

**PHYSIOLOGICAL AND YIELD RESPONSES OF CASSAVA
(*Manihot esculent* Crantz) TO FERTILIZER AND LEAF HARVESTING
TREATMENTS UNDER DIFFERENT CROPPING SYSTEMS IN
LUAPULA PROVINCE OF ZAMBIA**

By

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**A thesis submitted to the University of Zambia in fulfilment of the requirements for the
award of the degree of Doctor of Philosophy in Agronomy**

THE UNIVERSITY OF ZAMBIA

LUSAKA

2023

DECLARATION

I Sydney Mwamba, declare that the contents of this thesis represent my work and that this thesis has not been presented for academic examination for the award of any degree in any other University.

Signature

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Date

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APPROVAL

This thesis of Sydney Mwamba has been approved as fulfilling the requirements for the award of the degree of Doctor of Philosophy in Agronomy by the University of Zambia.

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ABSTRACT

Comparatively, Zambian smallholder cassava productivity is low. Zambian farmers produce 6 ton ha⁻¹, compared to 20–25 ton ha⁻¹ in Zambia. Therefore, understanding smallholder farmers' poor yields is necessary to develop cassava cropping systems for yield intensification. In this study, field trials were conducted to evaluate the performance of three cassava varieties for yield, physiology, and morphology under four fertilization regimes while three varieties were assessed for field performance under NPK fertilizer and no fertilizer (Control). In addition, three cassava varieties were evaluated for growth, yield, and radiation use efficiency (RUE) in response to three leaf harvesting intensities and two fertilizer management regimes. The trials were conducted for two seasons at the Zambia Agricultural Research Institute Station (ZARI) in the Mansa District of Luapula Province. For objective (i), Fertilization regimes were treated as the main plot, Mweru (V1), Bangweulu (V2), and Katobamputa (local) (V3) were subplots while for objective (ii), the same cassava varieties were used, either with NPK fertilization and no fertilizer treatment. Objective (iii) examined three cassava varieties (Bangweulu-V1, Mweru-V2, and Katobamputa-V3) under two fertilizer management regimes (M1=Control and M2 NPK+Lime) and variable leaf harvesting intervals (D1 = no leaf harvesting, D2 = 2-week, and D3 = 3-week respectively) using split-split plot design. At 75–410 days after planting (DAP), leaf area index (LAI), light interception, yield, and yield components were measured at six different times, along with daily weather data. Using a linear mixed model, analysis of the variance examined fertilization regimes, variety, and harvesting interval effects using R-statistical software. Tukey's Honest Significant test was used for mean separation. Cross-treatment Pearson correlation was used to compare continuous variables for treatment means while stepwise regression was used to determine the most important cassava yield components. Irrespective of the variety, NPK + lime followed by NPK only yielded more and had a superior response for cassava yield components than lime and the control. NPK fertilisation increased cassava RUE, light extinction coefficient, and yield across seasons and varieties. Harvesting 5-8 young cassava leaves per plant at 3-week intervals for home and commercial use may not affect yield, independent of fertilizer or variety according to this study. Cassava growth, root yield, LAI, and RUE were affected by bi-weekly leaf harvesting. In poor soil nutrient conditions, NPK fertilizer+ lime, and NPK fertilizer treatments can increase cassava productivity, physiology, and morphology under high-rainfall environments.

DEDICATION

This work is dedicated to my Lovely wife Chilufya Musendeka Mwamba, my children Mapalo Mwamba, Daniel Mwamba, Maluba Mwamba and my brother James Mulenga Muloshi.

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ABBREVIATIONS/ACRONYMS

Abbreviation	Description	Units
ANOVA	Analysis of the Variance	
AIC	Akaike Information Criteria	
CBSV	Cassava brown streak virus	
CMVD	Cassava mosaic virus disease	
DAP	Days after planting	
ET	Evapotranspiration	mm
FAO	Food and Agricultural Organisation	
FoSeZa	Food Security in Rural Zambia	
HI	Harvest index	
IITA	International Institute of Tropical Agriculture	
ISFM	Integrated soil fertility management	
IPAR	Cumulative intercepted radiation	
LAI	Leaf area index	
MAP	Months after planting	
NPK	Nitrogen, phosphorous, Potassium	
PH	Plant height	cm
RUE	Radiation use efficiency	gMJ ⁻¹
SE	Standard error	
ZARI	Zambia Agricultural Research Institute	
<i>K</i>	Canopy light Extinction coefficient	
<i>r</i>	Correlation coefficient	%
ton ha ⁻¹	Tones per hectare	

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Cassava (*Manihot esculent* Crantz) is an important staple food crop in the tropics and a feedstock for industrial starch processing (Alesiani et al., 2016; Rahman and Awerije, 2016; Prakash, 2013). Cassava is becoming increasingly an important commercial crop and is being cultivated on a large scale to meet the market. Currently, the average fresh storage root yield in smallholder farmers' fields in sub-Saharan Africa (SSA) is estimated to be at 7.2 ton ha⁻¹ (FAOSTAT, 2020) in comparison to yields reported in research trials that range from 8.6 - 55.5 ton ha⁻¹ on fresh storage root yield basis (Kaluba *et al.*, 2021; Mwamba et al., 2021; Ezui *et al.*, 2017; Eke-okoro and Njoku, 2012).

Sustainable intensification of cassava production is critical for food security in SSA owing to the low use of improved cassava varieties and low/no use of organic and inorganic fertilizers in poor soils, especially given that the projected population growth which depends on cassava for livelihood (Philips *et al.*, 2006; Snapp *et al.*, 1998). Continuous cassava cropping without nutrient replenishment and other poor management practices leading to nutrient leakage, water evaporation, and wind, as well as soil erosion, is said to be the primary causes of the poor soil conditions in SSA (Kolawole, 2013). Important soil nutrients such as nitrogen (N), potassium (K), magnesium (Mg) and calcium (Ca) are easily leached and lost in climates with high rainfall. In addition, large regions in Africa are characterized by high soil acidity coupled with toxic high aluminium (Al) concentrations and a large capacity for P fixation, rendering applied P less available to plants (Sanginga and Woomer, 2009).

Cassava can grow in soils with low soil fertility and moderate acidity under erratic rainfall conditions thus making it a resilient crop under extreme weather conditions when compared to cereals (Howeler, 2017). Cassava has a very high yield potential when growth conditions and

management are optimal and can yield over 90 tons ha⁻¹ of fresh storage roots (Adiele *et al.*, 2020; Byju and Suja, 2020). In addition, improved cassava varieties have shown the ability of crops potential to contribute to higher yields in cassava cropping systems (Pellet and El-Sharkawy, 1993).

Cassava is ranked as the most important staple food crop in Zambia after maize with more than >75% of farm households growing cassava in the Agro-Ecological Regions 3 (AER3) especially in Luapula, Northern, North Western and Western provinces and 15% of its overall cultivation at the country level is mainly under shifting cultivation (Alamu, *et al.*, 2019; Kabwe, 2014; Arega *et al.*, 2013; Haggblade and Nyembe, 2007; Barratt *et al.*, 2006).

Due to poor soil fertility, low use of improved varieties, and poor cropping practices the cassava yields among smallholder farmers are as low as 6 ton ha⁻¹ which is less than the potential yield ranges of 20–25 ton ha⁻¹ for new cassava varieties in Zambia (Kaluba *et al.*, 2021). Fertilization has been viewed as an expensive input while a lack of coordinated improved seed systems to deliver improved cassava cuttings as well as unsustainable cropping systems remain barriers to cassava intensification in Zambia (Chiona *et al.*, 2016). NPK fertilization, improved cassava varieties as well as improved cropping practices are critical to raising cassava productivity in cassava cropping systems. Leaf harvesting throughout the growing cycle of cassava is a common practice in most cassava growing areas in Zambia. Farmers frequently harvest cassava leaves as required without accounting for potential adverse effects on storage roots. A number of studies have investigated the impact of leaf harvesting on storage root production, nonetheless no consistent conclusions have been drawn due to differences in the intensity and frequency of leaf harvesting. Conversely, Lockard, *et al.* (1985) and Phengvichith. (2006) evaluated the effects of leaf harvesting at different frequencies on storage root yields and reported a reduction in storage root yields as the harvesting frequency increases regardless of

the variety used (local and/or improved variety). It is not clearly defined whether high leaf harvesting frequency but low intensity has a negative effect on yield, and whether interaction of crops nutritional status play a major role. A balanced N, P and K nutrient supply by inorganic and organic fertilizer is hypothesised to result in larger leaves, and faster leaf initiation, and may compensate the losses by harvesting of a few leaves and consequently stabilise cassava yields.

