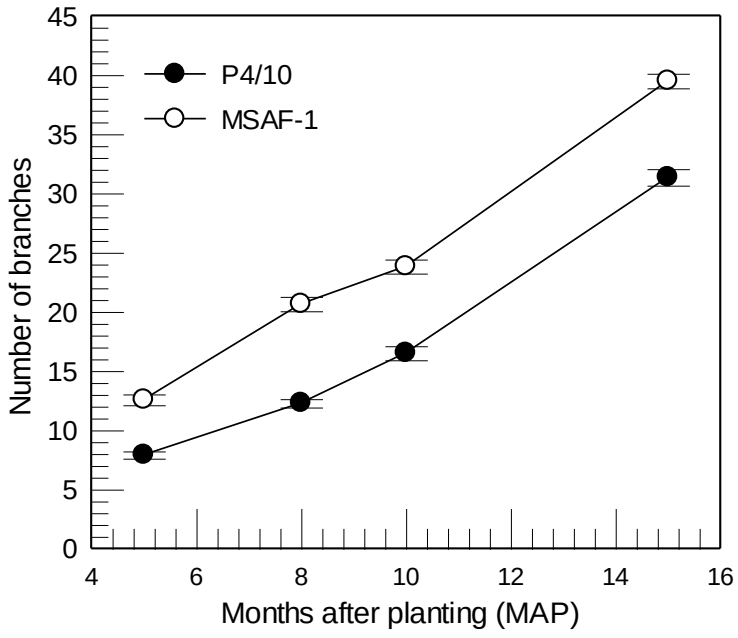

Figure 3.4: Changes in number of branches for P4/10 and MSAF-1 from 5 – 15 months after planting (MAP) in Mbombela, Mpumalanga, SA. The bars denote standard deviation of mean.

Rates of increase in number of branches for the two cultivars are presented in Table 3.4. The results showed that the rate of increase in number of branches of the two cultivars increased over time. The rate of increase in number of branches for MSAF-1 was significantly higher from 5 – 10 and 10 – 15 MAP than from 8 – 10 MAP. The rate of increase in number of branches for P4/10 were lower than the respective values for MSAF-1.

Table 3.4: Rates of increase in number of branches from 5 – 15 months after planting (MAP) for two cassava cultivars at Mbombela, SA.

Number of branches	Cultivars		LSD
	P4/10	MSAF-1	
At 15 MAP	31.4 b*	39.5 a	2.113
Mean rate of increase	2.179 a	2.491 a	0.396
Rate of increase by stage			
5 – 8	1.449 c[#]	2.694 a	
8 – 10	2.118 b	1.646 b	
10 – 15	2.968 a	3.133 a	
LSD	0.612	0.696	

* Mean maximum number of branches and mean rate of increase in number of branches for P4/10 and MSAF-1 followed by different letters differ significantly ($p < 0.05$) using the Turkey LSD test.

[#] Rate of increase in number of branches (branches month^{-1}) at different growth stages for each cultivar followed by different letters differ significantly ($p < 0.05$) using the Turkey LSD test.

Cassava branching habits vary widely, from single stemmed to an intensely branched habit (Howeler 2012) and branching habit is proportionally stable for every cultivar. The development of branches in leaf axils is greatly influenced by the environment, and usually a consequence of apical dominance. The MSAF-1 branches were more than P4/10 throughout the sampling periods. Due to this branching habit, MSAF-1 also generated higher number of leaves than P4/10 (Alves 2002). Bassey (2016) stated that the rates of increase in leaves and apices is dependent on the branching pattern and its manipulation through plant breeding methods could improve both LAI and HI.

3.3.5 Leaf area index (LAI)

Variability in LAI was observed amongst the two cassava cultivars from 5 – 15 MAP (Figure 3.5). Mean values of LAI for MSAF-1 were significantly higher than those for P4/10. Mean LAI increased with time and notably at 15 MAP. The LAI for P4/10 was 1.4 at 5 MAP and 2.2 at 15 MAP, while MSAF-1 was 2.0 at 5 MAP and 4.0 at 15 MAP. The two cultivars were still increasing even at 15 MAP.

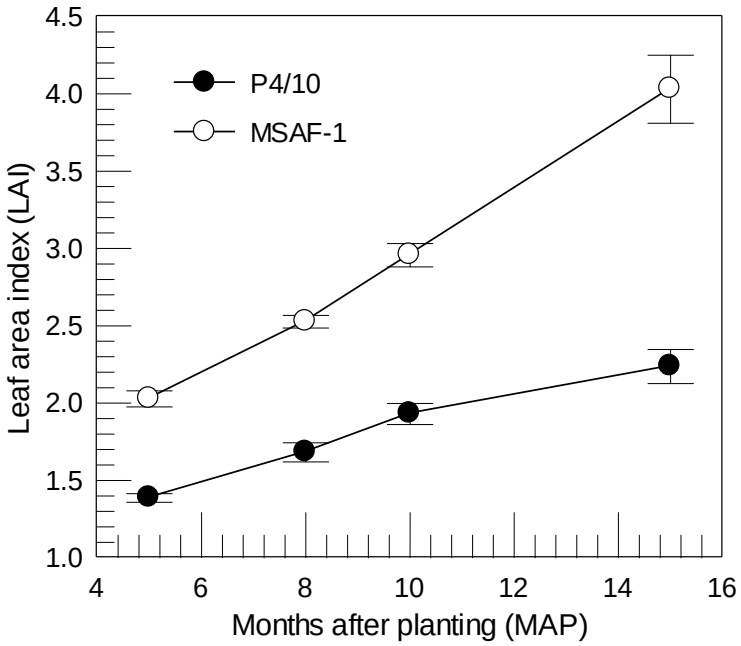

Figure 3.5: Changes in leaf are index for P4/10 and MSAF-1 from 5 – 15 months after planting (MAP) in Mbombela, Mpumalanga, SA. The bars denote standard deviation of mean.

Rates of increase in LAI for the two cultivars presented in Table 3.5 were not significantly different ($p < 0.05$) over time. However, the increase in LAI was almost twice for MSAF-1 than for P4/10. The LAD value for MSAF-1 (558.93 days) was higher than for the P4/10 (893.44 days).

Table 3.5: Rates of increase in leaf area index from 5 – 15 months after planting (MAP) for two cassava cultivars at Mbombela, SA.

Leaf area index (LAI)	Cultivars		LSD
	P4/10	MSAF-1	
At 15 MAP	2.20 b	4.00 a	0.55
Mean rate of increase	0.12 b	0.21 a	0.35
Leaf area duration (LAD)	558.93	893.44	
Rate of increase by stage			
5 – 8	0.11 a	0.17 a	
8 – 10	0.13 a	0.24 a	
10 – 15	0.13 a	0.22 a	
LSD	0.09	0.12	

* Mean maximum LAI and mean rate of increase in LAI for P4/10 and MSAF-1 followed by different letters differ significantly ($p < 0.05$) using the Turkey LSD test.

Rate of increase in leaf area index (LAI month^{-1}) at different growth stages for each cultivar followed by different letters differ significantly ($p < 0.05$) using the Turkey LSD test.

High LAI was reported to be associated with high yielding cultivars (Lahai et al. 2013), which was true for MSAF-1. Cassava experiments in CIAT, Colombia showed that dry matter production was mainly determined by LAI while dry matter distribution appeared to be governed by the preference for top growth (Cock et al. 1979). Higher LAI for MSAF-1 but lower yield than P4/10 confirms findings by Lahai and Ekanayake (2010) who reported one cassava cultivar had low photosynthetic efficiency and partitioning of DM to the storage roots but obtained high accumulation of DM into the leaves and stems than the other cultivars. The LAI means for MSAF-1 and P4/10 were within the range 2.5 – 3.5 for obtaining maximum storage roots yields (Alves 2002). Accumulation of DM in the storage roots is decreased when the source size is increased since the production of DM is influenced by the source size, for instance; from 3.0 – 6.0 LAI values (Alves 2002). Safo-Kantanka and Asare (1993) reported that storage root dry matter yield could only explain 40% of variation in starch yield of cassava.

3.3.6 Relationships between growth parameters

It is important to understand the correlation between the growth parameters and their contribution to yield at different growth phases in cassava. Regressions and correlations were performed using the data for plant height, stem diameter, number of branches and LAI from 5 – 15 MAP for the two cultivars. Figure 3.6 shows the regression analysis between plant height and; stem diameter, number of branches and LAI. P4/10 and MSAF-1 plant height was positively related with stem diameter (r^2 = 0.98 and 0.99), number of branches (r^2 = 0.99 and 0.97), and LAI (r^2 = 0.92 and 0.96). The taller cultivar (MSAF-1) had larger stem diameters than shorter cultivar (P4/10). Indications were that the taller cultivar also resulted in higher number of branches and LAI values.

Strong positive correlations (r > 0.91) for P4/10 and MSAF-1 were observed between: stem diameter and number of branches; stem diameter and LAI, and; number of branches and leaf area index as presented in Figure 3.7. This suggest that thicker stem diameter contributed to higher number of branches and LAI values. In addition, a greater number of branches resulted in higher LAI values.

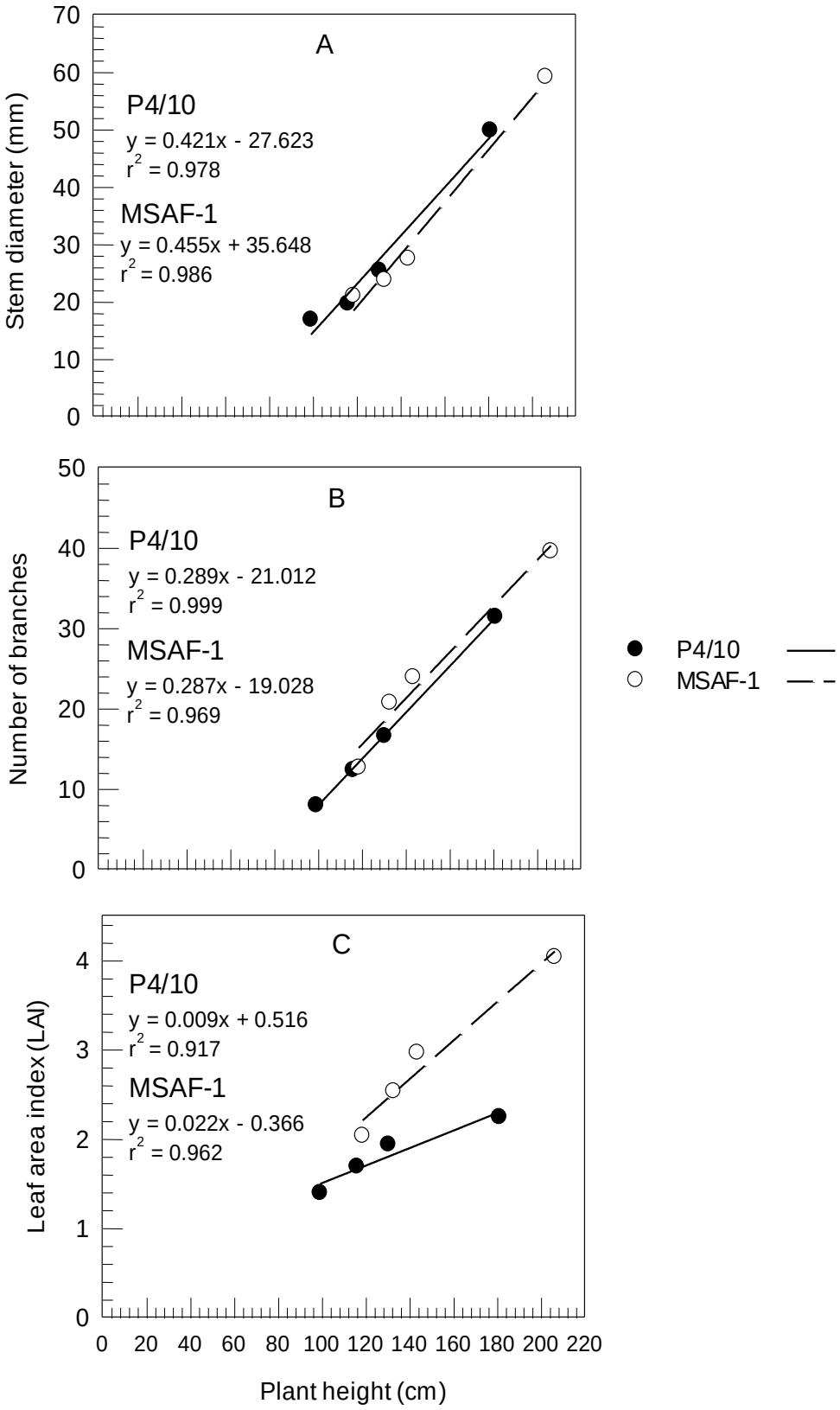

Figure 3.6: Regression of (a) plant height and stem diameter (b) plant height and number of branches (c) plant height and leaf area index for P4/10 and MSAF-1 from 5 to 15 months after planting (MAP). The fitted lines represent linear relationship.

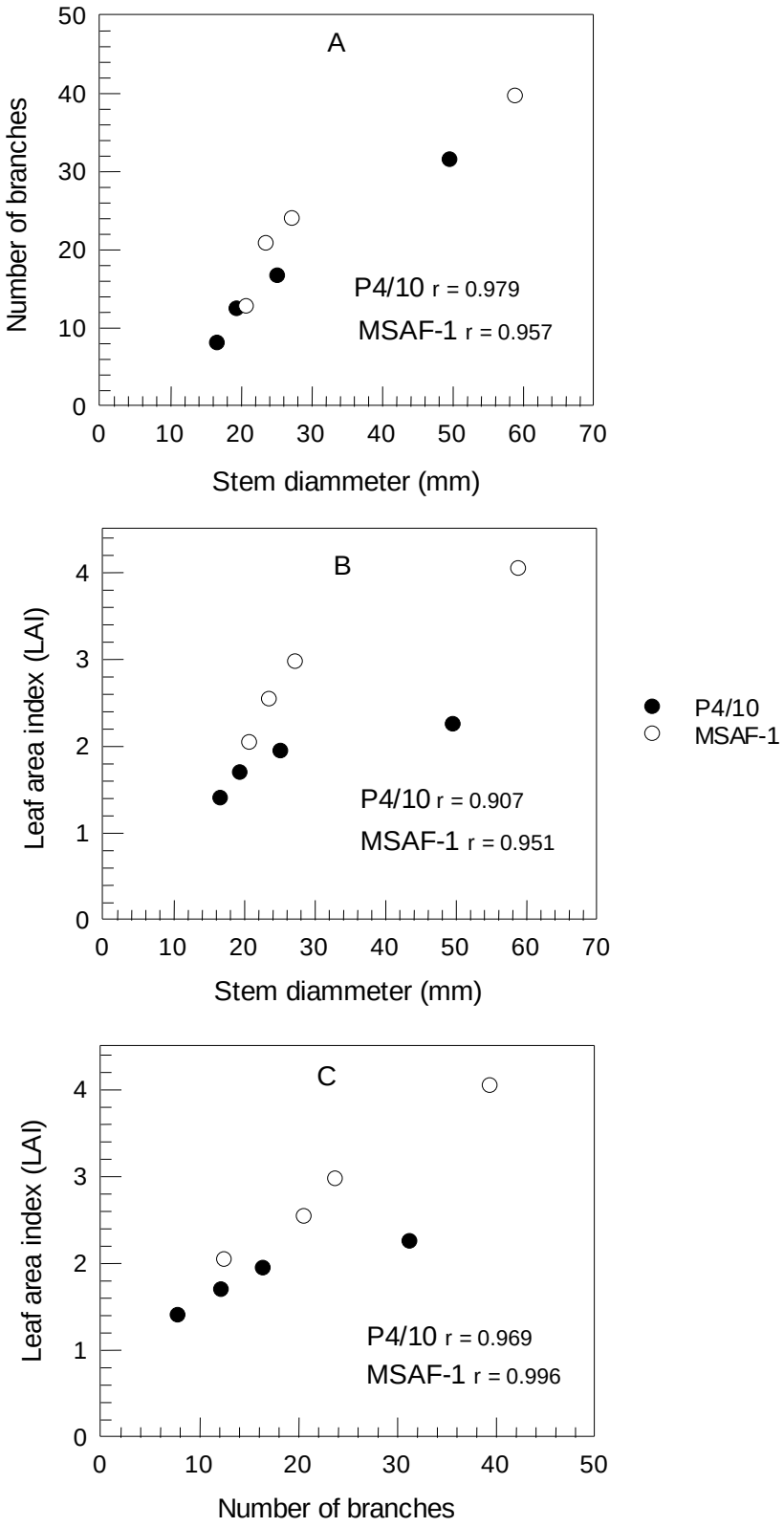

Figure 3.7: Scatter data between (a) stem diameter and number of branches (b) stem diameter and leaf area index (LAI) (c) number of branches and leaf area index for P4/10 and MSAF-1 from 5 to 15 months after planting (MAP).

3.3.7 Yield parameters

Both the cassava cultivars produced fresh aboveground biomass, fresh storage roots weight, storage roots, aboveground dry matter, storage roots dry matter and HI at 15 MAP. There were no significant differences ($p < 0.05$) between the total fresh biomass weights but the aboveground biomass and storage root dry matter yield for the two cultivars were found to be significantly different ($p < 0.05$) at 15 MAP (Figure 3.8). Total fresh biomass weight from MSAF-1 cultivar was heavier than P4/10. The aboveground and storage root dry matter from MSAF-1 were also heavier than P4/10. The total fresh biomass weight for MSAF-1 was 15.55 kg ha^{-1} and 13.14 kg ha^{-1} for P4/10. The MSAF-1 mean aboveground biomass and storage roots dry matter yield were significantly higher ($p < 0.05$) than for P4/10. The MSAF-1 cultivar mean aboveground biomass dry matter yield was 3.97 kg ha^{-1} while for P4/10 was 2.79 kg ha^{-1}. Meanwhile, the MSAF-1 mean storage roots dry matter yield was 5.66 kg ha^{-1} and the P4/10 was 3.73 kg ha^{-1}.