Cassava plants are known to be highly efficient in soil nutrient mining (Howeler, 2002). Nutrient removal is on an average of 4.5 kg N, 0.83 kg P and 6.6 kg K per ton of dry matter of storage roots harvested (Howeler, 1991). Conversely, smallholder farmers in Zambian farms rarely use manure or mineral fertilizer for cassava production (Kaluba *et al.*, 2021). The majority of farmers consider the crop as suited for poor soils and hence the neglect that it does not require fertilization (Pypers *et al.*, 2012, 2011;). Although cassava produces reasonable yields when grown on nutrient-limited soils, studies have shown that it responds positively to fertile soils, and might even require a high dosage of fertilizers to reach its maximum yield (Howeler, 2002). Cassava strongly responds well to potassium but also requires N, P and meso-/micro-nutrients to produce high yields (Fermont *et al.*, 2010; Howeler, 2002; Nguyen *et al.*, 2002). The general recommendations for mineral fertilizer have a ratio of 2-1-2 or 2-1-3 of N-P₂O₅-K₂O and are sometimes applied in a mixture with organic manure (Fermont, 2009; Nguyen *et al.*, 2000)

The suboptimal supply of N, P and K restricts the productivity of cassava varieties hence the need to understand the dynamics of nutrient requirements and their impacts on cassava growth as a critical component to the improvement of cassava yields under nutrient-limited conditions. Nitrogen, Phosphorous and Potassium(NPK) deficiencies affect cassava varietal growth and yield in three major ways: the decline of leaf growth rates and hence light interception

(reducing radiation use efficiency); through reduction of the leaf photosynthesis, and changes in the sink strength and partitioning of assimilates to the different plant organs (Pellet and El-Sharkawy, 1993; Kawano, 1992; Cock and El-Sharkawy, 1988). Assimilates are produced by the process of photosynthesis in the source organs (mainly leaves) while assimilates can be stored or transported from the source to the different sink organs via vascular connections (phloem) like roots in the cases of cassava. In agriculture, the net cumulative output of sink strength under a given source availability is yield where sink strength is the product of sink size and sink activity where; sink size is the total biomass of sink tissue (g), and sink activity refers to the specific uptake rate of the resource in $\text{mol g}^{-1} \text{s}^{-1}$ hence the influence on crop productivity (White *et al.*, 2016). Nitrogen availability is therefore known to play an important role in photosynthesis through chlorophyll content, leaf area development (LAI) and photosynthetic efficiency (Bojović and Marković, 2009; Sangakkara and Wijesinghe, 2014). Phosphorus availability strongly affects leaf growth and LAI, photosynthetic activity, the number of storage roots formed and hence yield, although responses varied among varieties (Pellet and El-Sharkawy, 1993). Potassium has numerous functions in crop growth and influences leaf appearance rates and leaf size (Howeler, 2017; Marschner, 2012).

Nonetheless, experience with fertilizer use on cassava in Africa is extremely limited and results are elusive. Some studies by Fermont, *et al.*, (2009); Munyahali *et al.*, (2017; Biratu, *et al.*; (2018) reported yield increases due to fertilizer use, while Wilson and Ovid, (1994) observed no effect of fertilizer application. However, the yield responses of cassava to mineral fertilization are highly variable and to some extent related to soil fertility levels, but independent of variety, disease incidence or harvest age (Pypers *et al.*, 2012, 2011; Fermont, 2009). The fertilizer optimization for cassava production in regions like Luapula province is even more challenging as both leaves and storage roots are harvested. Furthermore, cassava is commonly grown in a mixture with other arable crops and is often grown as a mono-crop only

in marginal fields where other crops fail to yield (Chikoti et al., 2019; Chiona *et al.*, 2016). Therefore, effective management and a good understanding of cassava nutrient requirements under different management systems are essential to maintain sustainable production to meet the present high demand for cassava for food and industrial use in the Luapula Province of Northern Zambia.

Despite the importance of cassava in these regions, yields are low due to various outlined constraints. In addition, cassava is under serious threat from cassava mosaic virus (CMV) and cassava brown streak virus (CBSV) causing serious yield losses from farmers' fields (Chikoti, 2016). Many studies (Pypers *et al.*, 2012, 2011; Fermont *et al.*, 2009) identified poor soil fertility as the most important constraint to cassava production. Imbalanced nutrient contents and high contents of undesirable nutrients such as zinc (Zn) and aluminium (Al) were also identified as soil fertility-related constraints to cassava production (Ezui *et al.*, 2015). Low precipitation especially either in the early growth stages (during the first 6 MAP) or during the entire crop cycle was identified as the second most important constraint and the most important factor explaining yield variability in cassava cropping systems (Fermont, 2009). It is therefore critical that integrated soil fertility management (ISFM) must be adopted as it offers the technologies aimed at increasing productivity through the use of improved germplasm, fertilizer application, organic matter management and adaptation to the local conditions of the smallholder farmers (Vanlauwe *et al.*, 2010)

This study evaluated the selected cassava varieties; two improved and one local variety in response to fertilization regimes (NPK fertilizer + lime, Fertilizer only, control and lime treatment) for physiology and morphological responses. In addition, the study also evaluated the response of cassava varieties to NPK application in low soil fertility conditions. Further,

the study evaluated three varieties under two fertilization regimes in response to leaf harvesting intensities on cassava productivity and physiology.

1.2 Statement of the problem

Smallholder farmers in northern Zambia yield less as 6 tons ha⁻¹ compared to the potential yields of 20 to 25 ton ha⁻¹ for released cassava varieties (Kaluba *et al.*, 2021). Poor cropping practices like leaf harvesting throughout the cassava growing cycle in farmers' fields without properly accounting for storage root yield are common, so understanding cropping systems is crucial to addressing the cassava yield gap and improving smallholder farmers' yields. Root removal takes a lot of nutrients from cassava, a nutrient-demanding crop. Replacement of nutrients with fertilizer is necessary to sustain soil fertility and cassava yields. Many tropical cassava growers utilize little or no fertilizer, limiting the production of high-yielding cultivars (Howeler, 2017).

1.3 Objective and Hypotheses

The current study aimed at evaluating sustainable cassava cropping systems under smallholder farmers in order to formulate integrated soil fertility management strategies critical at increasing and stabilizing cassava production and productivity through NPK fertilizer application and liming in low nutrient soils.

1.3.1 Main objectives

The main objective was to assess the yield performance, physiological and morphological performances of cassava varieties under different fertilization regimes in cassava cropping systems in Luapula Province of Zambia.

1.3.2 Specific objective

The study was conducted to:

1. Evaluate the performances of three cassava varieties on yield, physiology and morphological traits under four different fertilization regimes.
2. Evaluate the growth and yield performance of three cassava varieties under the NPK fertilization regime in low nutrient soils.
3. Assess cassava varietal responses to three leaf harvesting frequencies and two fertilizer management regimes on growth, yield and radiation use efficiency.

1.3.3 Hypotheses

The research hypotheses were:

1. Cassava fertilization regimes do not affect the yield, physiology and morphological traits of cassava varieties
2. NPK fertilizer application does not increase the performance of cassava varieties in low-nutrient soils
3. Fertilizer management regimes and leaf harvesting do not affect the performances of cassava varieties

1.4. Structure of the presentation of the thesis

Chapter One presents an introduction to the study by highlighting some background information on the global importance of cassava, cassava yield gaps and the need to intensify cassava production and the implications of cassava physiology on growth and yield. The study points out the problem the study addressed and its objectives.

Chapter Two is a review of the existing literature highlighting the gaps in the study of cassava starting with botany physiology as it relates to its production in the tropics. It looks at physiological and morphological determinants of cassava yield and productivity in the tropics and finally links them to cropping systems such as fertilization and soil amendments. It

discusses the impact of NPK fertilization on cassava productivity in the context of cassava varietal use and the impact of a common practice in cassava such as leaf harvesting.

Chapter Three describes all the materials and methods used in achieving the overall goal of the study for all three main objectives, which include soil sampling and characterisation, determination of soil nutrients, determination and modelling of varietal radiation use efficiency and data analysis.

Chapters 4-6 are the presentation of study introduction, results and discussion as well as conclusion of the specific experiments conducted in this study. Chapters 4-6 are based on the field experiments conducted at ZARI station in Mansa. Chapter 4 looks at the evaluation of morphological and physiological responses of cassava to four fertilization regimes whilst chapter 5 attempts to understand the genetic responses of cassava varieties to fertilization and puts common farmers cropping practice of no fertilizer in comparison to NPK fertilizer application which is only practised in cassava intercropping systems in Zambia. Chapter six focussed on the effect of fertilization regime and cropping practices on cassava physiology, growth, yield and yield components. The effect of the NPK+lime fertilization regime and the control on cassava performance were investigated. Chapter seven presents the summary of the most important results from three studies and their implication in terms of cassava productivity

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Classification, origin, production, distribution and use of cassava

Cassava (*Manihot esculenta* Crantz) is a perennial shrub of the family *Euphorbiaceae*, tribe *manihoteae* and subfamily *Crotonideae* (Byju and Suja, 2020; Alves, 2002; Cock, 1985). The crop is native to tropical Americas with the Amazon or North-eastern and Central Brazil as the centre of origin (Olsen and Schaal, 1999,2001). It is indigenous to Meso America and northern South America together with the other 98 species of the genus *Manihot*. Cassava was first introduced to Africa by the Portuguese in the sixteenth (16th) century and later to Asia in the 17th century (Cock, 1985). In Asia, around the late 18th and early 19th centuries, cassava production was initiated in India, Java (Indonesia) and the Philippines by European explorers who had obtained the crop from South America (Onwueme, 2002).

Currently, cassava is the sixth world food crop for more than 500 million people in tropical and subtropical Africa, Asia and Latin America (El-Sharkawy et al., 2012; El-Sharkawy, 2004). It is an important crop both as a cash crop and a subsistence crop for resource-limited farmers in Africa, Asia, Latin America and the Caribbean with a world production of more than 200 million tons of storage fresh roots annually (El-sharkawy, 1993). Cassava is principally consumed as food in a variety of forms such as boiled, fresh cassava, processed flours and starch. Cassava is an important food security crop or a famine reserve crop due to its wide adaptability to diverse climatic conditions (Liu *et al.*, 2014; Cock, 1985).

Cassava is adapted to diverse environmental conditions, as shown by its broad geographical distribution within the lowland tropics between 30 ° N and 30 ° S at elevations that range from sea level to 2000 m near the equator (El-Sharkawy, 2006; Alves, 2002). These zones include north-eastern Brazil, the northern coast of Colombia, coastal regions of Peru, the Sahelian region of West Africa and the drought-prone areas of eastern and southern Africa and parts of

Thailand (Okogbenin *et al.*, 2013; El-Sharkawy, 1993). Africa has emerged as the largest producer of cassava followed by Asia and the Americas. The crop has spread to more than 40 countries in Sub-Saharan Africa. Nigeria is the largest producer of cassava and Thailand is the world's largest exporter of the crop (El-Sharkawy, 2006)

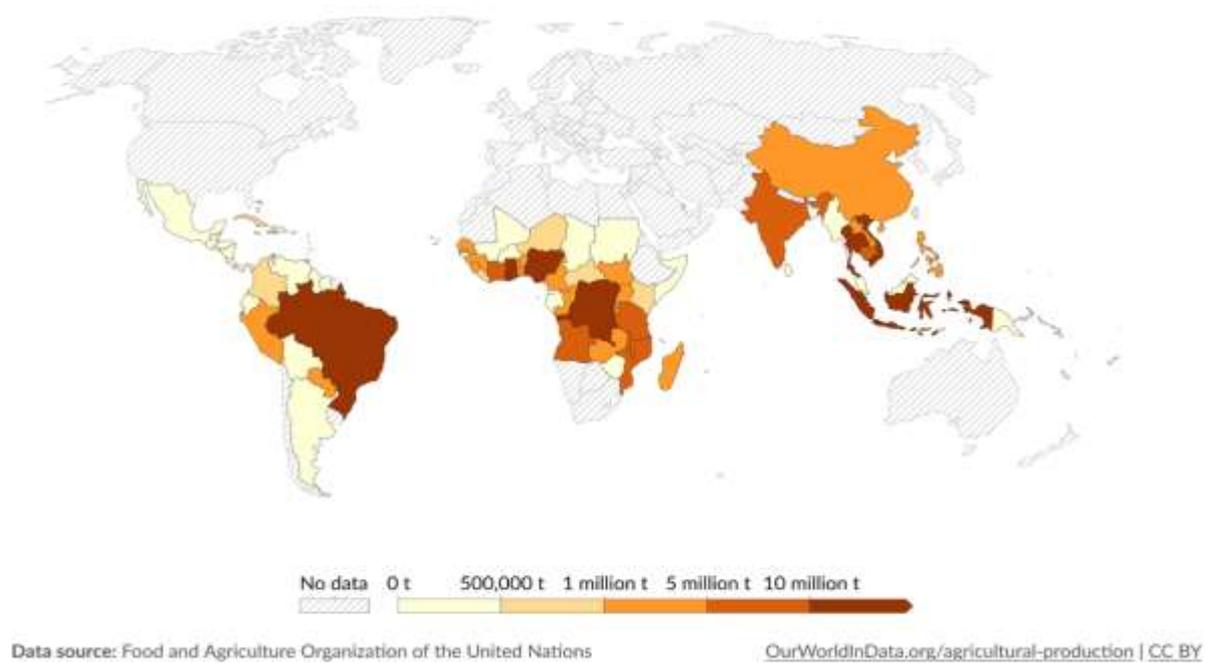


Figure 1: Map showing global and geographical production of cassava in metric tonnes for 2021

2.2 Cassava description and morphology

The genus *Manihot* consists of about 100 species, among which cassava, *Manihot esculenta* Crantz, is the only species commercially cultivated as a food crop (Fauquet and Fargette, 1990; Alves, 2002). Cassava is commonly known as tapioca, manioc, mandioca, yucca and mihogo in different parts of the world.

The starchy tuberous plant has been defined as rustic woody perennial shrub that can grow up to four (4) meters in height and exists wide variations in morphological characteristics, which indicate that it has undergone a high degree of interspecific hybridization (Byju and Suja, 2020;

Ceballos *et al.*, 2004; Kawano, 2003 Alves, 2002). Cassava consists of two distinct plant types: erect, with or without branching at the top, or the spreading types (Liu *et al.*, 2014; Alves, 2002). A big number of cassava genotypes are cultivated in a comparatively large diversity of ecologies making precise morphological description insufficient mainly due to genotype-by-environment interaction (Alves, 2002). Therefore, with the morphological characterization, the utilisation of molecular classification, mostly relying on DNA molecular markers, proves valuable in the assessment of the genetic variability within cassava germplasm (Fregene *et al.*, 2001; Elias *et al.*, 2000; Fregene *et al.*, 1994).

Variability in morphological characteristics of cassava is high, indicating a high degree of interspecific hybridization (Liu *et al.*, 2014; Fukuda *et al.*, 2010; Alves, 2002). The variability in morphological and agronomic traits is used to characterize the different cassava genotypes. Cassava leaves, formed by lamina and petiole, are simple and alternate, with an uneven 27 number of palmately veined lobes that range from three to nine in number (Alves, 2002). Inflorescent leaves are compacted in size and lobe number, while mature leaves are glabrous and surrounded by two stipules that remain attached to the stem when the leaf is completely developed (Fukuda *et al.*, 2010). The upper leaf surface is covered by a shiny and waxy epidermis (Alves, 2002). There is variation in apical leaf, petiole and mature leaf colours, presence or lack of apical pubescence, different shapes and numbers of leaf lobes, petioles of different lengths and protuberance of leaf scars (Liu *et al.*, 2014; Fukuda, *et al.*, 2010). The abaxial or lower leaf surface contains most stomata compared to the adaxial or upper leaf surface (El-Sharkawy and Cock, 1987). The number of primary stems produced by a cassava plant depends on the number of viable buds on the stakes (Alves, 2002). A mature stem is typically woody, cylindrical and formed by alternating nodes and internodes. The branching is sympodial with the main stem able to divide di-, tri- or tetra- chotomously, producing secondary branches (Fukuda, *et al.*, 2010; Alves, 2002). Mature stem diameter, plant height,

level of branching and number of nodes and apices per plant, vary depending on the variety, cultural practices and climatic conditions (Alves, 2002; Veltkamp, 1985). Primary tap root and fibrous root systems develop from cassava plants propagated either from true seeds or stem cuttings respectively (Alves, 2002). A limited number of fibrous roots start to bulk and form storage roots, which consist of the periderm, cortex and parenchyma tissues. The edible portion of the fresh storage roots, the parenchyma, constitutes about 85% of the total weight and is made up of xylem vessels radially distributed in a matrix of starch-containing cells (Pardales *et al.*, 1999). The colour, shape, length, diameter, weight, depth, carbohydrate, starch and dry matter contents as well as the protein, sugars and crude fibre contents of the storage roots vary extensively between genotypes (Alves, 2002).

2.3 Yield determinants of cassava

Several authors have reviewed the physiology of cassava growth and its implication on yield (El-sharkawy and Tafur, 2014; El-sharkawy and Tafur, 2010; Ekanayake *et al.*, 1988; Veltkamp, 1985; Cock *et al.*,1979).

2.3.1 Planting and sprouting

Cassava can be propagated from either stem cuttings or sexual seed, but the stem is a collective practice. Propagation through seed is mainly done for breeding purposes. In commercial cassava production, propagation of the crop is exclusively through stem cuttings of varying lengths (15-100 cm), which are planted horizontally, (Alves, 2002) vertically, or at an angle. The basal part of the cuttings is planted in such a way that its vertically or at an angle and inserted 5 to 10 cm deep in the soil (Chiona *et al.*, 2016; Veltkamp, 1985).

(Alves, 2002) reported that under favourable climatic conditions, the first leaves should appear 7-10 days after planting. Ntui, *et al.*, (2006) observed large varietal differences in the rate of sprouting when they studied 6 varieties, viz: ADP 3 (4), ADP 3(5), ADP 4(4), TMS 3055, TMS

419 and one local variety Panya, which were obtained from the Cross River Agricultural Development Programme, Calabar, Nigeria.

2.3.2 Root formation

Commercially, cassava is propagated exclusively by well-developed woody stem cuttings. Within one week, the mature stem cuttings are capable of producing roots from the soil-covered nodes (nodal roots) and 10 calluses formed at their lower end (basal roots). The cassava fibrous root system is very fine, uneven and superficial (Sieverding and Howeler, 1985). Studies have shown that the presence of fibrous roots has been reported to be as deep as 2.6 m (Chaweewan, 2016; Veltkamp, 1985; Connor *et al.*, 1981). About 2 to 3 months after planting, some of the fibrous roots (from 5-15 roots per plant) start to increase rapidly, developing storage roots for starch (El-Sharkawy and Cock, 1987; Veltkamp, 1985). The anatomical transformation from lignified xylem (in fibrous roots) to parenchymatous xylem (in storage roots) seems to be controlled by hormonal factors (auxins). The mature cassava storage root has three distinct tissues: bark (periderm), peel (or cortex) and parenchyma (Alves, 2002). Root size and shape are dependent on variety and environmental conditions; variability in size within a variety is more than that found in other root crops.

2.4 Canopy development

2.4.1 Effect of leaf area index, branching and leaf area duration on cassava yield

Generally, the leaf area index (leaf area per unit ground area) increases gradually during the first 1 to 2 months of the growth period. The growth follows a rapid increase and a decline thereafter (Veltkamp, 1985; Cock, 1976). The maximum reported LAI in cassava reported are about 7 to 8, although the most optimal values for maximum yield lie between 2.5 and 3.5 (De Souza *et al.*, 2017; Lebot, 2009; Cock, 1976). However, these values can only be maintained for relatively short periods. Keating. *et al.* (1982) in studies conducted in Queensland, Australia

reported leaf area indices up to 10 and exceeding 10 in periods with long days, although maximum leaf area indices of 3 to 4 were more normal during short periods.

Cock *et al.*, (1979) reported that crop growth rate in cassava increased with leaf area index (LAI) up to LAI 4; root growth rate increased up to LAI 3 to 3.5, then declined- an indication that sink source balance is critical for root growth. Maximum leaf area index (LAI) is reached in 4-to-5-month-old plants and then declines when leaf formation does not compensate for leaf shedding in the lower canopy layers (Ramanujam, 1985). Leaf life is reduced by shading but in full daylight, it is determined by a variety. Leaf formation rate per shoot apex is believed to have little genetic variation and decline with time; large differences in leaf formation rate per plant are <mainly determined by differences in branching patterns. Good yields in cassava were obtained by either late-branching types or continuous branching types with two branches at each branch level an indication that branching has a positive effect on yield (Lian and Cock, 1979). Cassava exhibits a balance between top growth and root growth which is largely determined by top growth potential mainly influenced by branching pattern. A positive relationship between leaf area duration and storage root yield has been documented (Alves, 2002; El-Sharkawy and Cock, 1987; Enyi, 1972). An optimal LAI for storage root growth of 3.0-3.5 has been suggested and indicates an association of storage root yield to leaf angle as varieties with vertically orientated leaves have been found to have high yielding ability than those with horizontally disposed leaves (Cock *et al.*, 1979; Lian and Cock, 1979; Williams and Ghazali, 1969). However, a study conducted by Cock, (1976), found that there was little if any advantage of a more vertical leaf orientation over a horizontal leaf orientation for clones that had leaf area indices up to about 4.