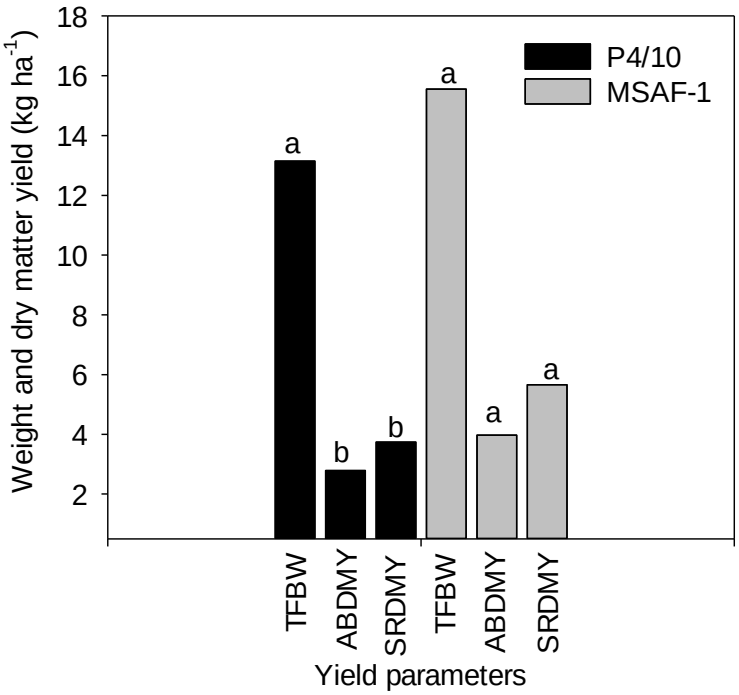

Figure 3.8: Total fresh biomass weight (TFBW), aboveground biomass and storage roots dry matter yield (ABDMY and SRDMY) for P4/10 and MSAF-1 at 15 months after planting (MAP), Mbombela, SA. Letters for each parameter of the two cultivars differ significantly ($p < 0.05$) using the LSD test.

Significant differences in parameters evaluated between P4/10 and MSAF-1 were largely due to genotypic variability since the cultivars were grown under the same conditions. According to Santo and Sarkodie-Addo (2016) minor variation on storage roots dry matter content could

be genetic and this may be attributed to the differences in efficiency of partitioning of dry matter (DM) to the sinks (storage roots) and a much greater sink capacity of a cultivar.

The total number of storage roots and HI for the two cultivars at 15 MAP are presented in Figure 3.9. The mean total number of storage roots for MSAF-1 (13.6) was significantly higher ($p < 0.05$) than for P4/10 (10.0). Meanwhile, the mean HI for MSAF-1 was significantly higher ($p < 0.05$) than for P4/10. The mean HI for P4/10 was 0.53 while for MSAF-1 was 0.62 mean.

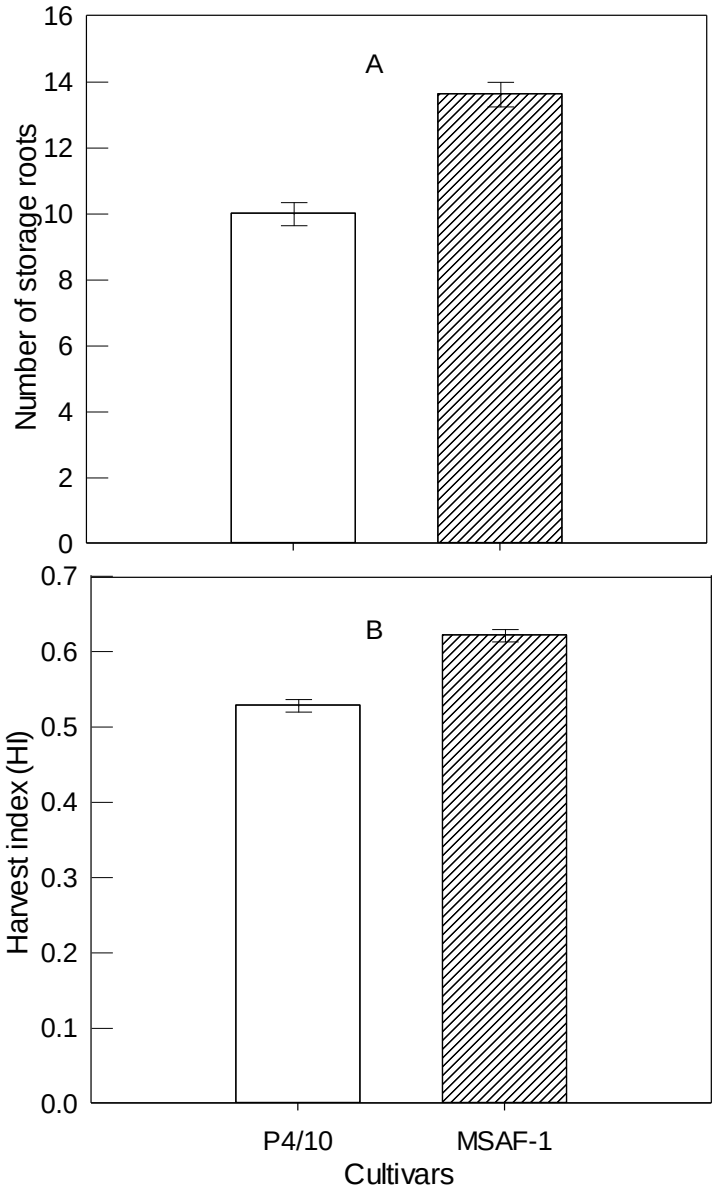

Figure 3.9: P4/10 and MSAF-1 (a) total number of storage roots and (b) harvest index for at 15 months after planting (MAP). The bars denote standard deviation of mean.

Cultivar MSAF-1 had higher yields than P4/10 since the number of storage roots and storage roots growth are the main contributors to yield differences among cassava cultivars (Alves 2002). According to Howeler (2012), an increase in cassava storage roots yield could be as a result of the increase in the single storage roots weight per stand.

Competition for available photosynthates between the aboveground and the below ground growth may be increased by high number of branches, which may have reduced HI in MSAF-1 as compared to P4/10 (Lian and Cock 1979). The P4/10 cultivar can be suitable for various intercrop system since it produced less branches than the MSAF-1. The MSAF-1 could be better utilized for leaf and storage roots consumption purposes.

The HI values for the two cultivars were greater than 41% which indicated a fairly effective redistribution of photosynthates and conversion of assimilates from leaves and stems into the storage roots (Howeler 2012). Távora et al. (1995) reported significant differences in HI values between cultivars, suggesting that HI can serve as an indicator for selecting cassava cultivars with higher yield potential. The number of storage roots determines sink capacity. Variation in the yields could be attributed to the efficiency of partitioning of dry matter to the sinks (Adjei-Nsiah and Issaka 2013, Gyau and Jnr 2015) because yield depends on the number of storage roots and mean storage root weight (Odedina et al. 2012). Fermont et al. (2008) reported that a decrease in dry matter production is associated with increased root yield. Over the years farmers have been using dry matter as an index for cultivating particular cultivars that suit their food needs for *fufu* and *ampesi* (Hayford Mathew 2009).

3.4 CONCLUSIONS

The MSAF-1 cultivar performed better than the P4/10 in all the assessments. Both cultivars had a fairly effective redistribution of photosynthates and conversion of assimilates from leaves and stems into the storage roots with relatively high HI values. The P4/10 cultivar can be suitable for various intercrop system since it produced a non-profuse branching and open canopy architecture as well as less top growth. The MSAF-1 could be better utilized for leaf and storage roots consumption purposes. The differences that were observed between the two cultivars are genetic since the cultivars were grown under the same conditions.

CHAPTER 4

GROWTH AND YIELD RESPONSES OF CASSAVA (*Manihot esculenta* Crantz.) TO DIFFERENT NPK COMBINATIONS

ABSTRACT

Optimal nutrient management is needed to close cassava yield losses since the crop is usually cultivated with minimal or even no fertilizer inputs. This study was conducted to examine the effects of different combinations of NPK on cassava growth and yield. The experiment was arranged in a three block RCBD under a greenhouse. Nitrogen and K were applied at 0, 100, 150 and 200 kg ha^{-1}, while P was applied at 0, 15, 20 and 30 kg ha^{-1}. Plant height, stem diameter, number of branches and number of leaves were measured over a period of 180 days after transplanting (DAT). At 180 DAT data was collected on total leaf area (LA), aboveground biomass and total number of storage roots. The results showed that the three-way interaction (N × P × K) had a significant influence on the growth and yield parameters. This indicated that each element played a significant role in promoting plant growth and the absence of one element led to slow growth compared to when all three elements were present. Plant height, stem diameter, number of branches and number of leaves increased with time and with increasing application rates of NPK. The mean maximum plant height ranged from 145.0 – 326.5 cm and the stem diameter ranged from 26.8 – 61.0 mm. The mean maximum number of branches ranged from 1.0 – 9.0 and the number of leaves ranged from 53.5 – 161.5. The lowest means for total LA, aboveground biomass and number of storage roots were 357.3 cm^2, 220.7 g and 2.0, while their respective highest means were 1964.7 cm^2, 1018.5 g and 9.0. Weak positive correlations were observed between the number of storage roots and; stem diameters (r = 0.40), number of branches (r = 0.45) and number of leaves (r = 0.523). This indicated that NPK fertilization promoted aboveground growth at the expense of below ground growth. The best combination for aboveground growth was $N_{200}P_{30}K_{200}$, while the best combination for below ground growth was $N_{200}P_{30}K_{150}$. Therefore, the best combinations for cassava output that should be recommended was $N_{200}P_{30}K_{150}$.

Key words: Fertilization, aboveground biomass, storage roots

4.1 INTRODUCTION

Cassava is one of the most important carbohydrates food source consumed per capita in Africa (Biratu et al. 2018). However, little or no fertilizer is used by farmers on cassava and information regarding the response of storage roots yield to fertilization is limited. The African continent produced about 57% (158 million tons) in the total of 277 cassava million tons that were produced worldwide in 2013 (Bennett 2015). Cassava storage roots contain about 3.2% protein and 92.2% carbohydrates of the total dry matter. The crops leaves serve as a vital source of minerals, proteins and vitamins in human and animal diets (Balagopalan 2002). The storage roots are mostly processed into cassava flour commonly known as *fufu* and *garri* in Nigeria. The sweet cultivars can be consumed in their raw form, cooked or eaten pounded (Ogundari and Ojo 2006).

The ability for cassava to produce in areas where crops like maize do not perform well, has led to many believing that fertile soils are not necessary in the production of cassava. However, research reports have stated that this is a misconception (Fening et al. 2009). Improved cassava cultivars storage roots yield underperformed when grown infertile soils without fertilizer addition.

Nitrogen and K are required nutrients for cassava and are always deficient in the coarse-textured soils that are most commonly used for cassava cultivation. Nitrogen is an important component of chlorophyll, protein, enzymes, vitamins and hormones. Nitrogen is also essential for cyanogenic glycosides lotaustralin and linamarin, producing the hydrocyanic acid (HCN) during cell impairment (Howeler, 2014). Sangakkara and Wijesinghe (2014) reported that applying N fertilizer increased storage root numbers and yield. Meanwhile, Biratu et al. (2018) found that N deficiencies in cassava reduced plant growth and yield. Potassium plays a major role in metabolism. Potassium promote the activity of net photosynthetic and catalyze the redistribution of assimilates to the storage roots (Biratu et al. 2018).

Nitrogen and K have synergistic interactions (Rietra et al. 2017). Mathias and Kabambe (2015) observed the synergetic effect between nitrogen and K in plant tissue, finding that low applications of N resulted in low plant tissue K concentration, while high applications of N resulted in high K concentration. Thummanatsakun and Yampracha (2018) reported that yield responses to the addition of N fertilizers decreased when the K content in the soil is under critical target level.

The inexistence of fertilizer recommendation rates has contributed a big part in the failure to meet the expanding pressure of the crop (Ezui 2017). Adequate and balanced supply

of nutrients increases the possibilities to produce remarkable cassava yields (Ezui et al. 2012). High storage root yields were obtained in a study when the NPK fertilizer levels were increased above 150% beyond the proposed application rate of 60-60-160 kg ha^{-1} (Kamaraj et al. 2008). However, increased fertilizer rate (90-90-240) kg ha^{-1} produced more storage roots than compared to higher rate 120-120-320 kg ha^{-1} (Kamaraj et al. 2008). These studies concluded that optimum fertilizer application rates differ widely depending on the nutritional status of the soil and the agro-ecological conditions of a certain area.

In order to maximize cassava yields, high rates of P should be applied in soils with very low P for one or two consecutive years (Howeler 2014). Howeler (2012) suggested that 50 – 100 kg ha^{-1} N should be applied in soils with low N and organic matter (OM). Sarfo (2016) reported that cassava plants producing a maximum yield of 30 t ha^{-1}, removes 233 kg ha^{-1} K, 187 kg ha^{-1} N, and 33 kg ha^{-1} P. Meanwhile, a harvest of 25 t ha^{-1} of cassava removes about 60 kg ha^{-1} N, 40 kg ha^{-1} P and 136 kg ha^{-1} K (Sarfo 2016). Overall, fertilizer application rates in Asia and South America range from 30 – 100 kg ha^{-1} N, 25 – 100 kg ha^{-1} P and 60 – 100 kg ha^{-1} K (Howeler 2012).

Howeler et al. (2013) reported that NPK requirements depend on the desired yield levels and the nature of the soil. Consequently, application rates cannot be established or adopted without supporting research about a particular area as it has different soils and agro-ecology. Research has also showed that cultivars adapt to a specific production area. The objective of this study was to examine the effects of different combinations of NPK on cassava growth and yield.

4.2 MATERIALS AND METHODS

4.2.1 Experimental site, design and treatments

This study was carried out at the Agricultural Research Council-Institute for Industrial crops (ARC-IIC) farm in Rustenburg, North West Province, South Africa (25°390′S 27°14.4′E). The experiment was established on the 17th of November 2017 and terminated on the 5th of May 2018, 180 days after transplanting (DAT).

The experiment was a factorial set up in a randomized complete block design (RCBD). The three factors were: N, P and K fertilizers and were applied at four different application rates. The N and K rates were 0, 100, 150 and 200 kg ha^{-1} while, the P rates were 0, 15, 20 and 30 kg ha^{-1}. There combinations of the three factors and their rates gave 64 NPK treatments. These treatments were replicated three times. Limestone ammonium nitrate (LAN-28%) was

used to supply N, while single super phosphate (SSP-14%) was used to supply P and potassium chloride (KCl-50%) was used to supply K. The cassava plants were planted in fertilizer bags. The bags spacing was 0.5 m within each block and 4m between blocks. Each bag weighed approximately 60 kg and one plant was planted per bag. The treatments were split into two equal applications. The first 50% was applied at 30 DAT and the second 50% at 65 DAT.

4.2.2 Cultural practices

The cassava cultivar *Manihot* South Africa (MSAF-2) was used for the experiment because it produces relatively small shoots, but high storage roots yield and it is pest and disease resistant (Melis 1984). Weeding was done at two weeks after planting and repeated as needed. Irrigation was applied at soil field capacity level which was determined at the beginning of the experiment. The plants water requirements would change from time to time but generally the plants were irrigated three times a week throughout the experiment. Bandit 350 SC (Insecticide-Arysta Life Science South Africa) was used to control scale insects.

4.2.3 Soil physical and chemical properties

A mixture of potting soil, sand and field (melanic) soil in the ratio 1:3:1 (60 kg) was used for the experiment. Approximately 1 kg soil sample of the mixture was taken before planting and analysed. The physical and chemical properties are presented in Table 4.1. In prior preparations to analyses, the soil samples were air-dried, jaw-crushed and sieved to pass in a 1 cm^2 mesh. Soil pH was determined using electrometric method in distilled water at 1:1 soil to water ratio. The macro-Kjeldahl digestion method was used for total N determination (Kjeldahl, 1883). The pH 7 ammonium acetate extraction method was used to determine Ca, K, Mg and Na (exchangeable cations) (Chapman 1965). The Olsen P extraction method was used for P, while carbon and aluminium were determined using diethylenetriamine pentaacetic acid (DTPA). Table 4.2 shows the irrigation water chemical analysis results. The water pH value was 7.4, indicating a neutral condition.

Table 4.1: Physico-chemical properties of the potting soil mixture.

Properties		Units		Percentage (%)
Soil pH	6.9	-	-	-
Total Carbon (C)	-	-	-	1.7
Elements		mg kg^{-1}	me (%)	
Al	-	0.0	-	-
Ca	-	1447	7.6	46.1
K	-	118	0.3	1.9
Mg	-	967	7.6	51.1
N	-	3	-	-
Na	-	26	0.1	0.7
P	-	32	-	-
Sand	-	-	-	85
Silt	-	-	-	5
Clay	-	-	-	10

Table 4.2: Chemical properties of water used for irrigation in the greenhouse.

Properties	(mg kg^{-1})	Percentage (%)
pH	7.35	-
K	0	2.495
C	50	4.609
Mg	56	0.609
Na	14	0.000
NH_{4+}	-	0.000
NO_3	14	0.226
H_2PO_4	0	0.000
HCO_3	373	6.115
SO_4	43	0.896

4.2.4 Plant measurements and data analysis

Plant height, stem diameter, number of branches and number of leaves were measured fortnightly between 40 and 180 DAT. At harvest (180 DAT) data was collected on total leaf area (LA), aboveground biomass and number of storage roots. Plant height was measured using a graduated stick from the soil to the topmost part of each plant. The stem diameter was measured using a vernier caliper. The number of branches and number of leaves per plant were counted on each plant. The LI-3100C area meter (LI-COR biosciences) was used to determine the total LA of each plant. The aboveground biomass (stems, branches, and leaves) was weighed and the total number of storage roots per plant were counted.

Data on plant height, stem diameter, number of branches, number of leaves, total leaf area, aboveground biomass and number of tubers on all the sampling dates was subjected to analysis

of variance over time. The Tukey's test was used to separate the means for each sampling period when the F-test was significant ($p < 0.05$). These statistics were conducted using SAS 9.4 version 6.1.7061 for windows general linear procedures (Cary, NC, SAS Institute Inc., 2012). Regression and correlation analyses were performed on selected growth parameters using SigmaPlot 14 (Systat Software Inc). The rates of increase for the linear growth phase for plant height, stem diameter, number of branches and number of leaves were computed by regressing each parameter. The b-values were used to depict the rate of change.