2.5 The interrelationship between dry matter production, partitioning, and radiation use efficiency in cassava

The interrelationship between dry matter(DM) production, partitioning, and radiation use efficiency in cassava is complex and influenced by several factors, including genotype, environmental conditions, and management practices (Souza *et al.*, 2017; Veltkamp, 1985). Plant dry matter production is the overall amount accumulated over time and depends on how much light the canopy intercepts, how well the plant uses it, and how much carbon dioxide remains for photosynthesis while partitioning distributes DM to plant sections. Cassava roots, stems, and leaves are important DM drains. Radiation usage efficiency (RUE) is DM production per light intercepted by the canopy and entails how well the plant utilises light for photosynthesis (Goudriaan and Monteith, 1990). Genotype, environment, and management factors affect how much DM is distributed to each plant component (Mahakosee *et al.*, 2022). By understanding these factors, it is possible to improve cassava production through breeding, improved management practices, and the use of appropriate technologies. Cassava root yield is determined by the total production of dry matter and its distribution (Holmes and Wilson, 1975). As the crop has the uniqueness of simultaneous development of the aerial apices and the roots, these two sinks compete for photosynthetic assimilates (El-Sharkawy and Cock, 1987). In terms of growth dynamics, it has been seen that top growth tends to take precedence over root growth. Furthermore, it has been found that the limitation of root sinks does not occur when there are nine or more roots per plant. To produce a high yield, it is crucial to maintain a well-balanced growth between the aerial and root components. This balance is typically achieved when there are multiple tubers per plant, namely nine or more (Cock and Sandoval, 1979). To achieve enhanced yields in cassava cultivation, it is crucial to optimise both light interception and radiation use efficiency (RUE). Ensuring the production of different cassava varieties is of paramount importance. Research conducted by. Ezui *et al.* (2017) and El-

Sharkawy *et al.* (1990) indicate that there is a relationship between biomass and root yield in cassava which is significantly affected by RUE. The total dry matter (TDM) produced in crop plants is positively related to the intercepted PAR, the efficiency of conversion of radiations to biomass and the slope that indicates RUE (Reynolds, *et al.*, 2000). Through an in-depth understanding of the complex connection with dry matter production, partitioning, and radiation use efficiency, as well as the influential factors encompassing genotype, environment, and management practises, it becomes feasible to enhance cassava production by means of breeding, enhanced management practises, and the adoption of suitable technologies.

2.6 Factors determining cassava productivity

2.6.1 Effect of NPK fertilizer on cassava growth and development

The yield of useful products per unit land area is defined as agricultural productivity (Marten, 1988) The use of modern high-yielding varieties, as well as improved use of chemical fertilizers, irrigation, and weed and pest control among cropping systems, has increased crop production over the past 50 years, which has come to be known as the "green revolution" (Fan *et al.*, 2012). The majority of cassava grows on acidic soils, primarily in the tropics (Sieverding and Howeler, 1985). These soils have low phosphorus (P) levels, which may limit cassava yield. Other elements, such as nitrogen (N) and potassium (K), may also be scarce. Cassava is well adapted to poor or degraded soils due to its tolerance to low pH, high levels of exchangeable aluminium (Al), and low phosphorus (P) concentrations in the soil solution (Howeler, 2009). Cassava is a nutrient-demanding crop, and it requires a balance of nitrogen, phosphorus, and potassium to thrive. When cassava is given adequate NPK nutrition, its leaf area index, RUE, plant height, number of leaves, stem diameter, and number of roots per plant all increase (Ezui, *et al.*, 2017; Sangakkara and Wijesinghe, 2014). Any imbalance in N, P, and K reduces cassava growth and yield.

Studies have shown that withholding N, P, and K resulted in a 3.0, 5.0, and 5.3 ton ha⁻¹ reduction in cassava root yield, respectively (Carsky and Toukourou, 2005). High nitrogen fertilizer applications may result in increased potassium requirements (Yampracha, 2019). When a cassava is given a high amount of nitrogen, it will need more potassium to maintain a healthy balance of nutrients. Studies have been conducted in the field on P nutrition to profile for optimal P fertilization and yield response to fertilization in cassava (Howeler, 1991; Howeler, 1985), as well as the establishment of soil-P critical values for crop response (Howeler and Cadavid, 1990). Long-term trials conducted by Howeler and Cadavid, (1990) for 8 years in the highly acid low-fertility soil at CIAT- Quilichao to determine the effect of cassava production and fertilization on soil fertility revealed that cassava has a strong response to P and N in the first year of cassava growth, but in the second year, cassava K became the most limiting nutrient and the importance of K increased over the years. When cassava plants lose more water, they need more K to help them retain the water balance an important function important for drought tolerance (Chua *et al.*, 2020).

Studies conducted at CIAT revealed that some cassava varieties highly adapted to low-P soils were identified in screening trials, demonstrating great variability in CIAT germplasm. According to Pellet and El-Sharkawy, (1993), some varieties highly adapted to low-P soils were identified during a screening process, demonstrating the high variability in CIAT germplasm with differences attributed in response to applied P being primarily due to contrasting patterns of dry matter partitioning and P-use. Recent studies have shown how NPK supply, specifically, influences physiological processes and productivity, resulting in differential growth and yield response among cassava genotypes (Adiele *et al.*, 2022; Ezui, *et al.*, 2017; Pellet and El-Sharkawy, 1997). This research is critical in the development of improved varieties for low-input sustainable agriculture in poor tropic soils, particularly in Sub-Saharan Africa.

2.6.2 The effect of NPK fertilizer on radiation use efficiency, yield and yield components

2.6.2.1 Root number

The number of fibrous roots which form storage roots depends on several factors such as variety, assimilate supply, shading, photoperiod and temperature (Alves, 2002) showed that the number of shoots per plant may affect the storage root number, with plants with more than one shoot producing more roots than plants with only one. Pellet. (1992) discovered that NPK fertilization significantly increased storage root number at various stages of growth. These results were also confirmed recently similar results (Adiele *et al.*, 2022). This is evidence that a balanced NPK application and a fair soil pH have an impact on the number of storage roots. Additionally, studies have shown that a positive and strong relationship between source activity (single-leaf photosynthesis) and sink size (storage root number) exists for cassava (Pellet and El-Sharkawy, 1993).

2.6.2.2 Storage root yield

Storage root biomass is non-existent in the first two months after planting and root growth is restricted to the fibrous root system. Studies show that four months after planting when canopy development almost reaches its maximum, the dry weight of the storage root is only about 20–30 % of the final yield in fertilized plants (Pellet and El-Sharkawy, 1997). This is an indication that fertilization plays a critical role in yield formation in cassava. Pellet and El-Sharkawy, (1993) found fertilization resulted in varieties CM 523-7 and CM 489-1 producing significantly higher final root yields than M Col 1684 and CMC 40 an indication that varieties adapt differently to fertilization. Yield in plants refers to the quantity of produce harvested from a single plant or the quantity of produce harvested per unit of land area. In cassava production, it is often defined in terms of marketable storage root yield, although leaves, stems or even seeds could potentially be additional economic products (Ceballos *et al.*, 2021; Hershey, 2008). Several efforts have been made to describe the ideal cassava plant type for maximum yields

and, according to (Cock, 1975) the highest yielding cassava plants would have a single erect stem, late branching, short thick internodes, and prolonged leaf retention capacity. However, he recognised the environmental limitations of this ideal plant and suggested that in fertile soils harvest index (HI) was important, and that under low soil fertility HI is irrelevant. Lenis et al., (2006) and Kikuzawa, (1995) on the other hand suggested that the most prominent trait associated with yield is leaf longevity. Several other indicators of high-yielding cassava have been suggested including late branching, large individual leaves or profuse branching (Cock *et al.*, 1979); narrow-lobed, vertically positioned leaves (Ramanujam, 1985); optimal leaf area index, large and numerous leaves and high HI (Pellet and El-Sharkawy, 1993). Lahai and Ekanayake,- (2009) suggested that dry mass production and partitioning are important determinants of storage root yield in cassava and that they could be important selection criteria in breeding for enhanced yield. Studies have indicated that selection for high-yielding cassava, requires a clear approach to select the ideal plant type based on late branching, large leaf size, and the number of roots on a mass-screening scale, but not for long leaf life (Cock *et al.*, 1979; Cock, 1975). Recent studies also indicate that selection for high storage yield requires high radiation use efficiency, light interception and optimal LAI (Adiele, *et al.*, 2022; Ezui et al., 2017)

2.6.2.3 Leaf area index

In cassava, a positive correlation between leaf area index or leaf area duration and yield, and storage root yield has been documented with an indication that leaf area is more critical in determining crop growth rate and storage root bulking in cassava production (Cock *et al.*, 1979 any new studies on this topic). Studies have shown that significant variety variation exists hence the need to characterise the development of leaf area index. In addition, LAI is positively influenced by NPK fertilization during growth and thus positively impacts yield (Ezui, *et al.*, 2017; Pellet and El-Sharkawy, 1997).

2.6.2.4 Radiation use efficiency

Radiation-use efficiency (RUE) is an effective and efficient approach to quantifying plant biomass accumulation. Early studies have demonstrated the increases in crop biomass in response to the amount of light available or intercepted by crop canopy were done by Veltkamp, (1985) and Loomis and Williams, (1963). The amount of solar radiation incident on the canopy was found to be inversely correlated with the canopy's photosynthetic capacity (Loomis and Williams, 1963). However, studies have compared plant productivity under various land use and management systems, as well as in various climates, by analysing efficiency based on incident radiation rather than intercepted radiation and following these estimates. Veltkamp (1985) calculated an efficiency in the use of incident radiation by assuming that 45% of all incoming radiation is in the visible spectrum and available for photosynthesis and that the production of 1g of dry matter corresponds to the fixation of 4250 calories of chemical energy. Importantly, Monteith andf Moss (1977) identified RUE as a reliable and theoretically sound approach for describing crop growth. RUE has decreased as a result of some important factors, including under-fertilized and drought-stressed conditions (Ezui *et al.*,2017; Sinclair and Muchow, 1999; Sinclair and Horie, 1989).

2.7 The effect of cropping practices and fertilisation on the productivity of cassava varieties

In Zambia Cassava is the second most important staple crop after maize for which an estimated 92 % of total production is utilized as human food and recently ethanol production (Chiona *et al.*, 2016). Cassava is therefore an important food security crop that can stimulate increased economic and rural development serving as a direct response to the crop diversification strategy.

Numerous factors determine cassava productivity and contribute to the gap between potential and actual yields achieved in farmers' fields. Crop yield potential is the crop yield that would

result from growing a crop in an optimum pest-free, disease-free, and weed-free environment with unlimited access to water and nutrients (van Ittersum *et al.*, 2013). As a result, a crop's potential yield depends on factors such as solar radiation, air temperature, and crop genetics at a particular location (van Ittersum *et al.*, 2013).

The potential yield is the maximum attainable yield achieved for a given variety under non-limiting conditions of water and nutrient supply, with effective control of biotic stress for sustained agriculture intensification (van Ittersum *et al.*, 2013; van Ittersum and Rabbinge, 1997). It is determined by significant elements like temperature, light or solar radiation, carbon dioxide, and crop or variety characteristics like canopy architecture, and it is predicated on the ideal planting density and other management (Van Ittersum *et al.*, 2013). Analysis of the cassava yield gaps in Africa, especially in East Africa, showed that pests, diseases, and ineffective crop and nutrient management techniques can seriously reduce cassava yields (Fermont, 2009). The lowest yield was obtained in areas with high pest or disease pressure, which can be ameliorated by using improved varieties. Understanding cropping practices and eco-physiological constraints in cassava production systems is essential for sustainable intensification in Zambia, where yields are less than 6 ton ha⁻¹ compared to a potential yield of 20–25 ton ha⁻¹ (Kaluba *et al.*, 2021). However, the majority of the cassava grown in Zambia is grown using traditional methods and information that has been passed down from one generation to the next (Chiona *et al.*, 2016). The knowledge behind this may not be supported by scientific understanding, which has contributed to cassava's extremely low productivity. Zambia's low yields are caused by several factors. Poor soils, low soil moisture, the use of low-yielding, disease-prone varieties, and a lack of knowledge of mechanization and production technology, among other things, are typical. Production of cassava is greatly hampered by several biotic constraints but the most important limiting factor is cassava mosaic disease (CMD) which affects cassava yields more in Zambia (Chikoti *et al.*, 2019; Chikoti *et al.*, 2016).

However, a study conducted by Ezui *et al.*, (2017) revealed that application of mineral fertilizer to poor soils increased yields even more, suggesting that low soil fertility is likely to be a significant biophysical barrier to sustained cassava production. Cassava is commonly cultivated in poor soils characterised by a significant deficiency in nutrients and organic matter content where under such environments, yields decrease when the crop is cultivated consecutively without the application of fertiliser (Cadavid., *et al.*, 1998). The use of nitrogen (N), phosphorus (P), and potassium (K) fertilisers has shown a substantial enhancement in both root and aboveground biomass, while concurrently leading to a reduction in root hydrogen cyanide (HCN) levels. A better understanding of the conditions under which positive effects of fertilizer occur can improve targeting and therefore achieve high profitability in cassava production. Furthermore, fertiliser use in Zambia is based on general recommendations for a variety of crop species, making it difficult to maximise crop productivity (Chapoto *et al.*, 2016). In addition, Zambia's Farmer Input Support Program (FISP), which is primarily focused on maize production, is the only program that subsidizes and uses fertilizer extensively. A review of nutrient-plant-specific fertilization recommendations based on current soil and plant requirements hasn't gotten enough attention up to this point (Chapoto *et al.*, 2016). In addition, production of cassava is traditionally done without fertilizer and instead shifting cultivation is practised as slash and burn for temporal fertilization which ultimately has an effect on long term land productivity (Kaluba *et al.*, 2021). Furthermore, conventional breeding has produced a steady supply of better varieties that have dramatically increased crop yields with economic benefits (Malik *et al.*, 2020). In recent times, there has been a heightened focus on the development of resistance against invasive pests and diseases, primarily driven by the growing concern about the emergence of cassava mosaic disease (CMD). Agronomic research encompasses the utilisation of modern technology to enhance profitability by prioritising

improved agronomic management practices, key to the sustainability of production systems (Malik *et al.*, 2020).

2.7.1 Effect of leaf harvesting on the yield of cassava root yield

In Zambia, cassava accounts for 15 % of national calorie consumption and is mainly produced by smallholder farmers (Dorosh *et al.*, 2007). In addition to its traditional culinary applications, cassava is increasingly being used as an industrial raw material in urban areas like Lusaka, Kitwe, and Ndola in the production of starch, ethanol, beer and animal feed (Haggblade and Nyembe, 2007). The majority of cassava producers are in Northern (210,706), Luapula (157,885), and North-Western (74,618) provinces, accounting for about 78.8% of all producers in Zambia (Sitko *et al.*, 2011).

Cassava is cultivated as a tuberous root crop and propagated using stem cuttings. Cassava leaves are considered as a popular and nutritious vegetable in African countries (Umuhozariho *et al.*, 2011). However, cassava leaves rich in carbohydrates, protein, vitamins, and minerals are an important leaf vegetable in Zambia. The impact of uncontrolled leaf harvesting in cassava fields on yields in Zambia is not well documented. If properly managed cassava can serve two purposes, particularly if agronomic techniques like planting improved varieties and fertilizing cassava would reduce yield gap and contribute to increased cassava yields in Zambia. However, cassava leaf harvesting is done indiscriminately in most farmers' fields leaving no room for accelerated leaf growth thus may affect canopy development and impact crop productivity. This calls for a defined and moderated approach to leaf harvesting in cassava fields since no studies have been documented in Zambia. Munyahali *et al.* (2017) found that harvesting of young leaves resulted in small or negligible effects on cassava growth and yields compared to the mineral fertilizers which increase both cassava growth and yields in the conditions of our study. They further found that leaf harvesting frequency at 2- week intervals

affected the yield of cassava in comparison to four 4- weeks intervals regardless of the fertilization regime. Lutaladio and Ezumah (1980), on the contrary, recommended monthly harvesting of leaves as it resulted in large leaf production with little losses in root yields in a study conducted in lowland conditions in DR Congo (Zaire). However,, it has been reported that increased foliage harvesting frequency results in lower root production 10 months after planting (Phengvichith *et al.*, 2006) Leaf harvesting in cassava depends on the farmer's needs and should be cautious for yield.

However, commercial leaf harvesting beyond the farmer's domestic requirements may be problematic. Leaf harvesting affects light interception, which can cause decreased photosynthesis, growth rate, and increased leaf temperature, potentially stressing the plant due to reduced leaf area index. Further leaf harvesting affects cassava by reducing root yield and increasing foliage production. Root yield is reduced by reducing photosynthates available for root growth as the efficiency of crop production is affected by reduced light interception from solar energy critical in the production of carbohydrates and other organic compounds (Monteith, 1977). Frequent leave harvesting results in a greater reduction in root yield, while frequent harvesting increases foliage production (Phengvichith *et al.*, 2006). Cassava leaf harvesting depends on variety, environmental conditions, and desired outcome, with dry conditions affecting root yield more. Decisions should be made based on these factors (Hue *et al.*, 2012). In addition, leaf area index is negatively affected by leaf harvesting that ultimately affects productivity. Studies have shown that most leaf area development coincides with high contribution to root yield and is crucial in assimilate manufacture hence the need to minimise leaf harvesting at peak period of leaf area development (Edet *et al.*, 2015). Increased Leaf retention trait may boost cassava productivity by increasing fresh biomass and root dry matter production (Lenis *et al.*, 2006).

2.7.2 The effect of NPK fertilizer and Lime on cassava root yield

Mineral fertilizer use in cassava production is a common practice in Latin America and Asia compared to Africa where there is little or no use of fertilizer (Kelly, 2006). This belief of no fertilizer use could be associated with the ability of cassava to yield better in poor soils where other crops fail. Recent findings, however, show that such an assertion provides an opportunity for increasing cassava yields under smallholder farming systems if the soil fertility status is improved (Fening *et al.*, 2009). An integrated soil fertility management (ISFM) is critical to cassava yield improvement through the combined use of improved germplasm/varieties, optimized use of fertilizers and organic amendments once adapted to smallholder farmers' local conditions in Sub-Saharan Africa (Pypers *et al.*, 2010). Studies have also shown that additional biological exhaustion (i.e., depression of soil life) causes a decline in cassava yields despite mineral fertilizer application (Howeler, 2014). Therefore, cassava intensification requires an integrated soil fertility management (ISFM) approach through the use of a judicious combination of agricultural inputs, especially fertilizers and improved varieties, to derive the best cost-reflective option for smallholder farmers (Vanlauwe *et al.*, 2015).

Cassava production in Africa is mainly dominated by smallholder farmers without the use of external inputs such as improved varieties and fertilization since they perceive cassava to grow in nutrient-depleted soils (Pypers *et al.*, 2012). Additionally, the potential for varietal responses and cassava adaptation to fertilization under Zambia's Agro-ecological Region III (AER), where significant precipitation, highly acidic soils, and a lengthy growing season are the region's defining characteristics, is not well documented. This explains some of the differences in yield between potential cassava yield and actual farm yields (El-Sharkawy, 2016; Ezui *et al.*, 2015; Alves, 2002). Mineral fertilizer application undoubtedly boosts yields because cassava is known to be a heavy miner of plant nutrients, particularly potassium (K), but it also

needs nitrogen, phosphorous, and micronutrients for yield sustainability (Byju and Suja, 2020; Howeler, 2001; Pellet and El-Sharkawy, 1997).