4.3 RESULTS AND DISCUSSIONS

4.3.1 Plant height

The effects of the different NPK combinations on cassava height over time are presented in Figure 4.1. The three-way interaction (N × P × K) was significant ($p < 0.05$) between 81 and 180 DAT but not significant between 40 and 68 DAT. These results showed that each element played a significant role in promoting plant height. The absence of one element led to shorter plants compared to when all three elements were present. Some NPK combinations performed better than other combinations. Plant height increased over time, with sampling periods from 68 – 130 DAT showing a near linear growth phase across all the treatments. The differences in plant heights with respect to most of the treatments, widened over time. Generally, plant height at lower NPK application rates were not different. Plant height means increased with increasing application rates of N and K in the NPK combinations. Generally, the combination of 150 kg ha^{-1} N together with 30 kg ha^{-1} P and 150 kg ha^{-1} K gave the tallest plants. This combination ($N_{150}P_{30}K_{150}$) mean maximum plant height was 56.6% taller than the mean maximum plant height of the shortest plant ($N_{200}P_{15}K_{0}$).

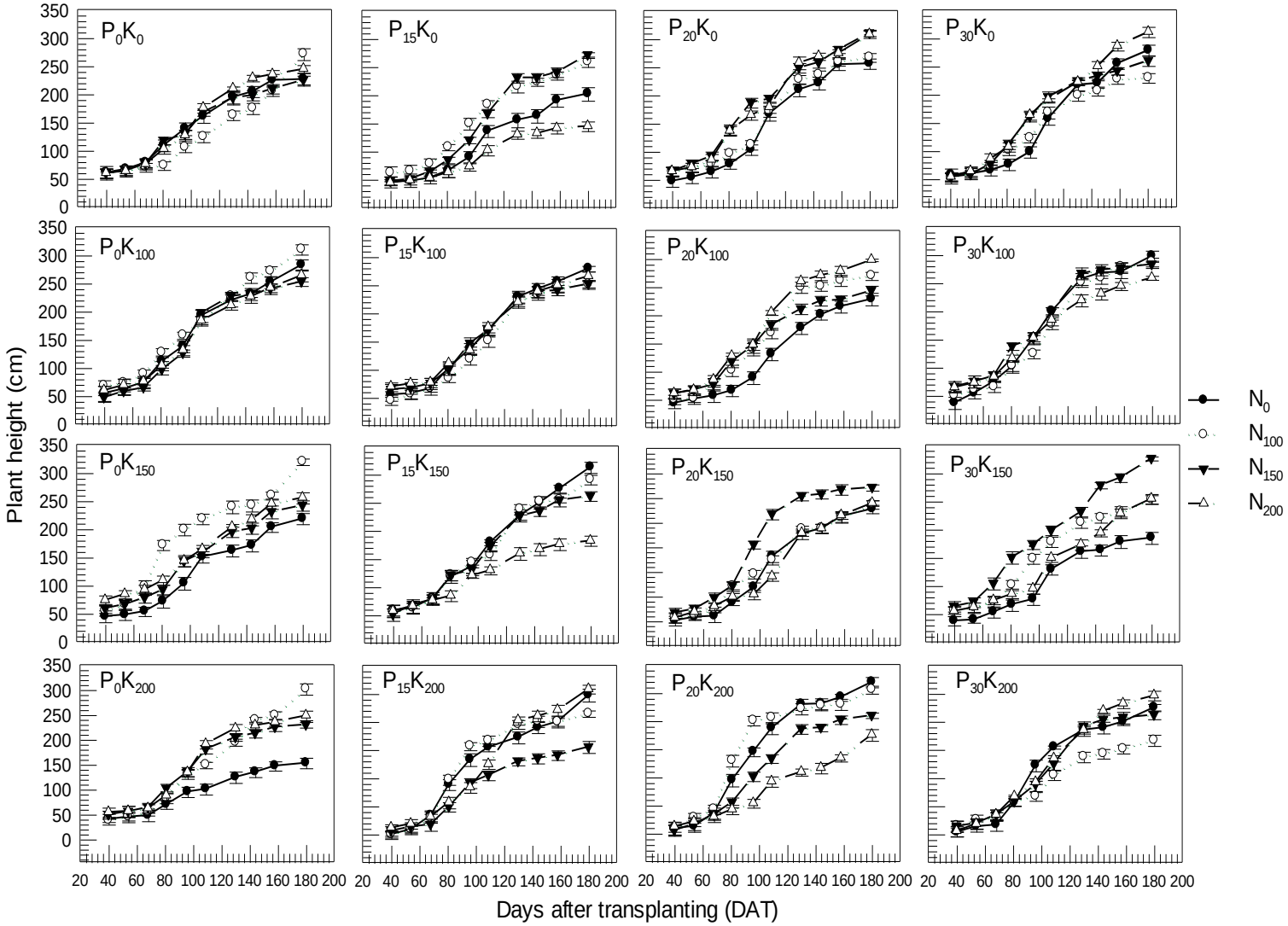

Figure 4.1: Effects of different combinations of NPK on cassava plant height from 40 – 180 days after transplanting (DAT). The bars denote standard deviation of mean.

Table 4.3 shows the mean maximum plant heights and rates of increase in height for the near-linear growth phase of all the treatments. The maximum plant height for each treatment during the study were obtained at different sampling periods and they ranged from 145.0 cm ($N_{200}P_{15}K_0$) to 326.5 cm ($N_{150}P_{30}K_{150}$). Meanwhile the rate of increase in height for the near-linear growth phase ranged from 1.14 cm day^{-1} ($N_0P_0K_{200}$) to 5.61 cm day^{-1} ($N_{100}P_{20}K_{200}$). Mean maximum plant heights for combinations with lower and zero application rates of the three elements were lower compared to mean maximum plant heights for combinations which had higher application rates of the three elements.

The results are in agreement with findings in Mali which showed that cassava growth was positively affected by the application rates of NPK fertilizer (Macalou 2018). The increase in plant height could be attributed to the dominance of the shoots between 15 and 180 DAP, while storage roots become the major sink for photosynthates during the rest of the growth cycle (180 – 360 DAP) (Alves 2002, Howeler 2012). El-Sharkawy (2003) reported that the different organs of the cassava plant markedly change DM distribution patterns during the growth cycle. Sometimes, N deficiency symptoms may not be visible in cassava plants, but the plants grow less vigorous and become shorter than normal (El-Sharkawy and De Tafur 2010). Hence, plant height means for NPK combinations without N were lower relative to those with N. In addition, the absolute increase that was observed between 81 and 130 DAT may be as a result of the plants benefiting from the second split application of the NPK treatments at 76 DAT.

The results from the present study are also in agreement with Suyamto and Howeler (2004) who reported that the application of 92 kg ha^{-1} N, 36 kg ha^{-1} P and 0 kg ha^{-1} K resulted in shorter cassava plants. Meanwhile the application of 30 kg ha^{-1} K when N and P were kept at the same levels, increased the plant height means from 109 to 116 cm. This showed that plants need the application of all three elements in order to grow taller. Another study carried out by Attalla et al. (2001), tested the effect of K fertilizer rates on cassava plants at: 100, 150 or 200 kg ha^{-1} K when N and P were kept constant at 30.9 kg ha^{-1} N and 31 kg ha^{-1} P, found that plant height increased with additional application rates of K. In the same direction increasing K application rates in the NPK treatment combinations resulted in higher mean plant heights in this study. The lack of differences in plant height at lower NPK application implies that amount of nutrients supplied were not adequate to elicit differences in plant heights.

Table 4.3: Effects of different combinations of NPK on maximum mean plant height and rate of increase in plant height for the near-linear growth phase of cassava.

Treatments			Maximum plant height	Rate of increase in height*	Treatments			Maximum plant height	Rate of increase in height
N_0	P_0	K_0	227.0 uv[#]	1.86 g-l	N_{150}	P_0	K_0	225.5 v	1.98 f-l
N_0	P_{15}	K_0	202.5 x	2.07 e-l	N_{150}	P_{15}	K_0	271.5 h-m	2.91 c-i
N_0	P_{20}	K_0	256.5 m-s	2.84 c-j	N_{150}	P_{20}	K_0	311.0 abc	2.88 c-i
N_0	P_{30}	K_0	279.0 g-j	3.44 b-e	N_{150}	P_{30}	K_0	260.5 l-q	2.95 c-h
N_0	P_0	K_{100}	283.0 f-i	2.77 c-j	N_{150}	P_0	K_{100}	253.5 o-s	2.94 c-h
N_0	P_{15}	K_{100}	279.5 g-j	2.58 c-k	N_{150}	P_{15}	K_{100}	252.5 o-s	2.48 c-l
N_0	P_{20}	K_{100}	228.9 tuv	2.34 c-l	N_{150}	P_{20}	K_{100}	244.0 rst	2.06 e-l
N_0	P_{30}	K_{100}	298.0 c-f	2.87 c-i	N_{150}	P_{30}	K_{100}	283.5 f-i	2.80 c-j
N_0	P_0	K_{150}	219.0 vw	2.33 c-l	N_{150}	P_0	K_{150}	242.5 stu	2.00 f-l
N_0	P_{15}	K_{150}	313.0 abc	2.09 e-l	N_{150}	P_{15}	K_{150}	262.0 k-p	2.30 d-l
N_0	P_{20}	K_{150}	278.0 g-k	3.13 b-g	N_{150}	P_{20}	K_{150}	321.5 ab	4.47 ab
N_0	P_{30}	K_{150}	185.5 y	2.39 c-l	N_{150}	P_{30}	K_{150}	326.5 a	2.12 e-l
N_0	P_0	K_{200}	153.5 z	1.14 l	N_{150}	P_0	K_{200}	230.0 tuv	2.77 c-j
N_0	P_{15}	K_{200}	298.0 c-f	2.27 d-l	N_{150}	P_{15}	K_{200}	205.5 wx	2.22 d-l
N_0	P_{20}	K_{200}	319.5 ab	3.11 b-g	N_{150}	P_{20}	K_{200}	260.5 l-q	2.64 c-k
N_0	P_{30}	K_{200}	275.5 g-l	3.13 b-g	N_{150}	P_{30}	K_{200}	262.5 k-p	2.65 c-k
N_{100}	P_0	K_0	271.5 h-m	1.83 g-l	N_{200}	P_0	K_0	245.0 q-t	2.30 d-l
N_{100}	P_{15}	K_0	259.5 l-r	2.43 c-l	N_{200}	P_{15}	K_0	145.0 z	1.53 i-l
N_{100}	P_{20}	K_0	267.5 i-o	3.34 b-f	N_{200}	P_{20}	K_0	308.5 bc	2.42 c-l
N_{100}	P_{30}	K_0	230.0 tuv	1.89 g-l	N_{200}	P_{30}	K_0	311.5 abc	2.06 e-l
N_{100}	P_0	K_{100}	310.5 abc	2.18 d-l	N_{200}	P_0	K_{100}	264.5 j-p	2.00 f-l
N_{100}	P_{15}	K_{100}	251.5 o-s	2.82 c-j	N_{200}	P_{15}	K_{100}	266.0 j-o	2.27 d-l
N_{100}	P_{20}	K_{100}	270.0 i-n	2.35 c-l	N_{200}	P_{20}	K_{100}	298.5 c-f	2.82 c-j
N_{100}	P_{30}	K_{100}	287.5 e-h	2.96 c-h	N_{200}	P_{30}	K_{100}	259.5 l-r	2.22 d-l
N_{100}	P_0	K_{150}	320.0 ab	2.74 c-j	N_{200}	P_0	K_{150}	256.0 m-s	1.78 g-l
N_{100}	P_{15}	K_{150}	291.0 d-g	2.38 c-l	N_{200}	P_{15}	K_{150}	182.6 y	1.46 jkl
N_{100}	P_{20}	K_{150}	287.0 e-h	2.19 d-l	N_{200}	P_{20}	K_{150}	290.0 d-g	3.72 bc
N_{100}	P_{30}	K_{150}	253.5 o-s	2.28 d-l	N_{200}	P_{30}	K_{150}	255.0 n-s	1.80 g-l
N_{100}	P_0	K_{200}	302.0 cde	2.37 c-l	N_{200}	P_0	K_{200}	249.0 p-s	2.76 c-j
N_{100}	P_{15}	K_{200}	265.0 j-p	3.56 bcd	N_{200}	P_{15}	K_{200}	308.5 bc	2.89 c-i
N_{100}	P_{20}	K_{200}	306.0 bcd	5.61 a	N_{200}	P_{20}	K_{200}	225.4 v	1.35 k-l
N_{100}	P_{30}	K_{200}	217.0 vwx	1.69 h-l	N_{200}	P_{30}	K_{200}	297.0 c-f	2.54 c-k
LSD (0.05)			7.61	0.64	LSD (0.05)			7.61	0.64
r^2			0.99	0.91	r^2			0.99	0.91
C.V (%)			1.45	12.73	C.V (%			1.45	12.73

* Rate of increase in height (cm day^{-1}) was computed as 'b'-values of the near-linear growth phase of each plant.

[#] Means with the same letter within the columns of maximum plant height and rate of increase in height are not significantly different ($p < 0.05$) using LSD test.

4.3.2 Stem diameter

The effects of the different combinations of NPK on stem diameter from 40 – 180 DAT are shown in Figure 4.2. The N × P × K interaction was significant ($p < 0.05$) for all the sampling periods for cassava stem diameters. A general increase in stem diameter over time was observed. However, the absolute increases in stem diameter were comparable and the differences amongst the treatments widened over time. Stem diameters for all nutrient combinations without N were significantly lower than those with N over time. Table 4.4 shows the maximum stem diameter means during the course of the study and the near-linear growth phase rates of increase for all the treatments. The maximum stem diameters were not obtained at the same sampling periods and they ranged from 26.8 mm ($N_{100}P_0K_0$) to 61.0 mm ($N_{200}P_{30}K_{150}$). Meanwhile the rate of increase for the near-linear growth phase ranged from 0.13 mm day^{-1} ($N_{150}P_{30}K_{100}$) to 0.39 mm day^{-1} ($N_{150}P_{30}K_{100}$).

The results showed that the three elements NPK were not independent of each other. The presence of each element played a significant role in promoting stem diameter growth. The absence of one element led to thinner stem diameters compared to when all three elements were present. Generally, the NPK combinations increased the mean maximum stem diameters with increasing N application rates. The results also showed that combinations with either too much N and too little K and P or too much K and too little N and P led to lower mean maximum stem diameters. However, some NPK combinations were better than other combinations. Therefore, the combination of 200 kg ha^{-1} N together with 30 kg ha^{-1} P and 150 kg ha^{-1} K gave the widest stem diameter plants. This combination of the highest mean maximum stem diameter ($N_{200}P_{30}K_{150}$) was 56.1% wider than the lowest mean maximum stem diameter ($N_{100}P_0K_0$).

These results are consistent with findings from Nigeria where cassava stem diameters increased with increased N and K rates (Uwah et al. 2013b). The findings from the present study are also similar to the study by Macalou (2018) who reported that cassava stem diameters from the application of NPK at 200 and 300 kg ha^{-1} were found to be significantly higher than for 100 and 0 kg ha^{-1}.

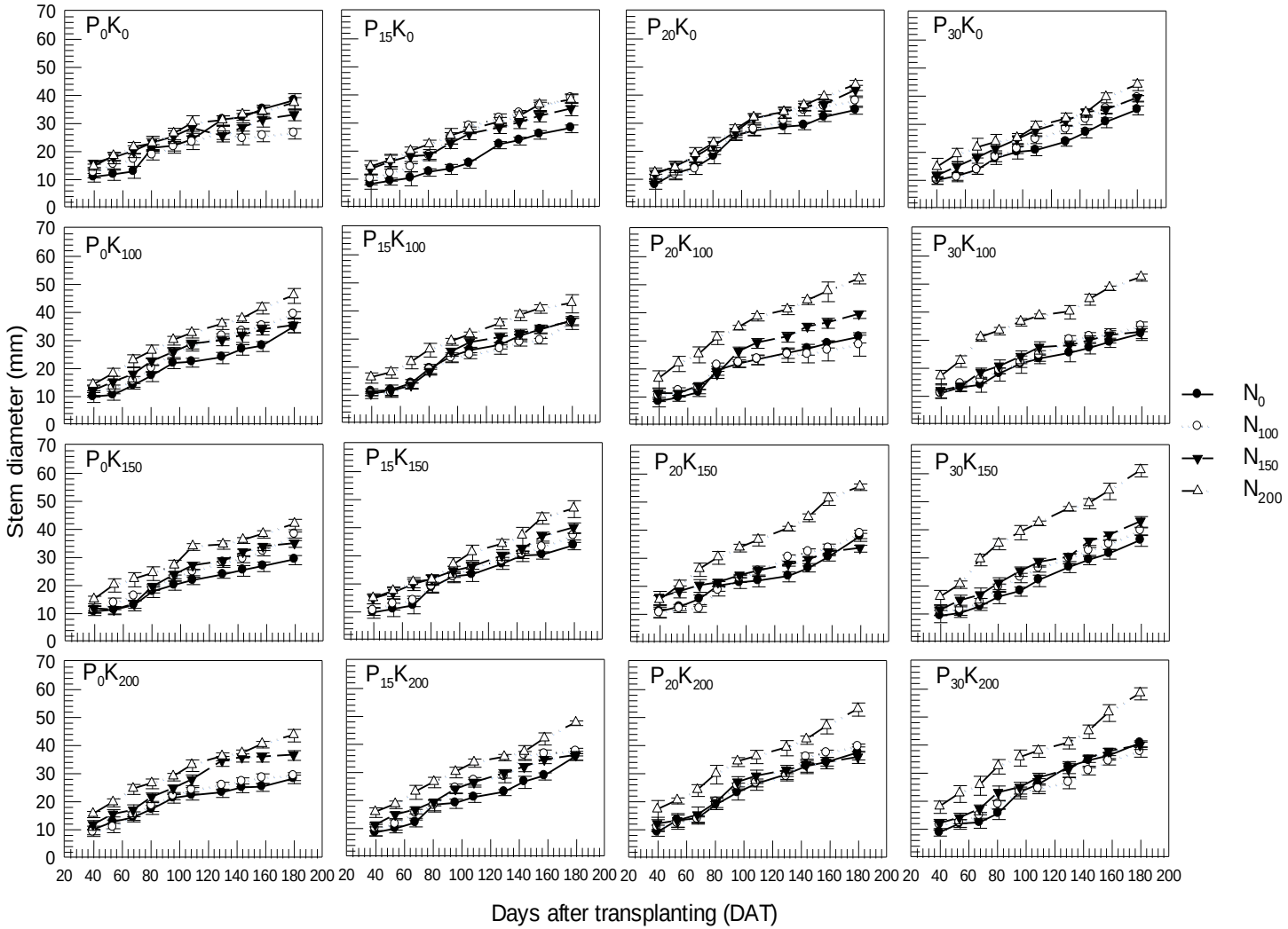

Figure 4.2: Effects of different combinations of NPK on cassava stem diameter from 40 – 180 days after transplanting (DAT). The bars denote standard deviation of mean.