Application of NPK fertilizer in cassava should be related to the crop's physiological and morphological effects, since biomass, Harvest Index (HI), stems biomass, storage root diameter, the number of storage roots per plant, plant height, seasonal leaf Area Index (LAI) and Chlorophyll index are considered important physiological and morphological indicators of cassava growth and productivity (Ezui *et al.*, 2015) and therefore these can be used as indicators for optimizing NPK application. The N application increases RUE and cassava yields, according to research (Byju and Suja, 2020; Spiertz, 2010). Furthermore, N stimulates canopy growth, and photosynthesis and is key to carbon fixation (Sinclair and Horie, 1989; Luening, *et al.*, 1995). In highly weathered, nutrient-deficient soils, P is the most limiting nutrient in cassava productivity (Howeler, 2001). Phosphorus is also an important plant nutrient for plant growth and plays a role in plant metabolism, structure and reproduction (Day and Ludeke, 2003) apart from being a key element in energy transport in plants (Howeler, 1981). This implies that P is a limiting factor for cassava productivity and production in highly weathered soils. However, the availability of NPK is also affected by the soil's acidic conditions, especially in Chromi-haplic Acrisol soils where liming may be essential to increased nutrient availability, improved soil structure and increased rates of infiltration (Sanchez *et al.*, 1997; Haynes, 1982). On the other hand, studies have revealed that K is critical to cassava production as it plays a critical role in maintaining the photosynthetic activity essential in root bulking and it is highly demanded in the second cycle of cassava growth (Marschner, 2012). In K-deficient soils, the application of K improves cassava productivity and RUE (Ezui *et al.*, 2017; Howeler, 1991; El-Sharkawy, 2016) apart from increasing the efficiency of light conversion into pPhoto-assimilates more than its interception efficiency (Ezui, *et al.*, 2017). On the other hand, reduced nutrient use efficiency potentially leads to reduced photosynthetic rate, stomatal conductance,

Chlorophyll index, LAI and biomass production (Dinh *et al.*, 2017). This implies that RUE in cassava is yet another factor influencing yield. Recognizing that the root yield response to the LAI follows an optimum curve is crucial. Root yield increases initially before plateauing and then declines as internal shading brought on by excessive LAI worsens. Due to this, assimilates are transported to roots less effectively and net assimilation is reduced (Cock *et al.*, 1979). In addition, Lenis *et al.* (2006) also found that leaf area retention was highly correlated to root dry yield under both drought and well-watered conditions. This indicates that both LAI and leaf retentions are important traits for achieving high root yield under stress and non-stress conditions. Furthermore, Lenis *et al.* (2006) discovered that under both drought and well-watered conditions, leaf area retention was strongly correlated with root dry yield. This suggests that for achieving high root yield both under stressful and non-stressful conditions, LAI and leaf retentions are critical traits. Cassava takes 60 to 80 days after planting (DAP) to reach a leaf area index of 1, while it takes 120 to 150 DAP to reach an LAI of three (3) to achieve 90% light interception (Veltkamp, 1985). Achieving an LAI of 3.5 as soon as possible and maintaining it for as long as possible is essential for obtaining a high root yield. Indicators of LAI greater than the ideal range of 5 to 6 cause excessive internal shading and significant leaf abscise (Keating. *et al.*, 1982). In addition to soil fertility, whether or not fertilizer is applied, moisture regime, ambient temperature, and genotype (vigour and branching habit) all have a significant impact on leaf area dynamics (Ezui, *et al.*, 2017). In cassava, fertilizer responses to levels of assimilate sinks like tuber number and starch as well as assimilate sources like LAI are likely related to yield responses (Marschner, 2012). To increase the assimilation of sources and sinks for high yields, fertilizer design and application rates should be adjusted accordingly.

Cassava is produced by resource-limited small-scale farmers on low-fertility acid soils (Ultisols and Oxisols) with almost no agrochemical inputs (Alves, 2002; Howeler, 1985). Nitrogen

phosphorous and potassium (NPK) fertilizer application is known to intensify crop yields and mitigate net soil nutrient mining due to continuous removal by cassava roots. However, in Zambia, smallholder farmers rarely apply sufficient fertilizers due to the high cost, limited availability and lack of awareness (Biratu, 2018). Without applying a significant amount of soil fertility amendments such as manures or mineral fertilizers to replenish the soil, the anthropogenic process in SSA has led to the removal of huge amounts of soil nutrients (Sanchez *et al.*, 1997). In Zambia, there are many causes of low cassava yields in smallholder farmer's fields which includes poor farming practices such as poor weed management, low use of improved varieties and importantly little or no use of inorganic fertilizer and pesticides (Kintché *et al.*, 2017; Ezui *et al.*, 2015). Nitrogen is essential for plant growth and development, phosphorus is important for root development, and potassium is involved in photosynthesis and water transport. Lime is used to correct soil acidity, which can be a limiting factor for cassava growth (Howeler, 2001; Howeler, 1981; Edwards *et al.*, 1977). Pellet and El-Sharkawy. (1997) in their study found a significant positive response of varieties to the application of NPK fertilizer through increased dry root yield, aerial and total biomass and mean LAI as compared with the unfertilized plots. Notwithstanding the slash-and-burn method being productive for three cassava growth cycles of up to 9 years, this practice is unsustainable in the long run due to soil nutrient depletion resulting in farmers shifting from one place to another place (Chase and Singh, 2014). Kaluba *et al.* (2021) in their studies in the Northern part of Luapula province found that exchangeable potassium was the common determinant of tuber yield in cassava at 12, 24, and 36 month after planting (MAP) in farmers' fields. The application of K fertilisers has been known to increase cassava productivity on K-deficient soils (Ezui *et al.*, 2015; Sogbedji *et al.*, 2015; Howeler, 1991). Further exchangeable K is known to has several functions in plant growth among them is the quick re-establishment of the leaf area of the crop, which consequently improves yield (Ezui, *et al.*, 2017; Fernandes *et al.*, 2017). Thus,

improving K supply must be matched with a balanced supply of other nutrients, especially N due to its interaction in influencing crop productivity. Furthermore, N is known to be an important crop element in cassava production, with studies showing that N application increases storage roots dry matter (DM), biomass DM, RUE, and intercepted photosynthetic active radiation (IPAR) (Ezui *et al.*, 2017; Pellet and El-Sharkawy 1993).

Phosphorus on the other hand is involved in every stage of growth in every living cell. P is essential in nutrient management for achieving maximum crop yields in agriculture (Barker *et al.*, 2015; Marschner, 2012). Pellet and El-Sharkawy, (1993) analysed physiological mechanisms affecting varietal adaptation to low-P soils and response to P fertilisation, emphasising the importance of biomass partitioning in improving root yield response to fertilisation.

It is thus important that fertilizer recommendation of NPK should target cassava productivity and nutrient use efficiency and this can be improved through the integrated use of NPK and manure in Zambia(Biratu *et al.*, 2018). In addition, Biratu, *et al.*, (2018) found that the combination of inorganic fertilizers and manure resulted in the highest agronomic efficiency of N, P and K at both Agro-Ecological regions II and III in Kabangwe and Mansa sites in Zambia sites. A recent study by indicate cassava growth and yield will benefit from an adequate supply of N and P, as well as moderate K, with additional K top-dressing during the second growth phase for maximum root yield application of NPK fertilizer treatment significantly increases the response of cassava varietal yield, physiology and morphological traits in low soil nutrient conditions under high rain-fed conditions.

Lime raises the pH of the soil, which can make it more suitable for cassava growth. It also helps to improve the availability of nutrients in the soil. On the other hand, application of calcium carbonate to soils also called liming can stimulate nutrient availability to plants,

especially phosphorus. It can also ameliorate acidic soils to enable cassava crops to grow and produce more edible roots (Rosa *et al.*, 2021). In addition, the application of lime to soil has been found to enhance the availability of calcium (Ca) and phosphorus (P). However, it is important to note that the presence of Ca might lead to an increase in the cooking time of store roots. Furthermore, the impact of Ca on cooking time is influenced by the level of soil P availability (Rosa *et al.*, 2021). A study in Enugu, Southeastern Nigeria, found that applying 5000 kg ha⁻¹ of lime and 2500 kg ha⁻¹ of gypsum raised soil pH by 19-20% relative to the control for both seasons in degraded Ultisol soils of Agbani. Applying 5000 kg ha⁻¹ lime and 2500 kg ha⁻¹ gypsum increased soil exchangeable Ca²⁺ by 57% relative to the control in both seasons (Anikwe *et al.*, 2016). This study stressed the importance of lime in controlling soil acidity in cassava cropping systems.

It is important to note that the use of NPK fertiliser and lime should be carried out following cassava agronomic recommendations. Excessive application of fertilisers may have detrimental effects on cassava, leading to a decrease in overall crop productivity.

2.7.3 The effect of improved cassava varieties on cassava productivity

A significant step toward the realization of sustainable agricultural intensification is the use of improved crop varieties that are disease- and drought-resistant (Montpellier panel Report, 2013). Due to their inefficient nutrient and water use, studies have shown that traditional varieties frequently fail to produce the best yields when faced with drought and low soil fertility (Vanlauwe *et al.*, 2015). The improved varieties, in contrast, are disease and/or drought resistant and have high yield potential, which is essential to raising agricultural productivity. Additionally, they reduce nutrient competition with weeds and increase responsiveness to increase the agronomic use efficiency of nutrients and water (Vanlauwe and Giller, 2006). Moreover, the improved varieties increase resilience to biotic stress and benefit from a

reduction in the use of pesticides, hence avoiding environmental side effects (water pollution and biodiversity disappearance). Therefore, it is evident that using improved disease-resistant varieties results in increased cassava growth and yields as well as improved crop responses to fertilizer application (Munyahali, 2018). Additionally, enhanced technology adoption can accelerate economic growth, improve household incomes and help millions of farmers to escape from poverty traps (Berger *et al.*, 2017; Wossen *et al.*, 2017).

2.7.4 Effect of fertilization and variety on cassava profitability

Fertilisation and variety can seriously impact cassava economics. Improved cassava cultivars and fertilisation have been demonstrated to increase yields and revenues. Studies conducted in Zambia found that improved cassava varieties and fertilisation increased the yields of cassava and its yield components (Biratu *et al.*, 2018). The profitability impact of fertilisation and variety depends on variables such as differential diverse yields of cassava, resistance to pests and diseases and soil nutrition (Fermont, 2009). The costs associated with inputs, such as fertilisers and other related expenses, exhibit regional variations (Pypers *et al.*, 2010). Furthermore, the pricing of cassava is contingent upon other market circumstances (Munyahali, 2018). According to Senkoro *et al.* (2018), the yield increases due to fertilizer application such as N were 3.18, 6.63 and 7.47 Mg ha⁻¹ in Ghana, Kenya, and Tanzania, respectively, with agronomic efficiency (AE) of 53, 110, and 124 kg kg⁻¹.

In addition the study found that the value cost ratio (VCR) for N at all sites was >2 indicating sufficient profit opportunity to make N application attractive to many financially constrained farmers in the study countries (Senkoro *et al.*, 2018).

In general, cassava growers have the potential to generate economic gains through the utilisation of improved varieties and the application of fertilisers (Haque and Afreen, 2006). Prior to implementing these strategies, it is crucial to consider all relevant elements carefully

(Barker *et al.*, 2015). The above studies indicate possible positive impact of improved cassava production management practices.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Study area description

The study was conducted in Mansa, Zambia, at the Zambia Agriculture Research Institute (ZARI) station, which is located at 28.9508° E, 11.24135° S, and 1230 meters above sea level. The study was conducted in the Agro-ecological Region 3 (AER3), which has a growing season of 120–150 days and an average annual precipitation of more than 1200 mm. Extremely acidic, highly weathered soils are characteristic of AER3 (Nhamo, 2016). Soils are low in available plant nutrients for growth, with a high composition of exchangeable aluminium and manganese (Chapoto *et al.*, 2016).

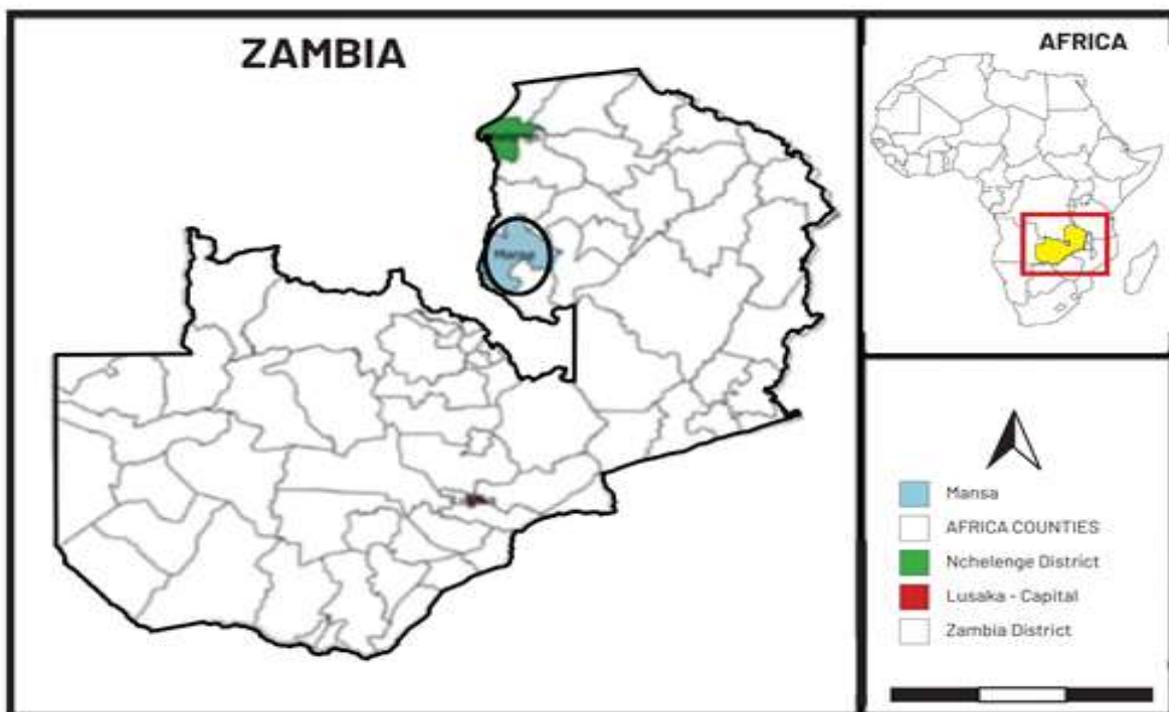


Figure 2: Showing the main study area Mansa and Nchelenge as Food Security for Rural Zambia (FoSeZa) Project piloting districts in the Luapula province of Zambia respectively.

3.1.2 Determination of NPK, pH, Organic matter and trace elements

Soil samples were taken for laboratory analysis to determine soil nutrient content (NPK), pH, organic matter and trace elements. This was done before trial establishment by taking a composite soil sample with a soil auger from at least 10 random sampling spots per field at 0-30 cm of topsoil. The soil was then air-dried, sieved, and analysed for standard physical-chemical properties. The hydrometer method was used to analyse soil texture, the Dumas combustion method was used to determine total N and organic carbon, and the Bray 1 method was used to determine available P (Bray and Kurtz, 1945). All analyses were carried out at the University of Zambia's Department of Soil Sciences laboratories.

3.2 Plant materials

Three varieties comprising two improved varieties (Mweru and Bangweulu) from the Root and Tuber Commodity Research Team released by Zambia Agriculture Research Institute (ZARI) and a local cassava landrace, Katobamputa, were used in the study. The varieties were selected for their wide adaptability and high-yielding traits. Mweru was selected because of its wide adaptability and resistance to diseases, while Bangweulu and Katobamputa were selected for their high yielding in marginal soil conditions.

3.3 Experimental design and trial management

A split-plot design in a completely randomized block was used with a fertilization regime as the main plot and variety as a subplot. The main plot had four fertilization regimes: M1-lime; M2-NPK fertilizer + lime; M3- no fertilizer regime and M4-NPK fertilizer only and subplots had three varieties; V1-Mweru, V2-Bangweulu and V3-Katobamputa. Fertilizer and lime at the rate of NPK 100:23:80 kg ha⁻¹ and 300 kg Ha⁻¹ rates were calculated respectively. The individual nutrient requirement from straight fertilizers of urea 46% (N) giving 217 Kg of urea per ha was calculated to meet 100 kg ha⁻¹ of N; triple superphosphate 46% (P₂O₅) giving 150 kg per ha to achieve the above phosphorous application rate of 23 kg ha⁻¹ and 50 % Muriate of

Potash (K₂O) amounting to 160 kg per ha to meet 80 kg ha⁻¹ of potassium were calculated. The lime application was done using the recommended rate in Agro-ecological Region III of Zambia following a lime requirement of 1.5 × Al (cmol kg⁻¹). Fertilizer and lime were applied to planting holes of cassava. The planting density was 10,000 plants Ha⁻¹ planted at a spacing of 1m × 1 m.

3.4 Data collection

The data collection for morphological performance traits was plant height, number of tubers per plant, root diameter and for physiological traits LAI, light interception, total daily solar radiation, and index of chlorophyll content were measured. Plant height was measured from the base of the plant to the tip of the emerging new leaf using a measuring tape (Tsuji *et al.*, 2005b). Four leaf chlorophyll index content measurements were taken on two leaves from either side of the midrib from the central lobe of the first fully developed leaf using the spad meter (SPAD 502, Konica Minolta and Tokyo Japan). For plant growth characteristics, measurements were taken on 5 tagged plants located in the middle of the plot. The readings were averaged over the growing cycle. Six sequential harvests were performed, with the first harvest at 75 DAP, and final harvests were performed on 396 and 410 DAP for the first and second growing cycles respectively (2018 and 2019 growing seasons). A plot size of 36 m² (6 Cassava cuttings × 1m × 6 m) was planted at 1m× 1 m to achieve a target cassava plant population of 10,000 plants/ha. The experimental plot size had 36 plants enough to support plant sampling for data collection. In addition 5-8 fresh young cassava leaves were harvested at three different intervals (D1= Control, D2= two weeks and three weeks) from three varieties under two fertilizer management regimes. Plants were selected in the middle of the whole plots for sequential and final harvests in a 3m × 3 m plot. To determine dry weights, plant parts were separated into storage roots, leaves and stems. Consequently, the fresh weights were determined in the field using the digital balance. For the roots and stems, 300 and 200 g of

leaves were sampled for dry weight determination. The materials were oven-dried to a constant weight under 80 °C for 48 hrs. Finally, dry matter content was calculated as the ratio of sample dry weight to sample fresh weight (Sánchez *et al.*, 2006).

Furthermore, the harvest index (HI) was calculated as the ratio of storage root dry weight to total plant biomass at all sampling stages until the last harvest, while the number of storage roots per plant was counted and averaged for 5 plants.