Table 4.4: Effects of different combination of NPK on maximum mean stem diameter and rate of increase in stem diameter for the near-linear growth phase of cassava.

Treatments			Maximum stem diameter	Rate of increase in diameter*	Treatments			Maximum stem diameter	Rate of increase in Diameter
N_0	P_0	K_0	38.0 h-o[#]	0.24 i-r	N_{150}	P_0	K_0	32.9 m-s	0.15 x-D
N_0	P_{15}	K_0	27.9 rs	0.13 BCD[+]	N_{150}	P_{15}	K_0	34.9 k-r	0.15 x-D
N_0	P_{20}	K_0	34.4 l-s	0.27 f-n	N_{150}	P_{20}	K_0	41.6 e-l	0.31 c-g
N_0	P_{30}	K_0	34.9 k-r	0.20 q-x	N_{150}	P_{30}	K_0	39.2 f-n	0.23 n-u
N_0	P_0	K_{100}	34.6 l-s	0.24 k-s	N_{150}	P_0	K_{100}	35.2 j-r	0.22 o-v
N_0	P_{15}	K_{100}	36.3 h-p	0.19 r-y	N_{150}	P_{15}	K_{100}	36.1 h-q	0.39 a
N_0	P_{20}	K_{100}	31.1 o-s	0.18 t-B	N_{150}	P_{20}	K_{100}	39.3 f-n	0.22 n-u
N_0	P_{30}	K_{100}	32.0 n-s	0.19 s-z	N_{150}	P_{30}	K_{100}	32.7 m-s	0.13 D
N_0	P_0	K_{150}	29.1 p-s	0.13 D	N_{150}	P_0	K_{150}	35.1 j-r	0.18 t-A
N_0	P_{15}	K_{150}	33.5 m-s	0.15 y-D	N_{150}	P_{15}	K_{150}	39.8 e-n	0.18 t-A
N_0	P_{20}	K_{150}	37.5 h-o	0.26 f-o	N_{150}	P_{20}	K_{150}	33.4 m-s	0.13 A-D
N_0	P_{30}	K_{150}	36.0 h-q	0.20 q-v	N_{150}	P_{30}	K_{150}	42.8 e-j	0.23 n-u
N_0	P_0	K_{200}	28.0 rs	0.21 o-v	N_{150}	P_0	K_{200}	36.4 h-p	0.28 e-m
N_0	P_{15}	K_{200}	35.5 j-r	0.13 CD	N_{150}	P_{15}	K_{200}	35.9 i-q	0.17 v-D
N_0	P_{20}	K_{200}	37.2 h-o	0.23 l-s	N_{150}	P_{20}	K_{200}	35.6 j-r	0.38 ab
N_0	P_{30}	K_{200}	40.4 e-m	0.29 d-j	N_{150}	P_{30}	K_{200}	39.7 e-n	0.22 n-u
N_{100}	P_0	K_0	26.8 s	0.18 t-A	N_{200}	P_0	K_0	35.1 j-r	0.19 s-z
N_{100}	P_{15}	K_0	38.7 g-o	0.29 d-i	N_{200}	P_{15}	K_0	38.1 h-o	0.20 q-w
N_{100}	P_{20}	K_0	37.6 h-o	0.25 i-r	N_{200}	P_{20}	K_0	43.5 e-i	0.32 cde
N_{100}	P_{30}	K_0	39.1 f-n	0.25 h-q	N_{200}	P_{30}	K_0	43.9 e-h	0.23 m-t
N_{100}	P_0	K_{100}	39.1 f-n	0.35 abc	N_{200}	P_0	K_{100}	45.9 d-g	0.26 g-p
N_{100}	P_{15}	K_{100}	35.7 i-r	0.14 z-D	N_{200}	P_{15}	K_{100}	42.6 e-k	0.22 n-v
N_{100}	P_{20}	K_{100}	28.3 qrs	0.15 w-D	N_{200}	P_{20}	K_{100}	51.9 bcd	0.25 i-r
N_{100}	P_{30}	K_{100}	34.8 k-r	0.21 q-v	N_{200}	P_{30}	K_{100}	52.3 bcd	0.22 o-v
N_{100}	P_0	K_{150}	38.0 h-o	0.23 l-s	N_{200}	P_0	K_{150}	41.8 e-l	0.21 p-v
N_{100}	P_{15}	K_{150}	36.9 h-o	0.18 u-C	N_{200}	P_{15}	K_{150}	46.6 def	0.24 j-s
N_{100}	P_{20}	K_{150}	38.5 g-o	0.23 l-s	N_{200}	P_{20}	K_{150}	55.3 abc	0.33 bcd
N_{100}	P_{30}	K_{150}	39.4 f-n	0.23 l-s	N_{200}	P_{30}	K_{150}	61.0 a	0.382 ab
N_{100}	P_0	K_{200}	29.0 p-s	0.21 p-v	N_{200}	P_0	K_{200}	43.5 e-i	0.29 c-h
N_{100}	P_{15}	K_{200}	37.2 h-o	0.28 e-k	N_{200}	P_{15}	K_{200}	47.5 cde	0.25 h-q
N_{100}	P_{20}	K_{200}	39.3 f-n	0.28 e-l	N_{200}	P_{20}	K_{200}	52.9 bcd	0.22 o-v
N_{100}	P_{30}	K_{200}	37.4 h-o	0.25 i-r	N_{200}	P_{30}	K_{200}	58.3 ab	0.31 c-f
LSD (0.05)			3.62	0.02	LSD (0.05)			3.62	0.02
r^2			0.97	0.98	r^2			0.97	0.98
C.V (%)			4.68	5.02	C.V (%)			4.68	5.02

* Rate of increase in diameter (mm day^{-1}) was computed a 'b'-values of the near-linear growth phase of each plant.

[#] Means with the same small letter and capital letters within the columns of maximum stem diameter and rate of increase in diameter are not significantly different ($p < 0.05$) using LSD test.

[+] The capital letters represent mean separation beyond the letter 'z'

4.3.3 Number of branches and leaves

The three-way interaction (N × P × K) was significant ($p < 0.05$) for all the sampling periods for the number of branches and leaves. Figure 4.3 shows the effects of the different combinations of NPK on number of branches from 40 to 180 DAT. The number of branches of some treatments did not change but some treatments increased with time. The results also showed that the number of branches increased with increasing application rates of N in the NPK combinations. The mean maximum number of branches and leaves are presented in Table 4.5. The maximum number of branches and leaves were attained at different sampling periods during the course of the study. The mean maximum number of branches ranged from 1.0 ($N_0P_{30}K_0$) to 9.0 ($N_{200}P_{20}K_{200}$). Meanwhile, the mean maximum number of leaves ranged from 53.5 ($N_0P_{30}K_0$) to 161.5 ($N_{200}P_{30}K_{200}$). The best combination for number of branches and leaves in this study was 200 kg ha^{-1} N, 30 kg ha^{-1} and 200 kg ha^{-1} K.

The findings from this study relate to other studies since the maximum number of branches were also attained between 90 – 180 DAT (Távora et al. 1995), which is the most active vegetative growth phase for cassava according to Ramanujam and Biradar (1987). The results from this study are also similar with those from a study that was carried out by El-Sharkawy et al. (1990), who reported that the number of leaves significantly increased with increasing N application rates at 6 months after planting (MAP) where four rates of N (0, 30, 60 or 90 kg ha^{-1} N) were in combination with 120 kg ha^{-1} P and 120 kg ha^{-1} K. The application of N fertilizers at: 30, 60 or 90 kg ha^{-1} were reported to increase the number of leaves in cassava by 14.4%, 78.9% and 163.1% respectively, over the control (0 kg ha^{-1} N) (El-Sharkawy et al. 1990). Findings similar to this study were also observed by El-Sayed et al. (1992) who reported that N rates: 50 or 100 kg ha^{-1} in combination with 40 kg ha^{-1} P and 75 kg ha^{-1} K showed more number of leaves per cassava plant than when N was 0 kg ha^{-1}. In addition, the findings from this study are also in agreement with Attalla et al. (2001) who found that number of leaves per plant increased with increasing K when the K rates were: 100, 150 or 200 kg ha^{-1} K.

The loss of leaves between 84 and 98 DAT was similar to the observations by El-Sharkawy (2007) who reported that cassava leaf life is normally from 40 to 210 days. Leaf formation is reduced as the plant ages and during low temperatures (Mitprasat et al. 2011). The loss of leaves from this study may also be attributed to the fact that it was carried out in a greenhouse which promoted leaf shading (Zhang et al. 2010). Alves (2002) reported that shading levels of up to 75% have a very low effect on leaf life, but shades from 90 to 100% levels result to leaf abscission within 10 days.

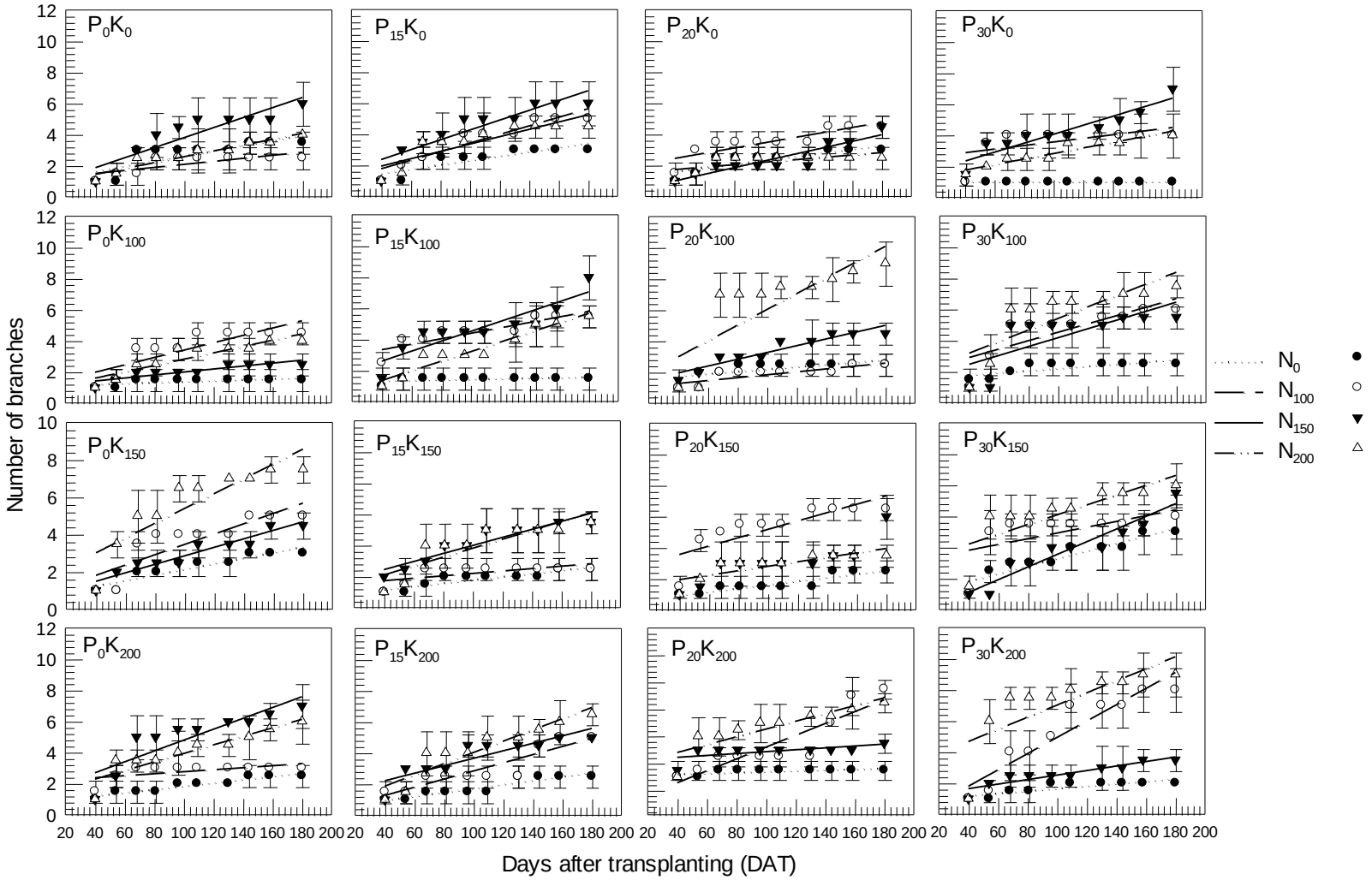

Figure 4.3: Effects of different combinations of NPK on number of branches for cassava from 40 – 180 days after transplanting (DAT). The bars denote standard deviation of mean and the straight lines were fitted by regression of data of the treatments.

Table 4.5: Effects of different NPK combinations on the number of cassava branches and leaves.

Treatments			Maximum number of branches	Maximum number of Leaves	Treatments			Maximum number of branches	Maximum number of Leaves
N_0	P_0	K_0	3.5 d-i*	79.0 q-x	N_{150}	P_0	K_0	6.0 a-f	102.5 e-q
N_0	P_{15}	K_0	3.0 e-i	86.0 p-w	N_{150}	P_{15}	K_0	6.0 a-f	130.0 b-e
N_0	P_{20}	K_0	3.0 e-i	99.0 h-s	N_{150}	P_{20}	K_0	4.5 b-i	97.0 i-s
N_0	P_{30}	K_0	1.0 i	53.5 x	N_{150}	P_{30}	K_0	7.0 a-d	119.5 b-k
N_0	P_0	K_{100}	1.5 hi	63.5 wx	N_{150}	P_0	K_{100}	2.5 f-i	97.0 i-s
N_0	P_{15}	K_{100}	1.5 h	95.5 i-t	N_{150}	P_{15}	K_{100}	8.0 ab	132.0 bcd
N_0	P_{20}	K_{100}	2.5 f-i	113.0 c-p	N_{150}	P_{20}	K_{100}	4.5 b-i	108.5 c-p
N_0	P_{30}	K_{100}	2.5 f-i	87.0 o-w	N_{150}	P_{30}	K_{100}	5.5 a-g	104.0 d-q
N_0	P_0	K_{150}	3.0 e-i	87.5 n-w	N_{150}	P_0	K_{150}	4.5 b-i	122.5 b-i
N_0	P_{15}	K_{150}	2.5 f-i	79.5 q-x	N_{150}	P_{15}	K_{150}	5.5 a-g	115.5 c-n
N_0	P_{20}	K_{150}	2.5 f-i	65.5 vwx	N_{150}	P_{20}	K_{150}	6.0 a-f	101.0 g-r
N_0	P_{30}	K_{150}	5.0 b-h	89.5 m-w	N_{150}	P_{30}	K_{150}	7.5 abc	130.0 b-e
N_0	P_0	K_{200}	2.5 f-i	71.5 s-x	N_{150}	P_0	K_{200}	7.0 a-d	120.0 b-k
N_0	P_{15}	K_{200}	2.5 f-i	101.5 f-q	N_{150}	P_{15}	K_{200}	5.5 a-g	112.0 c-p
N_0	P_{20}	K_{200}	1.5 hi	67.5 t-x	N_{150}	P_{20}	K_{200}	3.5 d-i	108.0 c-p
N_0	P_{30}	K_{200}	2.0 ghi	67.0 u-x	N_{150}	P_{30}	K_{200}	3.5 d-i	110.5 c-p
N_{100}	P_0	K_0	2.5 f-i	102.5 e-q	N_{200}	P_0	K_0	4.0 c-i	94.0 j-u
N_{100}	P_{15}	K_0	5.0 b-h	98.5 h-s	N_{200}	P_{15}	K_0	4.5 b-i	98.5 h-s
N_{100}	P_{20}	K_0	4.5 b-i	109.5 c-p	N_{200}	P_{20}	K_0	2.5 f-i	115.5 c-n
N_{100}	P_{30}	K_0	4.0 c-i	122.5 b-i	N_{200}	P_{30}	K_0	4.0 c-i	101.5 f-q
N_{100}	P_0	K_{100}	4.5 b-i	113.0 c-p	N_{200}	P_0	K_{100}	4.0 c-i	103.0 e-q
N_{100}	P_{15}	K_{100}	5.5 a-g	115.0 c-o	N_{200}	P_{20}	K_{100}	9.0 a	122.0 b-j
N_{100}	P_{20}	K_{100}	2.5 f-i	73.0 r-x	N_{200}	P_{15}	K_{100}	5.5 a-g	101.0 g-r
N_{100}	P_{30}	K_{100}	6.0 a-f	128.0 b-g	N_{200}	P_{30}	K_{100}	7.5 abc	126.0 b-h
N_{100}	P_0	K_{150}	5.0 b-h	121.5 b-j	N_{200}	P_0	K_{150}	7.5 abc	129.5 b-f
N_{100}	P_{15}	K_{150}	2.5 f-i	92.0 k-v	N_{200}	P_{15}	K_{150}	5.5 a-g	126.0 b-h
N_{100}	P_{20}	K_{150}	6.5 a-e	147.0 ab	N_{200}	P_{20}	K_{150}	3.5 d-i	117.0 c-m
N_{100}	P_{30}	K_{150}	6.0 a-f	120.0 b-k	N_{200}	P_{30}	K_{150}	8.0 ab	130.5 b-e
N_{100}	P_0	K_{200}	3.0 e-i	90.0 l-w	N_{200}	P_0	K_{200}	6.0 a-f	99.0 h-s
N_{100}	P_{15}	K_{200}	5.0 b-h	91.0 l-w	N_{200}	P_{15}	K_{200}	6.5 a-e	118.0 c-l
N_{100}	P_{20}	K_{200}	7.5 abc	133.5 abc	N_{200}	P_{20}	K_{200}	6.5 a-e	110.0 c-p
N_{100}	P_{30}	K_{200}	8.0 ab	101.5 f-q	N_{200}	P_{30}	K_{200}	9.0 a	161.5 a
LSD (0.05)			1.72	12.99	LSD (0.05)			1.72	12.99
r^2			0.92	0.96	r^2			0.92	0.96
C.V (%)			18.42	6.18	C.V (%)			18.42	6.18

* Means with the same letter within the columns of the same parameter are not significantly different ($p < 0.05$) using LSD test.

4.3.4 Relationship between growth parameters

Plat height did not have a significant relationship with any of the parameters that were measured. This indicated that NPK application was increasing plant height at the expense of the other growth parameters. The regression results between mean maximum stem diameter and; number of branches, number of leaves and, number of branches and number of leaves are

shown in Figure 4.4. Positive regressions were observed between stem diameters and number of branches (r^2 = 0.53) and stem diameters and number of leaves (r^2 = 0.49). Meanwhile a stronger positive regression was observed between number of branches and number of leaves (r^2 = 0.76). There findings from this study are similar to the results obtained by Samuolienė et al. (2010) in Mali, in which cassava stem diameter was positively correlated with number of branches and leaves. The strong correlation between number of branches and leaves implied that the number of leaves increased with number of branches.

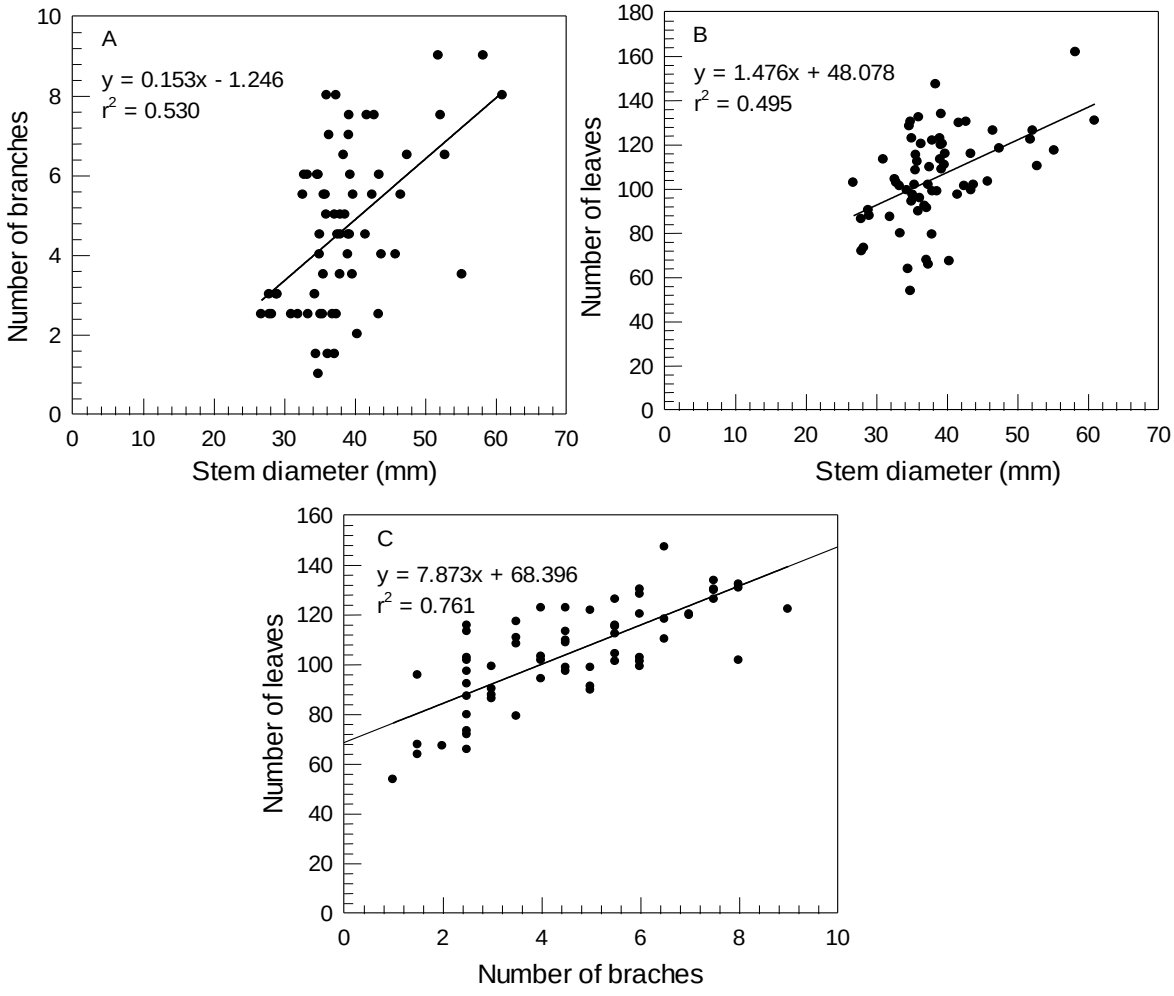

Figure 4.4: Regression of stem diameter and; (a) number of branches, (b) number of leaves and, (c) number of branches and number of leaves. The straight lines were fitted by regression of data from all NPK combinations.

4.3.5 Total leaf area

The three-way interaction (N × P × K) was significantly different ($p < 0.05$) at 180 DAT for total LA (Figure 4.5). The mean maximum total LA was 1964.7 cm^2 ($N_{200}P_{30}K_{200}$) and the

mean minimum was 357.3 cm^2 ($N_0P_{15}K_0$). Generally, the total leaf area increased with increasing NPK application rates.

The NPK combination influenced total LA than individual elements. This showed that each element played a significant role in promoting LA. The absence of one element led to lower total LA values compared to when all three elements were present. Even though, the performance of some NPK combinations was better than other combinations. The NPK combinations with N had higher total leaf area than those treatments without N. The best combination for achieving high total LA values was 200 kg ha^{-1} N together with 30 kg ha^{-1} P and 200 kg ha^{-1} K. High application rates of NPK certainly led to greater growth and hence greater total LA than in the NPK combinations with 0 kg ha^{-1} N. This indicated that for cassava growth more fertilizers should be applied.

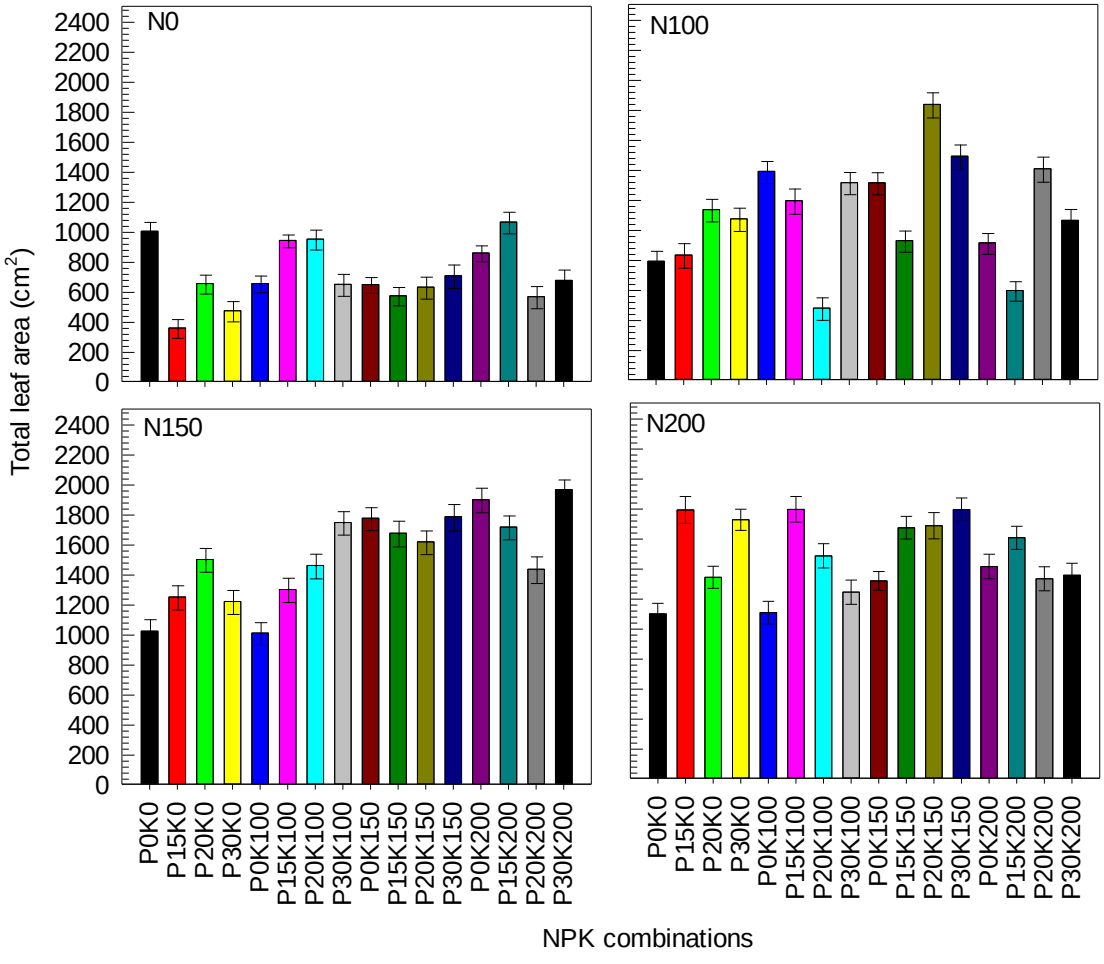

Figure 4.5: Effects of different combinations of NPK on total leaf area for cassava at 180 days after transplanting (DAT). The bars denote standard deviation of mean.

4.3.6 Aboveground biomass

The three-way interaction (N × P × K) was significantly different ($p < 0.05$) for the aboveground biomass (Figure 4.6). The mean maximum aboveground biomass was 1018.5 g ($N_{200}P_{30}K_{200}$) and the minimum mean was 220.7 g ($N_0P_{15}K_0$). Generally, the aboveground biomass increased with increasing NPK application rates.

The synergistic interaction indicated that the combined application of the three nutrients (N, P and K) produced more aboveground biomass than individual applications of the nutrients. The NPK combinations with N had higher aboveground biomass than those treatments without N. The best combination for achieving high aboveground biomass values was 200 kg ha^{-1} N together with 30 kg ha^{-1} P and 200 kg ha^{-1} K. High application rates of NPK certainly led to greater growth and hence greater shoot biomass than in the NPK combinations with 0 kg ha^{-1} N. This indicated that for cassava growth nutrients should be applied at higher rates.

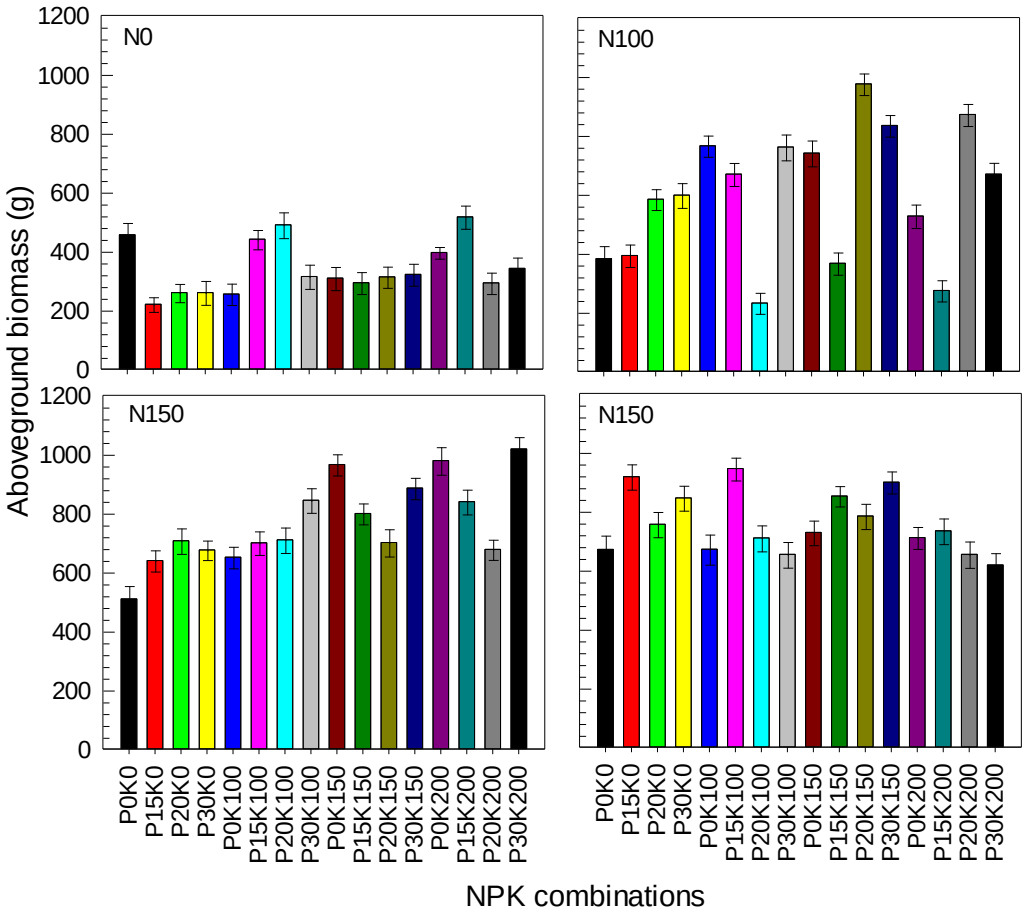

Figure 4.6: Effects of different combinations of NPK on aboveground biomass (g) for cassava at 180 days after transplanting (DAT). The bars denote standard deviation of mean.

4.3.7 Relationship between aboveground biomass and selected aboveground parameters

Correlations between aboveground biomass weight and stem diameter, and regression between aboveground biomass and; number of branches and number of leaves at 180 DAT are shown in Figure 4.7. A positive correlation was observed between aboveground biomass and stem diameter (r = 0.54). There were stronger regressions between aboveground biomass and; number of branches (r^2 = 0.61), and the number of leaves (r^2 = 0.82). The strong regressions that were observed between aboveground biomass and number of branches and leaves indicated that the number of leaves and number of branches have some profound effects on the final aboveground biomass for cassava.

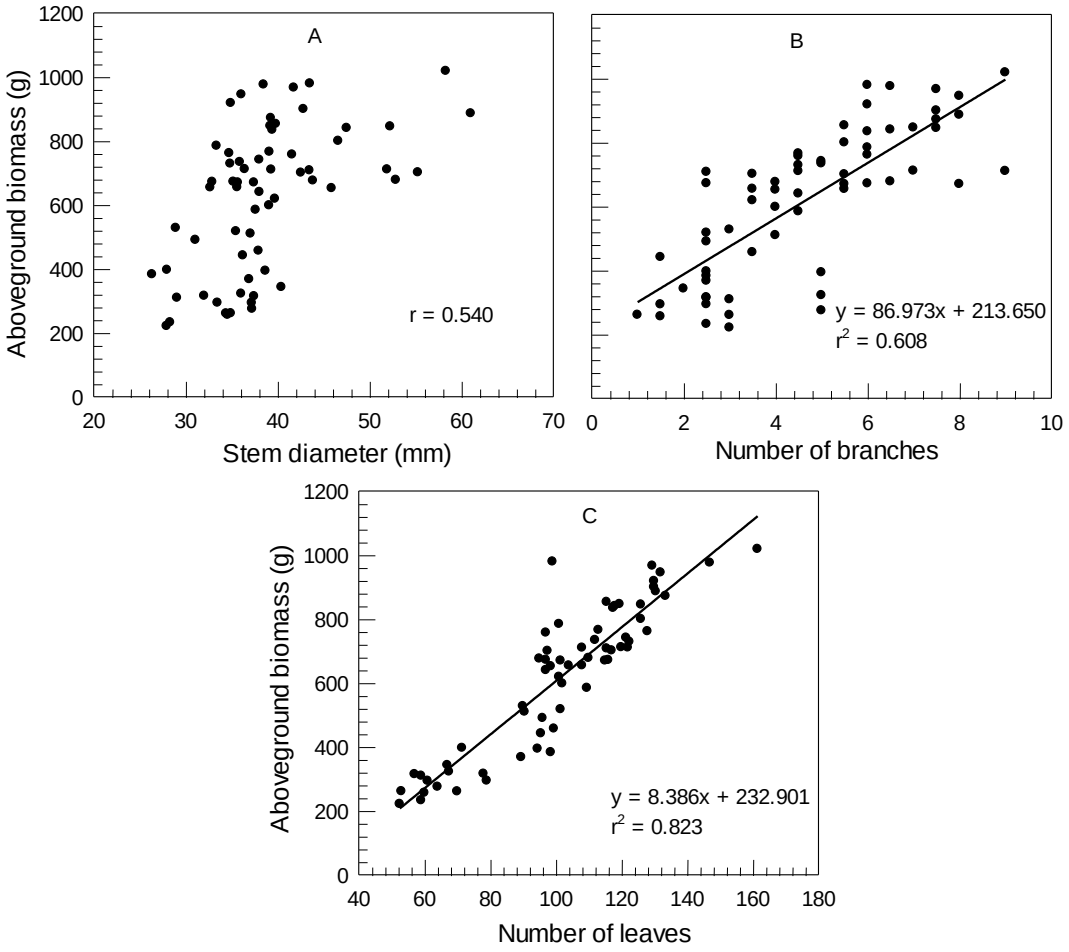

Figure 4.7: Scatter data between (a) aboveground biomass weight and stem diameter, and regression between aboveground biomass weight and (b) number of branches and (c) number of leaves at 180 days after transplanting (DAT). The straight lines was fitted by regression of all the NPK combinations data.

4.3.8 Number of storage roots

The three-way interaction (N × P × K) was significantly different ($p < 0.05$) for the total number of storage roots at 180 DAT (Figure 4.8). The mean maximum number of storage roots was 9 ($N_{200}P_{20}K_{100}$) and the minimum was 2 ($N_0P_{15}K_0$). The mean number of storage roots increased with increasing N application rates in the NPK combinations. The best combination for number of storage roots was 200 kg ha^{-1} N, 30 kg ha^{-1} P and 150 kg ha^{-1} K. The findings from the present study are in agreement with a previous study in Kenya and Uganda by Fermont et al. (2010) which found that the increase in the application rates of N, P and K fertilizers respectively, resulted in an increase in number of storage roots per plant.

In Malawi, the same trend was observed by Mathias and Kabambe (2015) who reported a significant inorganic fertilizer effect on the number of storage roots per cassava plant through the application of 200 kg ha^{-1} of the NPK compound 23:21:0. The positive contribution of cassava number of storage roots to yield gain was shown in a study by Amarullah et al. (2016), in which the number of storage roots and the tuber weight during maximum vegetative phase were found to be positively correlated with the yield.

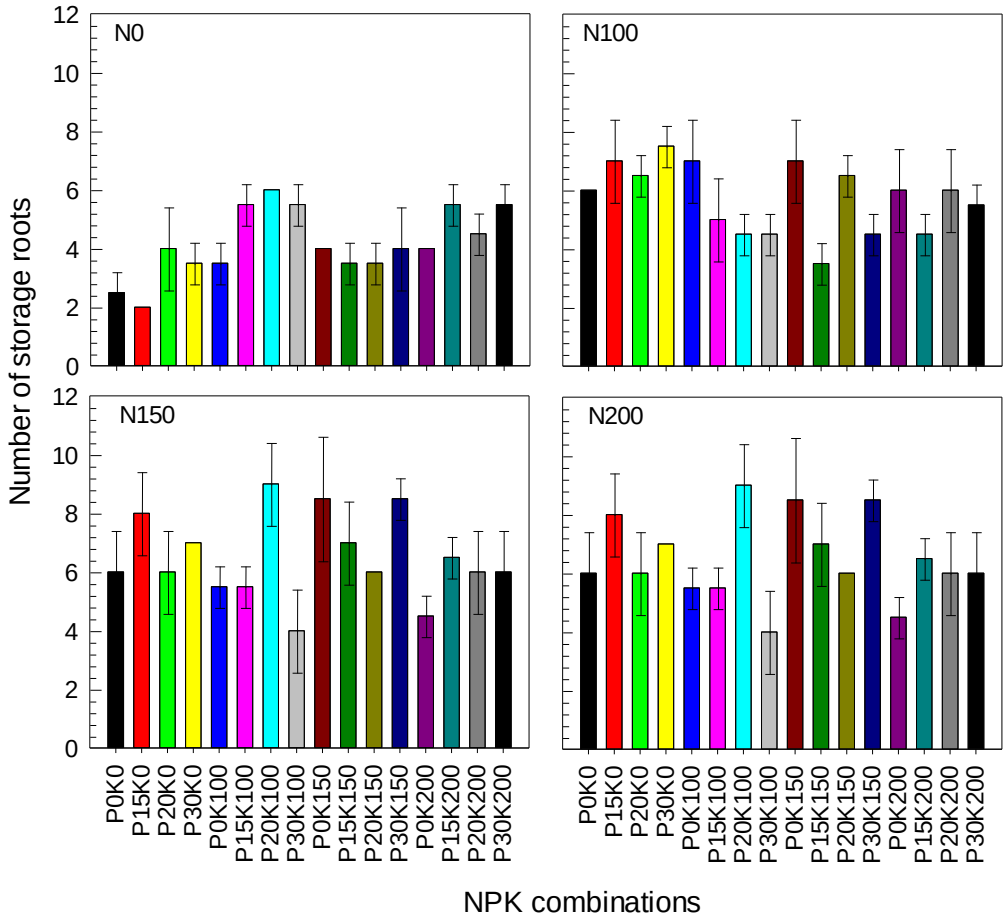

Figure 4.8: Effects of different combinations of NPK on total number of storage roots for cassava at 180 days after transplanting (DAT). The bars denote standard deviation of mean.

4.3.9 Relationship between total number of tubers and selected aboveground parameters

Correlations between number of storage roots and: stem diameter, number of branches and number of leaves at 180 DAT are shown in Figure 4.9. The correlations observed between these parameters were rather low (r = 0.40, 0.45 and 0.52). These low values imply competition between the aboveground and below ground parameters at 180 DAP. Rubaihayo et al. (2001) in Uganda, reported that growth traits showing positive correlations with number of storage roots suggested that the traits contributed to yield. This implies that, from the maximum vegetative phase, growth parameters begin to show a significant positive contribution to storage roots weight. Amarullah et al. (2016) reported that, the weight of fresh storage roots increased at storage roots filling phase and subsequently.

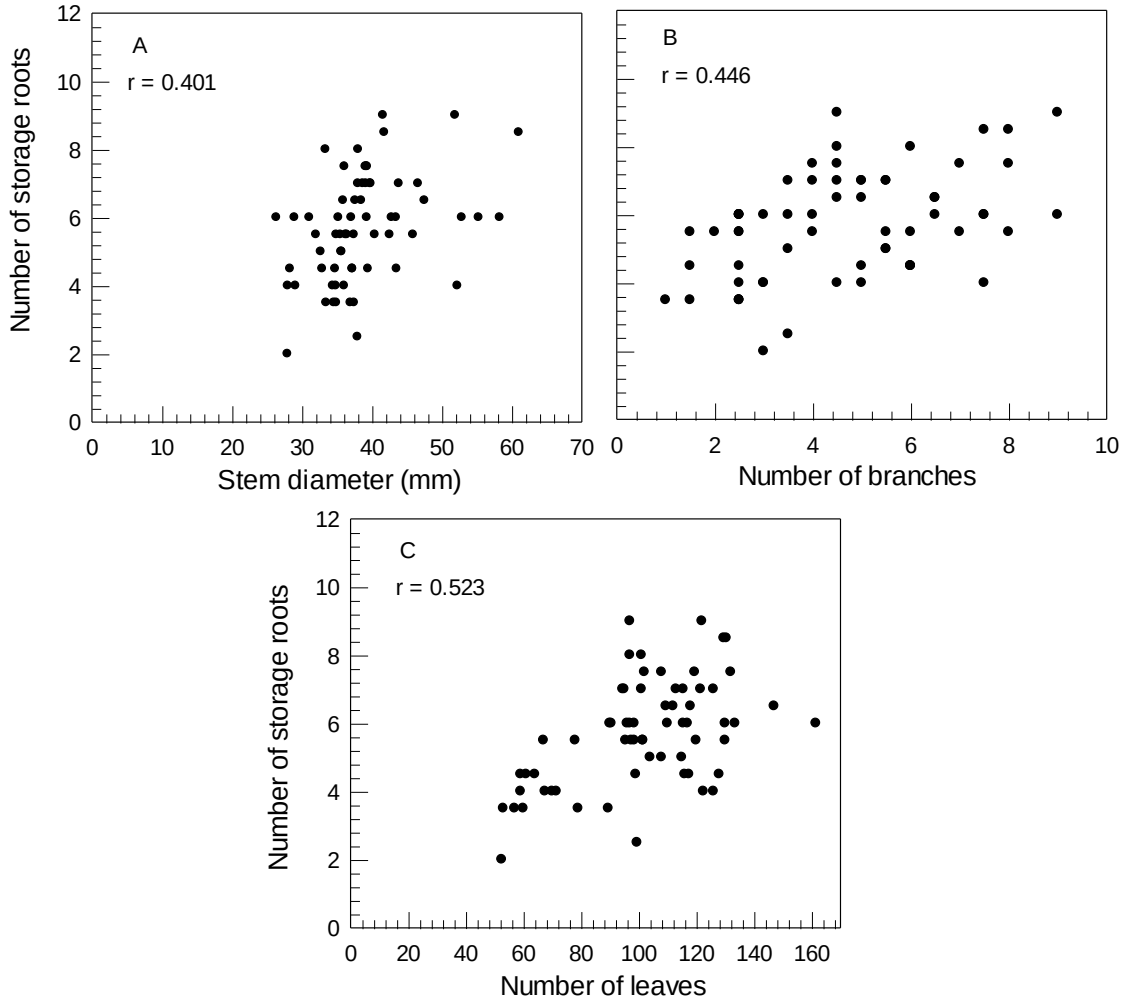

Figure 4.9: Scatter data between number of storage roots and; (a) stem diameter, (b) number of branches and (c) number of leaves at 180 days after transplanting (DAT).

4.3.10 Relationship between parameters at 180 DAT

Regression between: total LA and aboveground biomass, correlations between total LA and number of storage roots and aboveground biomass and number of storage roots at 180 DAT are shown in Figure 4.10. However, the cassava fresh storage roots yield was not reported in this study because the cassava plants were harvested in six months and did not have enough time to reach a comparable yield. A strong positive regression was observed between total LA and aboveground biomass ($r^2 = 0.93$). Meanwhile a positive correlation was observed between total LA and number of storage roots ($r = 0.58$). A positive correlation was also observed between aboveground biomass and number of storage roots ($r = 0.57$). These results indicated that total leaf area is more relatable to aboveground biomass than the total number of storage roots. In contrary, the low correlation values between the total number of storage roots and: total leaf area and aboveground biomass indicated that the plants aboveground parameters had

competition for nutrients during this growth phase. Growth was more promoted to the aboveground parameters at the expense of below ground parameters.

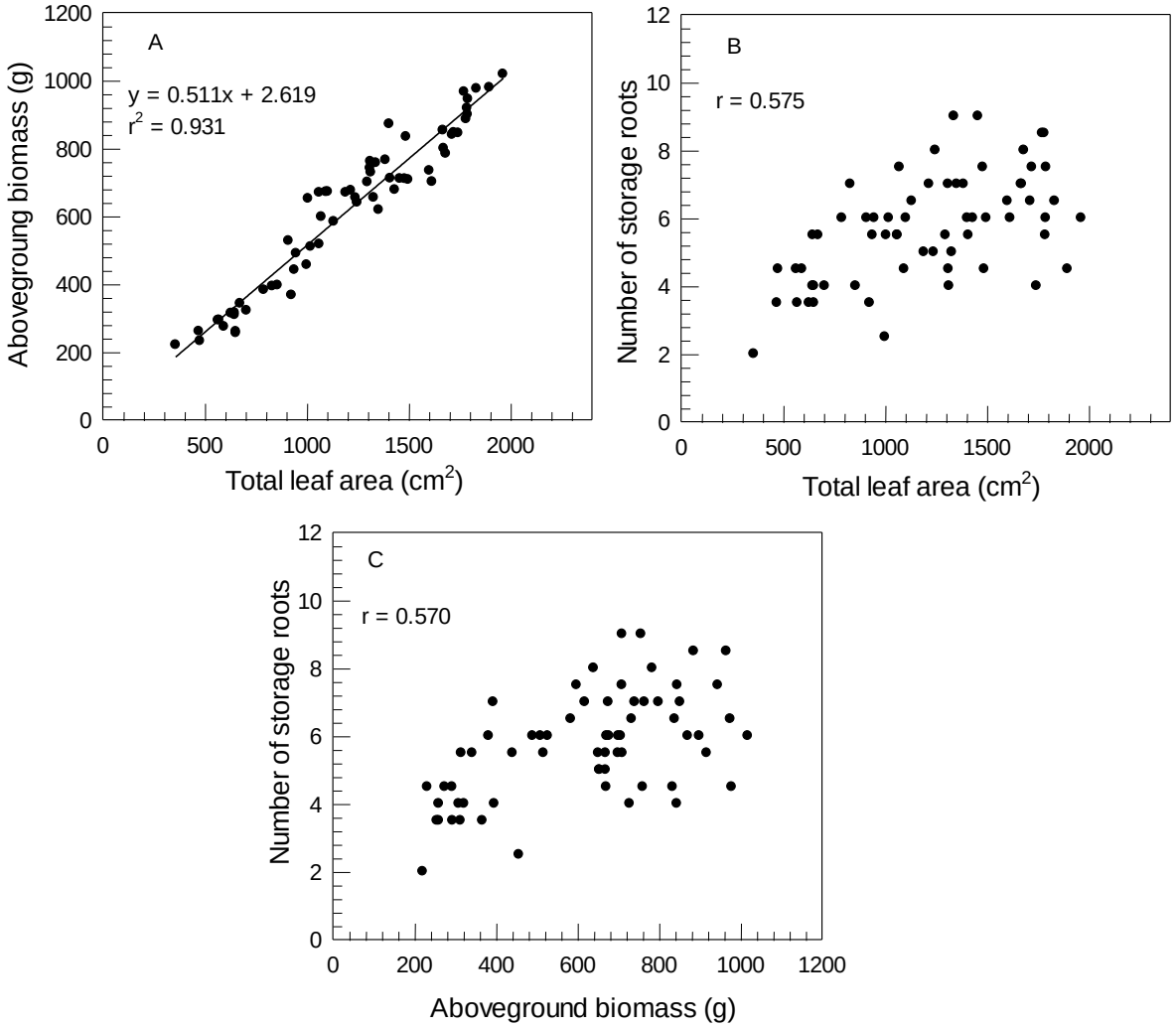

Figure 4.10: Regression between (a) total leaf area and aboveground biomass, and scatter data between (b) total leaf area and number of storage roots and (c) aboveground biomass and number of storage roots at 180 days after transplanting (DAT). The straight line was fitted by regression of all the NPK combinations data.

4.4 CONCLUSIONS

The N × P × K interaction had significant influence on both growth and yield parameters of cassava. All the parameters increased with increasing application rates of NPK. Each element played a significant role in promoting both growth and yield parameters. The NPK fertilization promoted aboveground growth at the expense of below ground growth since lower correlations values were observed between aboveground parameters and number of storage roots. Generally, the shoots are dominant between 15 and 180 DAP, while storage roots growth is the major sink during the rest of the growth cycle (180 – 360 DAP). The best combinations for cassava output that should be recommended were obtained through the application of 200 kg ha^{-1} N, 30 kg ha^{-1} P and 150 kg ha^{-1} K.

CHAPTER 5

THE POTENTIAL USE OF SPAD-502 METER TO ASSESS NITROGEN STATUS IN CASSAVA (*Manihot esculenta* L.)

ABSTRACT

A greenhouse study was conducted to evaluate the utility of the soil-plant analyses development (SPAD)-meter for assessing nitrogen (N) status in cassava plants fertilized at N rates of 0, 100, 150 and 200 kg ha^{-1}. The SPAD-meter readings were collected from five different leaf positions (Lf_1 – Lf_5) located at the top of the main stem, recorded nine times between 15 and 180 days after transplanting (DAT). Blades of the youngest fully developed leaf (YFDL) collected at 3 – 4 months after planting (MAP) are the best tissue indicator for cassava plants nutritional problems. Therefore, the five leaves which were used to take SPAD readings were harvested and taken to the laboratory for N analysis at 98 DAT. Nitrogen sufficiency indices (NSI) were then used to estimate the N status of the plants. The results showed that SPAD readings increased with time as well as increasing N application rate. Mean readings for the lower leaves (Lf_4 and Lf_5) and Lf_3, (48.1, 44.6 and 45.2) were significantly higher ($p < 0.05$) than readings for the uppermost leaves (Lf_1 and Lf_2) (32.5 and 38.4) at 98 DAT. At 98 DAT, the mean readings for lower leaves and Lf_3 were positively correlated with the N application rates and leaf N concentration levels but, the uppermost leaves were negatively correlated. This indicated that N was more distributed in the lower leaves. Readings from the lower leaves were generally higher and had stronger relationships with the N application rates and leaf N concentration levels than Lf_3 and the upper leaves. Therefore, average readings for Lf_4 and Lf_5 were used for calculating NSI values. The N_{200} treatments had the highest average NSI = 1.04 compared to N_{100} (NSI = 0.99) and N_0 (NSI = 0.88). This showed that the deficiency of N was immediately indicated in a low levels of chlorophyll, which were adequately recorded by the SPAD-meter. In conclusion, the SPAD meter can be used for estimating N status in cassava using the Lf_4 and Lf_5 at 98 DAT. The results showed that N should be applied at 200 kg ha^{-1} for cassava plants.

Keywords: Chlorophyll-meter readings, cassava leaf N, nitrogen sufficiency index

5.1 INTRODUCTION

The SPAD-meter is an instrument that enables non-destructive evaluation of the foliar tissue N, thus, substituting traditional methods for determining chlorophyll levels in plants (Argenta et al. 2004). The green pigment that is present in all cyanobacteria and green plants, responsible for absorbing light in order to provide energy for photosynthesis is called chlorophyll (Kalaji et al. 2017).

Nitrogen is important in dry matter accumulation and for the establishment of a large sink capacity through increased leaf area and plant branching (Han et al. 2015). There is more than 70% of plant N contained in chlorophyll (Dunn et al. 2018a). According to Blackmer and Schepers (1994) and Muchecheti et al. (2016) proper management of N increases chlorophyll content. In general, N functions in plants are closely related to photosynthesis. Howeler (2002, 2012) stated that plants demand N more than the other nutrients because N is plays a main role in the formation of macromolecules for chlorophyll and proteins. Anand and Byju (2008) found that chlorophyll content of cassava leaves and SPAD readings have a positive correlation with N content and storage roots yield. Lahai et al. (2013) reported a strong correlation between cassava leaves chlorophyll content and storage roots yield.

The utility of SPAD readings can be influenced by various factors (Costa et al. 2001). These factors include; plant growth stage, cultivar, leaf position in a plant canopy, the point of measurement on a leaf and leaf thickness (Yang et al. 2014b). Researchers have adopted constructive measures for minimizing the factors that influence the use of SPAD readings. Varvel et al. (1997) and Hussain et al. (2000) used SPAD sufficiency index to manage the effects of growth stages, and cultivars. Meanwhile, the ratio of SPAD readings was used in rice (*Oryza sativa* L.) for predicting N status at different leaf positions to minimize the influence of growth stages and cultivars by Wang et al. (2006) and Lin et al. (2010).

Several studies have shown that the SPAD-meter could be an effective tool in developing N fertilizer programs (Debaeke et al. 2006, Yang et al. 2014a, Dunn et al. 2018b). However, some studies have indicated that recommendations for N may be too high when based on SPAD-meter (Schröder et al. 2000, Scharf et al. 2002) or when recommendations are based on yield levels only (Chakwizira et al. 2016, Lazicki and Geisseler 2016). Optimization of N application rates using soil mineral N (SMN) could improve efficiency of N when an initial large SMN supply variation is predicted. However, this method is not reliable due to uncertainties on N mineralization and availability over the season. An intentional delay in N application coupled with a N supplementation after crop has established, can preserve N in the

soil. Almost all post-emergence qualitative predicts the crops response to N application but do not specify the amount of N that must be applied. In remote sensing, SPAD readings are compared with chlorophyll levels between rows where cultural practices are suspected to be affecting crop growth (Yang et al. 2014b).

SPAD readings can also be used to manage N by calculating NSI for different application rates of N and relative ratios thereof (Padilla et al. 2017). Nitrogen sufficiency index values less than 95% indicate N deficiency (Muchecheti et al. 2016). Yield response functions for different monitoring approaches have been used to derive most sufficiency values (Ordoñez et al. 2015, Padilla et al. 2015). The use SPAD-meter in measuring canopy and leaf greenness is preferable suited for quantifying N relative to tissue tests (Padilla et al. 2017). Optimal nutrient management is needed to close cassava yield gap since the crop is usually cultivated with minimal or even no fertilizer inputs. The objective of this study was to evaluate the utility of SPAD-meter for assessing nitrogen (N) status in cassava plants fertilized with different rates of N.

5.2 MATERIALS AND METHODS

5.2.1 Experimental site, design and treatments

This study was carried out in a greenhouse at the Agricultural Research Council-Institute for Industrial Crops farm (ARC-IIC) (25°40′05″S 27°14′19″E), located in Rustenburg, North West, SA. The experiment was established in November 2017 and terminated in May 2018.

The experiment was laid out in a randomized complete block design (RCBD). Treatments consisted of four N application rates (0, 100, 150 and 200 kg ha^{-1}) that were replicated three times. Limestone ammonium nitrate (LAN, 28% N) was used and applied in two equal splits, the first at 30 DAT and the second at 65 DAT.

5.2.2 Cultural practices

Cassava cultivar *Manihot* South Africa (MSAF-2) was used for the experiment because it produces high storage roots through relatively small shoots. In addition, it is pest and disease resistant (Melis 1984). Weeding was done two weeks after planting and repeated as needed. Irrigation was applied at field capacity level. Irrigation was applied at soil field capacity level which was determined at the beginning of the experiment. The plants water requirements would change from time to time but generally the plants were irrigated three times a week throughout

the experiment. Bandit 350 SC (Insecticide-Arysta Life Science South Africa) was used to control scale insects.

5.2.3 Soil and water analysis

A mixture of potting soil, sand and field (melanic) soil in the ratio 1:3:1 (60 kg) was used for the experiment. Approximately 1 kg soil sample of the mixture was taken before planting and analysed. The physical and chemical properties are presented in Table 5.1. In prior preparations to analyses, the soil samples were air-dried, jaw-crushed and sieved to pass in a 1 cm^2 mesh. Soil pH was determined using electrometric method in distilled water at 1:1 soil to water ratio. The macro-Kjeldahl digestion method was used for total N determination (Kjeldahl, 1883). The pH 7 ammonium acetate extraction method was used to determine Ca, K, Mg and Na (exchangeable cations) (Chapman 1965). The Olsen P extraction method was used for P, while carbon and aluminium were determined using diethylenetriamine pentaacetic acid (DTPA). Table 5.2 shows the irrigation water chemical analysis results. The water pH value was 7.4, indicating a neutral condition.

Table 5.1: Physicochemical properties of the potting mixture soil.

Properties		Units		Percentage (%)
Soil pH	6.9	-	-	-
Total Carbon (C)	-	-	-	1.7
Elements		mg kg^{-1}	me (%)	
Al	-	0.0	-	-
Ca	-	1447	7.6	46.1
K	-	118	0.3	1.9
Mg	-	967	7.6	51.1
N	-	3	-	-
Na	-	26	0.1	0.7
P	-	32	-	-
Sand	-	-	-	85
Silt	-	-	-	5
Clay	-	-	-	10

Table 5.2: Chemical properties of water used for irrigation in the greenhouse.

Properties	(mg kg^{-1})	Percentage (%)
pH	7.35	-
K	0	2.495
C	50	4.609
Mg	56	0.609
Na	14	0.000
NH_{4+}	-	0.000
NO_3	14	0.226
H_2PO_4	0	0.000
HCO_3	373	6.115
SO_4	43	0.896

5.2.4 Measurements

The SPAD readings were recorded nine times over a period of 180 DAT using the SPAD-502 meter. The readings were taken on five upper leaves of one main stem of the cassava plant, starting from the third youngest fully developed leaf (YFDL) going downwards to the seventh YFDL. These leaves were designated as $Leaf_1$ (Lf_1) to $Leaf_5$ (Lf_5) for each sampling period, with Lf_1 and Lf_2 as the uppermost leaves and Lf_4 and Lf_5 as the lower leaves then Lf_3 as a stand-alone leaf. Three readings were taken on the centre of each leaf lobe and averaged to give the reading for the sampling period for each leaf position. Plant tissue analysis was done once at 98 DAT since the blade of the youngest fully developed leaf (YFDL) collected at 3 – 4 MAP was reported as the best tissue indicator for cassava plants nutritional problems (Howeler 2012). The five leaves ($Leaf_1$ to $Leaf_5$) which were used to take SPAD readings were harvested and taken to the laboratory for N analysis.

In the laboratory, samples were washed with distilled water to remove gross contaminants such as dust and soil. This procedure was done as quickly as possible in order to avoid the loss of soluble elements. The leaf samples were then dried at 70 ^{O}C in a forced draught oven, ground and sieved through a 2-mm mesh using Wiley mill. In between grinding of different samples of N treatments, the mill was cleaned by brushing with 70% alcohol to avoid cross contamination. The total N was determined by the macro-Kjeldahl digestion method.

The NSI values were calculated using the SPAD readings with the formula (5.1) (Muchecheti et al. 2016):

$$\text{Sufficiency index} = \frac{\text{Average SPAD reading of target}}{\text{Average SPAD reading of reference}} \quad (5.1)$$

Where; N_0, N_{100} or N_{200} were the average SPAD readings of target and N_{150} was the average SPAD readings of reference.

5.2.5 Statistical analysis

The data from SPAD readings for the five leaves was subjected to analysis of variance (ANOVA) in RCBD for the four different application rates of N for each sampling day. Mean separation was done using Tukey's standardized test at $p < 0.05$. All the statistical analyses were conducted using SAS 9.4 version 6.1.7061 for windows general linear procedures (Cary, NC, SAS Institute Inc., 2012). Polynomial regression analyses were performed using SigmaPlot 14 (Systat Software Inc).

5.4 RESULTS AND DISCUSSIONS

5.4.1 SPAD readings with time

The SPAD readings of all the leaves (Lf_1, Lf_2, Lf_3, Lf_4 and Lf_5) were significantly different ($p < 0.05$) in all the N application rates (N_0, N_{100}, N_{150} and N_{200}) over time (Figure 5.1). Generally, readings for all the leaves increased with time at all the N application rates. Leaf position affected the readings of each leaf across all N application rates. There were both linear and quadratic relationships. SPAD readings for the leaves that showed quadratic relationships decreased as plants aged. There was an increase in the absolute SPAD readings as distance from the top of the plant stem increased. The lower leaves (Lf_4 and Lf_5) together with Lf_3 readings were generally higher compared to the upper leaves (Lf_1 and Lf_2). The rate of increase for the readings was higher between 15 and 98 DAT but then started decreasing between 98 and 180 DAT especially for all the leaves that showed quadratic relations.

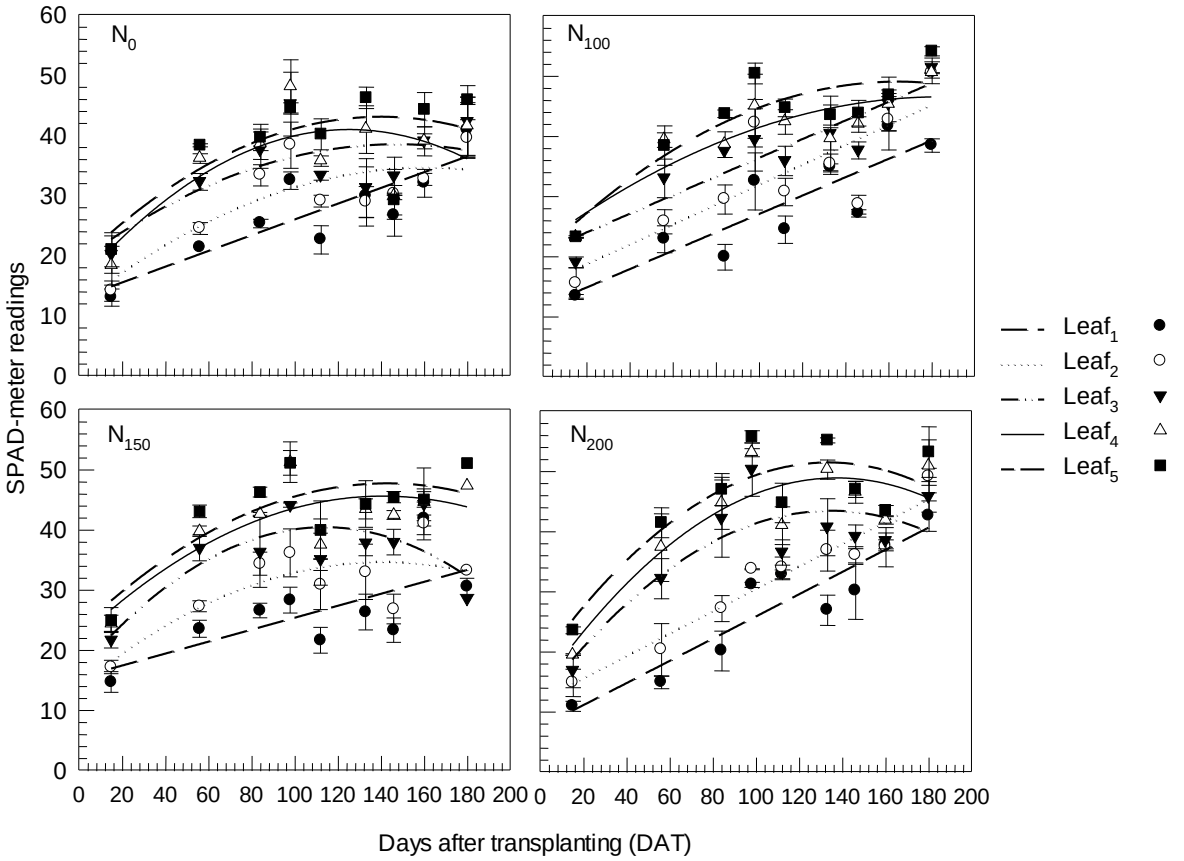

Figure 5.1: SPAD readings of leaves at different positions over time for cassava grown at different N rates. The bars denote standard deviation of mean and the lines were fitted by regression of the SPAD readings data.

It was also noted that there was a slight change in the readings from 98 – 180 DAT. The readings for Lf_3, Lf_4 and Lf_5 (45.2, 48.1 and 44.6) were significantly higher relative to those for Lf_1 and Lf_2 (32.5 and 38.4) at 98 DAT. Regression parameters for SPAD-readings over time at different application rates of N are presented in Table 5.3. The results showed that there were stronger relationships for Lf_3 to Lf_5 at N_{100} (r^2 = 0.84, 0.78 and 0.79), N_{150} (r^2 = 0.66, 0.67 and 0.67) and N_{200} (r^2 = 0.71, 0.79 and 0.75) relative to N_0 (r^2 = 0.51, 0.56 and 0.54). Meanwhile, the relationships for the uppermost leaves (Lf_1 and Lf_2) were very strong at N_{200} (r^2 = 0.86 and 0.93). The relationships were almost similar for Lf_1 and Lf_2 at N_{100} (r^2 = 0.76 and 0.68) and at N_0 (r^2 = 0.75 and 0.66). At N_{150} the relationship for Lf_1 was weak (r^2 = 0.49) relative to Lf_2 (r^2 = 0.62). Correlations values were greater when N was applied (N_{100}, N_{150} and N_{200}) than when no N was applied (N_0).

Table 5.3: Regression parameters for SPAD-readings (y) over time (x) at different application rates of N.

	Regression equations	Coefficients of determination (r^2)
N_0		
$Leaf_1$	$y = 0.131x + 12.843$	$0.747_{\pm 4.272}$
$Leaf_2$	$y = -0.0009x^2 + 0.283x + 11.839$	$0.662_{\pm 5.106}$
$Leaf_3$	$y = -0.0009x^2 + 0.2660x + 18.872$	$0.505_{\pm 5.933}$
$Leaf_4$	$y = -0.002x^2 + 0.407x + 15.371$	$0.559_{\pm 6.435}$
$Leaf_5$	$y = -0.001x^2 + 0.345x + 18.906$	$0.539_{\pm 6.679}$
N_{100}		
$Leaf_1$	$y = 0.153x + 11.515$	$0.755_{\pm 4.882}$
$Leaf_2$	$y = 0.166x + 15.390$	$0.682_{\pm 6.338}$
$Leaf_3$	$y = 0.155x + 20.829$	$0.839_{\pm 3.799}$
$Leaf_4$	$y = -0.0007x^2 + 0.262x + 22.582$	$0.782_{\pm 4.075}$
$Leaf_5$	$y = -0.001x^2 + 0.347x + 20.564$	$0.793_{\pm 4.579}$
N_{150}		
$Leaf_1$	$y = 0.099x + 15.398$	$0.495_{\pm 5.628}$
$Leaf_2$	$y = -0.001x^2 + 0.293x + 14.009$	$0.622_{\pm 4.831}$
$Leaf_3$	$y = -0.002x^2 + 0.421x + 16.499$	$0.656_{\pm 4.804}$
$Leaf_4$	$y = -0.001x^2 + 0.3351x + 21.906$	$0.666_{\pm 5.034}$
$Leaf_5$	$y = -0.001x^2 + 0.341x + 23.326$	$0.669_{\pm 5.173}$
N_{200}		
$Leaf_1$	$y = 0.185x + 7.319$	$0.864_{\pm 4.109}$
$Leaf_2$	$y = 0.186x + 11.851$	$0.927_{\pm 2.917}$
$Leaf_3$	$y = -0.002x^2 + 0.466x + 12.009$	$0.711_{\pm 5.885}$
$Leaf_4$	$y = -0.002x^2 + 0.509x + 13.766$	$0.791_{\pm 5.362}$
$Leaf_5$	$y = -0.002x^2 + 0.499x + 18.116$	$0.749_{\pm 5.648}$

Consistent with previous studies for other crops, SPAD readings increased with time. SPAD readings in maize and rice increased with growth and development stages (Costa et al. 2001, Yang et al. 2014b). There was no constant relation established between SPAD readings and the sampling days. This is because some leaves (Lf_1 to Lf_3) showed both quadratic and linear responses. Basyouni et al. (2015) also found both significant linear and quadratic relationships between time and SPAD readings at different N application rates in a study that used SPAD-meter to assess N status of poinsettia (*Euphorbia pulcherrima* L.). The sharp increase in readings for N_{100}, N_{150} and N_{200} between 15 and 98 DAT can be attributed to the time and method of N application. Applying 50% of the fertilizer at 30 DAT and the other 50% at 60 DAT guaranteed constant availability of N to the cassava plants which resulted in increased SPAD readings. Muchecheti et al. (2016), reported that split N application affected chlorophyll readings of spinach (*Spinacia oleracea* L.). Splitting inorganic fertilizer applications within a season results in higher yields (Janssen and Wienk 1990).

The decline in SPAD readings from 98 DAT could mean that the concentration of N in the leaves was declining. This could be due to the redistribution or translocation of N from the plant leaves to the stems and storage roots thus reducing the N concentration in the leaves. This was in line with the results obtained by Maia et al. (2012), where bean leaves increased until 36 days after emergence (DAE) in all application rates of N and became practically stable until the last day of sampling, 64 DAE. The decline in readings as plants aged may also be attributed to cassava leaf longevity. Veltkamp (1985) reported that cassava leaf size increased to a maximum and then declined with time in all cultivars that were studied and under different climatic conditions. In addition, El-Sharkawy (2003) reported that a cassava leaf mean maximum size was observed between three and four months after planting (MAP).

The higher readings observed on Lf_3, Lf_4 and Lf_5 could mean that N was more distributed in the lower leaves as plants aged. Madakadze et al. (1999) reported that N partitioning in leaves within the same canopy is different. Optimization of N allocation in this case would allow for higher photosynthesis rates in the lower leaves compared to the upper leaves (Connor et al. 1995). Charles-Edwards et al. (1987) reported that leaf N has a strong positive correlation with photosynthesis enzymes, and this means that the photosynthesis rates are higher in the leaves with high concentration of N. Therefore, N content for Lf_4 and Lf_5 was higher than the average for Lf_1 – Lf_3. The influence of leaf position on SPAD readings in the present study was comparable to that reported by Yang et al. (2014b) on rice, where readings from lower leaves were higher compared to the uppermost leaves. The differences between the upper leaves and lower leaves may indicate that metabolic activity is greater in lower leaves compared to the upper leaves (Durhman et al. 2006, da Silva et al. 2012). Decreased N competition in the lower leaves increased metabolic activity thus increasing N content in the lower leaves. Decreased N competition in the lower leaves increased metabolic activity thus increasing N content in the lower leaves.

The significant differences ($p < 0.05$) between readings of the uppermost and the lower leaves, could also be due to the leaf greenness differences viewed between upper leaves and lower leaves that were observed even before the SPAD readings were recorded. Wang et al. (2006) and Yang et al. (2014a) reported that leaf greenness can be influenced by leaf stage of growth (Wang et al. 2006, Yang et al. 2014b). The differences between the readings for the leaves could also be attributed to the small leaf sizes of the uppermost leaves compared with the lower leaves. Yang et al. (2014b) found similar results in rice. Their study reported that readings of the lower leaves were higher compared to those of the upper leaves. In addition,

Lin et al. (2010) demonstrated that rice leaf thickness contributed to the variation in SPAD readings between leaves of the same plants, the thicker the leaves the higher the SPAD reading. In general, the lower leaves of the cassava plants were thicker compared to the uppermost leaves and the differences in leaf thickness of one plant are as a result of the difference in stage of development of the leaves within the same plant. However, older leaves SPAD readings can be lower than those for younger leaves (Piekielek et al. 1995).

5.4.2 SPAD readings and leaf N concentration

The results of leaf N analysis are shown in Table 5.4. The N_{150} treatment had the highest leaf N concentration level followed by N_{200}, N_{100} and N_0 in decreasing order.

Table 5.4: Leaf N concentration for different N rates on cassava at 98 days after transplanting (DAT).

Nitrogen (kg ha^{-1})	Leaf N concentration (%)
0	4.460 ±1.541
100	4.735 ±1.577
150	5.625 ±1.803
200	5.120 ±1.739

Since differential partitioning of N brought about differences in the SPAD readings at different leaf position, there was need to identify the best indicator leaf position/s within the same plant. Relationships between N application rates, leaf N concentration and SPAD readings taken from the cassava plants at 98 DAT are shown in Figure 5.2. The SPAD readings for Lf_3, Lf_4 and Lf_5 were significantly higher ($p < 0.05$) at N_{100}, N_{150} and N_{200} than for Lf_1 and Lf_2. However, significant differences were also observed between the upper leaves (Lf_1 and Lf_2) at N_0 (33.5 and 38.4), at N_{100} (32.6 and 42.2), at N_{150} (28.3 and 36.1), and at N_{200} (31.2 and 37.8). Readings for the lower leaves (Lf_4 and Lf_5) and Lf_3 positively correlated with N application rates and leaf N concentration but were negatively correlated with N rates for the upper leaves (Lf_1 and Lf_2). $Leaf_1$ and Lf_2 were therefore eliminated as indicator leaf/leaves of the chlorophyll content of the plants.

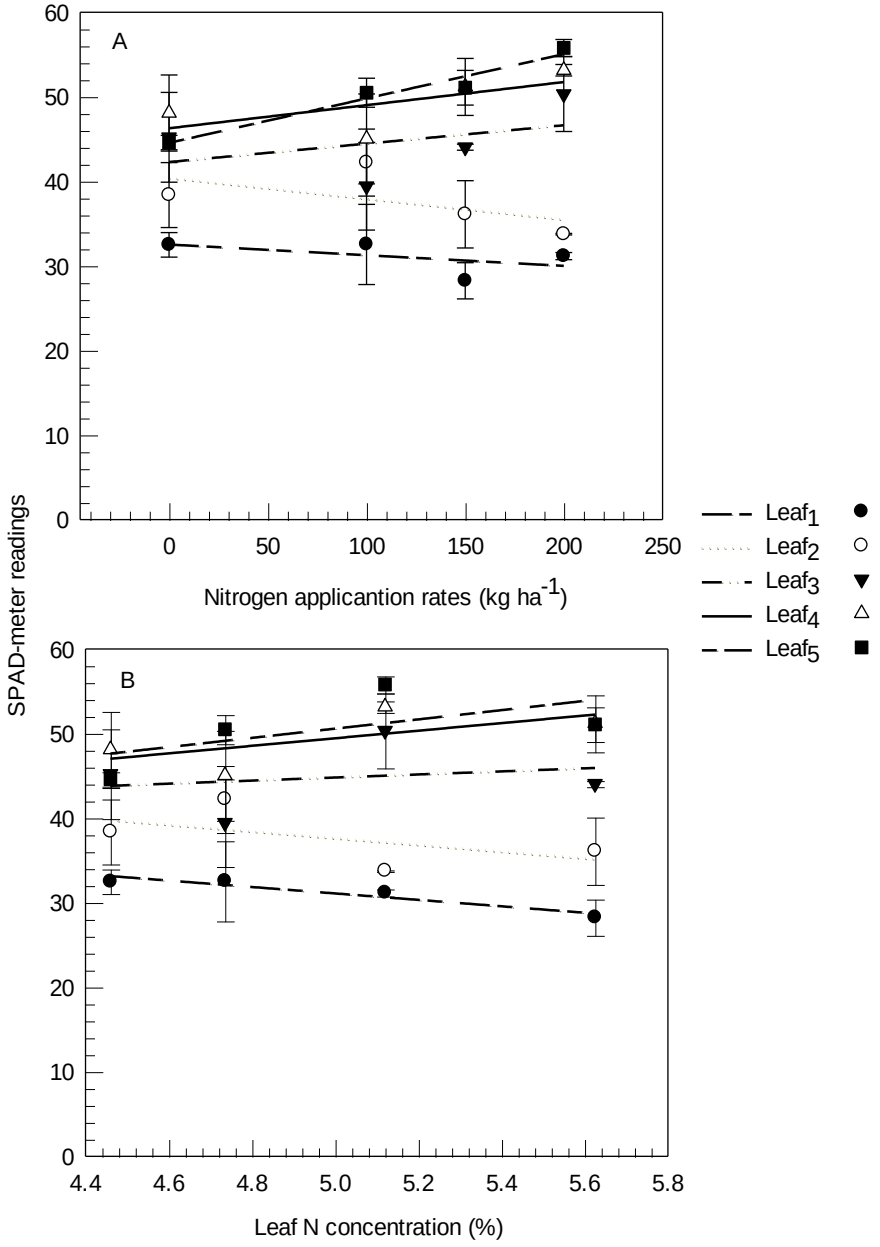

Figure 5.2: Relationship between SPAD readings and: (a) N application rates and (b) leaf N concentration for cassava at 98 days after transplanting (DAT). The bars denote standard deviation of mean and the lines were fitted by regression of the SPAD readings data.

The lower leaves and Lf_3 could be used as indicators of the cassava plant's chlorophyll content. However, Lf_3 had lower readings compared to Lf_4 and Lf_5. $Leaf_4$ and Lf_5 on the other hand, even obtained an intersection at N_{150} and there were no significant differences ($p > 0.05$) between the lower leaves (Lf_4 and Lf_5) at N_0 (48.1 and 44.6), at N_{100} (45.0 and 50.5), at N_{150} (51.2 and 51.2), and at N_{200} (53.2 and 55.8). Therefore, both leaf positions could be used as indicator levels of the cassava plant's chlorophyll content and evaluating leaf N status. Yang

et al. (2014b) also recommended the lower leaves should be used for N status analysis in rice. In contrast, the upper leaves were recommended by Muchecheti et al. (2016) for spinach and Piekielek et al. (1995) for maize. The positive linear correlations between SPAD readings and N application rates and leaf N concentration levels for the lower leaves and Lf_3 indicated a good potential of the SPAD-meter to monitor leaf N status in cassava at 98 DAT in the present study. SPAD readings can thus give reliable information on fertilizer use for cassava.

When leaf N concentrations is estimated using SPAD-meter readings is beneficiary because N deficiency can be immediately rectified (Yang et al. 2014b). However, SPAD readings are not good indicators of excess N since not all leaf N is transformed into chlorophyll (Dwyer et al. 1995, Varvel et al. 2007). Different cultivars are characterized by unique greenness thus calibration of a SPAD-meter to assess crop N status might not be practical (Schepers et al. 1992). Since SPAD-meter leaf N predictions may not be reliable, Peng (1992) reported that SPAD readings could be improved by using SPAD/SLW (specific leaf weight) ratio as an independent variable. This adjustment of readings could accurately predict leaf N status of different cultivars at different growth stages. Peng (1992) stated that leaf thickness and SLW varies with light intensity and therefore adjusting SPAD reading for SLW might also improve predictions of N.

5.4.3 Nitrogen sufficiency

Following the positive correlations between SPAD readings and; N application rates and leaf N concentration, the average reading of the lower leaves (Lf_4 and Lf_5) were used to calculate the N sufficiency indices (NSI) for the cassava plants. The NSI values were calculated at 95% and 100%. The N deficiencies were diagnosed by dividing the SPAD readings for N_0, N_{100} and N_{200} by those for N_{150}. Additional doses of N should be applied at critical sufficiency index levels of 95% since they correspond to N deficiency that can lead in a reduction of yields (Hussain et al. 2000, Varvel et al. 2007, Muchecheti et al. 2016). The sufficiency index at 100% was chosen as a measure of assessing whether treatments were sufficient in N. The N_0, N_{100} and N_{200} treatments were characterized as N deficient when their sufficiency indices were > 95% for two successive weeks.

Figure 5.3 showed that N_{200} SI values were sufficient (NSI > 95%). Nitrogen deficiency on non-fertilized leaves (N_0) was observed throughout the course of the experiment as NSI were less than 95%. The increase in nitrogen use efficiency (NUE) increases N sufficiency over time. The N_{200} and N_{100} severity of N deficiency decreased over time but increased with

time for N_0. The N_{200} treatments had the highest average NSI values (1.04) and were able to maintain minimal N deficiencies over time as compared to N_0 (NSI = 0.88) and N_{100} (NSI = 0.99). Nitrogen was generally sufficient from 84 DAT for the N_{200} treatments, while N_{100} was sufficient from 160 DAT as NSI > 0.95.

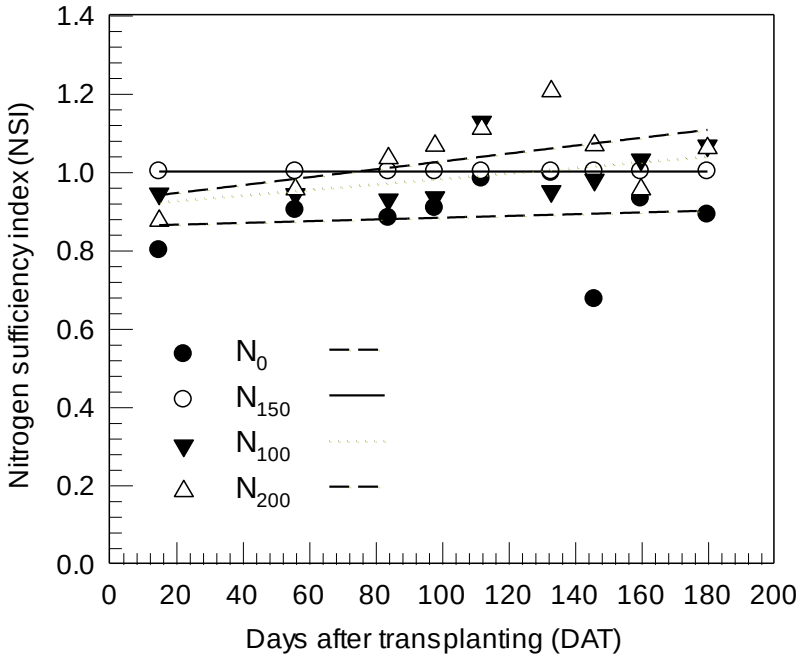

Figure 5.3: Nitrogen sufficiency index (NSI) of cassava between 15 and 180 days after transplanting (DAT). Each point was based on the average SPAD readings of the lower leaves (Lf_4 and Lf_5) of each plant. NSI at 1.0 as the reference point.

Generally, N_0 had low NSI values compared to N_{100} and N_{200}. This indicated that in a low chlorophyll content N deficiency is immediately reflected, which was adequately registered by the SPAD-meter since N_0 SPAD readings were also lower relative to those for N_{100} and N_{200} (Blackmer and Schepers 1994, Dwyer et al. 1995, Varvel et al. 1997). Nonetheless, N additions from various sources and the initial N status of the soil also contributed in the changes of NSI values over time. Absorption of N by the plants and excessive leaching depleted available N in the soil hence N deficiency increased over time for N_0. Meanwhile, the addition of N increased NSI values for N_{100} and N_{200} over time. This means application of N decreased deficiencies for the plants that were treated with N_{100} and N_{200}. Nitrogen deficiencies at N_0 were typified by visual observations of poor leaf greenness and lower levels of leaf N resulting in lower SPAD readings that could ultimately lead to low yield. Meanwhile, SPAD readings and leaf N concentrations were high for N_{100} and N_{200} which could promote photosynthetic rates and thus higher distribution of dry matter to the storage roots.

Nitrogen deficiency can be corrected by applying N fertilizers or by irrigating plants with nitrate rich water.

5.4 CONCLUSIONS

Cassava SPAD readings increased over time. The readings for the lower leaves (Lf_4 and Lf_5) and Lf_3 were generally higher than those for the uppermost leaves (Lf_1 and Lf_2) over time. Readings for the lower leaves were positively correlated with N application rates and leaf N concentration. Optimization of N allocation allowed higher photosynthesis rates in the lower leaves compared to the upper leaves since there was preferential distribution of N to lower leaves. Nitrogen deficiency decreased with time for the N_{200} and N_{100} but increased with time for N_0. Both N_{100} and N_{200} treatments were N sufficient at NSI > 0.95. N application eliminated deficiencies thus increased photosynthetic rates which would lead in higher production of assimilates to be accumulated in the economic yield the crop. The lower leaves could be used to monitor N status for cassava since their SPAD readings were closely related to leaf N concentration.

CHAPTER 6

GENERAL CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The study focused on addressing agronomic challenges facing the production of cassava in SA. The three main factors investigated included cultivars adaptability, optimization of NPK and leaf N assessment. A field experiment was set up to assess growth and yield parameters of two local cassava cultivars (P4/10 and MSAF-1) in Mbombela, Mpumalanga, SA (Chapter 3). The growth and yield parameters for these two cultivars were found to be significantly different. The taller cultivar (MSAF-1) (206.5 cm) had larger stem diameter (59.0 mm), higher; number of branches (39.5), LAI (4.0), LAD (893.44 days), total fresh biomass (15.55 kg ha^{-1}), aboveground biomass dry matter yield (3.97 kg ha^{-1}), storage root dry matter yield (5.66 kg ha^{-1}), number of storage roots (13.6), as well as higher HI (0.621) than those for P4/10; 181.2 cm, 49.7 mm, 31.4, 2.2, 558.93, 13.14 kg ha^{-1}, 2.79 kg ha^{-1}, 3.73 kg ha^{-1}, 10.0, 0.5 at 15 MAP, respectively. The differences between the parameters could be attributed to genotypic variation of the cultivars since they were grown under the same conditions. Both the MSAF-1 and P4/10 had a fairly effective redistribution of photosynthates and conversion of assimilates from leaves and stems into the storage roots. This supported the hypothesis that the environmental conditions in Mbombela will enhance growth and improve the yield of cassava.

In a bid to optimize NPK application rates for the growth and yield of cassava, 64 NPK treatment combinations were evaluated in a greenhouse (Chapter 4). The underlining premise was that the NPK combination effects would improve cassava growth and yield than the individual elements. All the growth and yield parameters that were assessed for the objective of this experiment were found to be significant. Generally, cassava growth and yield increased with time and increasing application rates of NPK. Combinations with low or zero N and K negatively affected cassava growth and yield. In addition, combinations that supplied either too much of one element compared to the other elements negatively affected the growth and yield of cassava. The different parameters were thus promoted by different NPK application rate combinations. The best NPK combinations for cassava output was 200 kg ha-1 N, 30 kg ha-1 P and 150 kg ha-1 K. Following regression analysis, strong positive relationships were observed between: number of branches and number of leaves (r^2 = 0.76), aboveground biomass and number of branches (r^2 = 0.61), aboveground biomass and number of leaves (r^2 = 0.82). Meanwhile, weak positive correlations were observed between the number of storage roots

and; stem diameters (r = 0.40), number of branches (r = 0.45) and number of leaves (r = 0.52). Conversely, NPK fertilization enhanced aboveground growth at the expense of storage roots yield.

In the experiment that was set up to evaluate the utility of SPAD-meter (Chapter 5), the readings increased with time as well as increasing N application rate. The readings for Lf_3, Lf_4 and Lf_5 (45.2, 48.1 and 44.6) were significantly higher ($p < 0.05$) than values of Lf_1 and Lf_2 (32.5 and 38.4) at 98 DAT. At 98 DAT, the lower leaves (Lf_4 and Lf_5) and Lf_3 readings were also positively correlated with the N application rates and leaf N concentration levels but, the uppermost leaves (Lf_1 and Lf_2) were negatively correlated. This indicated that there was preferential distribution of N to lower leaves thus optimization of N allocation allowed higher photosynthesis rates in the lower leaves compared to the upper leaves. Generally, there were no significant differences between the readings for Lf_4 and Lf_5 but Lf_3 were lower across all the N rates over time and therefore the average of Lf_4 and Lf_5 was used for calculating nitrogen sufficiency index (NSI) values. The N_{200} treatments had the highest average NSI value (1.04) compared to N_{100} (NSI = 0.99) and N_0 (NSI = 0.88). This indicated that N deficiency was immediately reflected in a low chlorophyll content, which was adequately registered by the SPAD meter.

6.2 RECOMMENDATIONS

Based on the studies presented, the following recommendations can be made:

- MSAF-1 cultivar is recommended for Mbombela conditions as it maintained a greener canopy than the P4/10.
- P4/10 cultivar can be suitable for various intercrop system since it produced low number of branches and MSAF-1 could be better utilized for leaf and storage roots consumption purposes.
- The application of 200 kg ha^{-1} N, 30 kg ha^{-1} P and 150 kg ha^{-1} K had a higher yield than the other NPK rates and therefore recommended for cassava production.
- The SPAD meter can be used for estimating N status using the lower leaves (Lf_4 and Lf_5) and N should be applied at 200 kg ha^{-1} for cassava plants.

6.3 FUTURE RESEARCH AREAS

- More cultivars should be introduced and evaluated in several areas of SA.
- There is an opportunity to explore how growth and yield of other cultivars will react to the application of 200 kg ha-1 N, 30 kg ha-1 P and 150 kg ha-1 K in other soil types.
- Another experiment with a higher proportion of potassium against nitrogen fertilizer should be conducted since the yield of cassava was affected by these two elements.
- Exploration of the utility of SPAD-502 on how other cultivars will react to N management in other soil types.
- Improved cultivars should be used because of genetic gains.
- More than one season trials should be conducted for NPK optimization and evaluation of cultivars.

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