At each of the six data collection stages, the diameter of the storage root was measured with a digital Vernier calliper. Daily rainfall and temperature data were collected from an automatic weather station that was less than 1 km from the experimental site. The intercepted photosynthetically active radiation (PAR) was measured at each of the three locations in the plot using the 1-meter line quantum sensor and LI-COR 190R (LI-COR Inc., Lincoln, NE, USA). The leaf area index (LAI) was measured in established cassava plots at three different locations using the LAI2200 (LI-COR Inc., Lincoln, NE, USA). PAR and LAI were determined in all plots during the six different dates of sampling from 75 days after planting till the last day of the final date of harvest in both 2017/2018 and 2018/2019. Three measurements of data were recorded at each of the three different locations per plot. The basis for inter-seasonal comparison for LAI, light interception, RUE, and Chlorophyll index was to

3.5 Parameter estimation

Yield or dry matter of total biomass was obtained by summing up DM yields of storage roots, stems, harvested leaves and fallen leaves for each treatment. The dry matter of fallen leaves was estimated by summing all collected oven-dried leaves from each treatment plot at the time of sampling dates.

DM kg ha⁻¹ = (DM plot (kg)/number plants harvested in a plot) × plant population (plants ha⁻¹). The relationship between light interception and LAI was calculated according to Veltkamp, (1985)

$$\ln (I/I_0) = -K \times \text{LAI} \quad (1)$$

Where:

I = light received under the canopy

I_0 = incoming light above the crop canopy

K = extinction coefficient

Radiation Use Efficiency (RUE) for different treatment combinations was calculated as a slope of the linear regression of total plant biomass (gm⁻²) and cumulative intercepted radiation (IPAR) (MJm⁻²) during different times of growing seasons (Byju and Suja, 2020; Fukuda, et al., 2010; Manrique et al., 1991). In this study, it was assumed that 45% of daily solar radiation (DTR) was photosynthetically active radiation (PAR) (Veltkamp, 1985)

$$\text{IPAR} = \sum \text{DTR} \times 0.45 \times Q \quad (2)$$

Where:

DTR = daily total radiation

Q = proportion of intercepted radiation during the growing season.

The cumulative IPAR was calculated daily from the day of planting to a specific plant sampling interval date of harvest for plotting against produced biomass (leaves, stems, storage roots and fallen leaves). For optimization of RUE, the intercept of linear regression was set to zero since no cassava biomass production may occur without light interception by the canopy.

3.6 Statistical analysis

To satisfy the Analysis of Variance (ANOVA) assumptions, the data were examined for normality before analysis. For study objectives 1 and 2 under various levels of agricultural management options, analysis of the variance was used to determine the effects of interactions between fertilizer management regimes and varieties. Three single effects as well as interactions on fertilizer management regimes, varieties, and leaf harvesting on cassava were investigated under study objective 3. R statistical software (R Core Team, 2020) was used for the analysis of the variance using linear mixed models with lmer function (lme4) and estimated marginal means (emmeans) packages for mean comparison using Tukey's honest significance test respectively. For this study, the linear mixed model was selected as a method of statistical analysis due to the hierarchical structure of the split-plot and the split-split experimental designs respectively. The general linear mixed model equation is described below.

$$Y_{ijkl} = \mu + V_r + F_s + Y_t + FV_{rs} + FY_{st} + VY_{rt} + FVY_{rst}.bi + w_{ij} + \varepsilon_{ijkl} \quad (3)$$

$$Y_{ijkl} = \mu + V_r + F_s + H_t + Y_u + FV_{rs} + FH_{st} + FY_{st} + VY_{ru} + VH_{rt} + FVHY_{rstu}.bi + w_{ij} + \varepsilon_{ijkl} \quad (4)$$

where μ is the grand mean, V_r main effect of variety r (assigned to ijk units), F_s is the main effect of fertilizer managements (where different managements are assigned to subplot ijk), FV_{rs} is the interaction between fertilizer application regimes and variety, FH_{st} is the interaction between fertilizer regimes and leaf harvesting, FY_{st} is the interaction between fertilizer regimes

and year, VH_{rt} is the interaction between variety and leaf harvesting. VY_{rt} is the interaction between variety and year effect, FVY_{rst} is the interaction of fertilizer regime, variety and the year effect, b_i is the effect of block i , w_{ij} is the whole plot j within block i and ε_{ijkl} is the random error for unit $ijkl$ and $FVHY_{rstu}$ is the interaction of fertilizer application regime, variety leaf harvesting and the year effect, b_i is the effect of block i , w_{ij} is the whole plot j within block i and ε_{ijkl} is the random error for unit $ijkl$.

In the analysis of variance, varieties and leaf harvesting were considered random while fertilizer application regimes were considered fixed. To determine the strength of the relationship of variables and their strength of association, a Pearson correlation analysis was conducted in R. In addition, stepwise regression was conducted to determine the most important traits contributing to yield, stem dry matter and biomass formation using Akaike Information Criteria (AIC) AIC was used to compare different possible models and determine the best fit for the data in terms of the yield determinants of cassava root yield. Reference evapotranspiration for both seasons was calculated using CROPWAT Software Version 8.0.1.1 released by the Food Agriculture Organisation (FAO).

CHAPTER FOUR

4.0. MORPHOLOGICAL AND PHYSIOLOGICAL RESPONSES OF CASSAVA TO FERTILIZATION REGIMES

4.1 INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is a major staple food in sub-Saharan Africa (SSA) and is currently cultivated in 40 of the 53 countries in SSA, which accounts for half of the global output (FAOSTAT, 2019). Cassava cultivation has increased as a result of its adaptability to erratic rainfall patterns and relatively marginal soils (Howeler, 2017). These traits are essential because they influence yield, especially in future climates with greater climatic variability. In Zambia, cassava farmers' actual yields differ greatly from the attainable yields. (Kaluba *et al.*, 2021; Howeler, 2017). The potential yield in Zambia is 20–25 ton ha⁻¹, while smallholder yields typically range from 6–8 ton ha⁻¹. A major limitation of cassava productivity is inherently low soil fertility and continuous mono-cropping of cassava without fertilization (Sanchez *et al.*, 1997). Cassava, or manioc (*Manihot esculenta* Crantz), is a low-input crop with the ability to yield well in adverse environments with low fertility and acidic soils where other crops failed (El-Sharkawy *et al.*, 2012; Howeler, 2001). The Northern part of Zambia is characterized by highly weathered, leached soils with extreme acidity where crop production is dominated by cassava (Haynes, 1982). Cassava yield is limited by the availability of nitrogen (N) phosphorus (P) and potassium (K). Recent studies report that a sufficient supply of potassium (K) and nitrogen (N) is critical for yield stability and productivity (Ezui *et al.*, 2017). Availability of K is critical for cassava bulking and substantially limits cassava root yield if the crop is repeatedly grown without adequate fertilization due to the large export of K in the harvested tubers (Howeler, 1991). Under a mono-cropping system, P supply is the main limitation to cassava productivity rather than K in the first cycle (first year) of cassava crop production (Howeler, 2001). However, the demand for K increases with the age of cassava particularly in the second

and third years of the crop growth. Additionally, low organic matter may also limit nitrogen (N), thus affecting plant canopy development for cassava (Howeler, 2001).

The objective of this study was to evaluate the performance of three cassava varieties on yield, physiology and morphological traits under four fertilization regimes. Specific objectives were to:

- i. Determine the effect of four fertilizer application regimes on the growth and yield performance of cassava varieties
- ii. Assess the effect of four fertilizer application regimes on RUE and light extinction coefficient of cassava varieties

The study hypothesised that:

- i. Fertilization regimes and varietal responses affect cassava growth and root yield performance.
- ii. Fertilization increases RUE and modulates cassava varietal responses.

4.2 RESULTS AND DISCUSSION

4.2.1 Climatic data

The first and second growing seasons both experienced different amounts of precipitation, with the 2017/18 season receiving more than the 2018/19 season. According to Figure 3, there was a 400 mm difference in seasonal rainfall between the seasons. When comparing the two growing seasons, the 2017–18 season had better monthly rainfall distribution. The 2018–19 growing season did, however, experience higher rainfall in March, which was twice as much as what was experienced in March of the previous year (Figure 2). This is despite the season beginning with low monthly rainfall distribution. This period is critical for tuber formation in cassava since good rainfall is needed. Reference

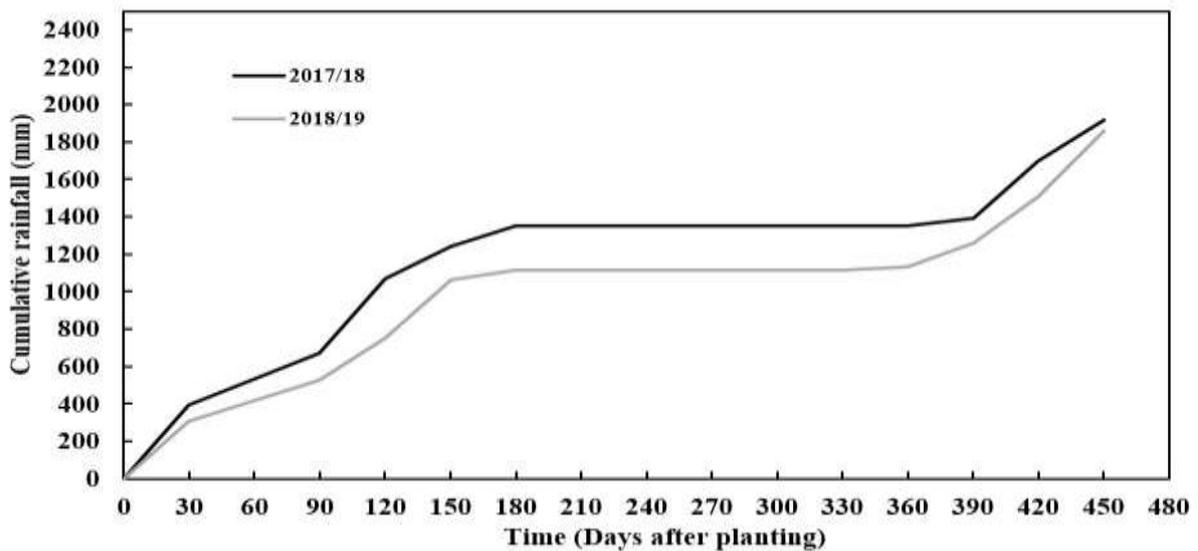


Figure 3: Cumulative daily rainfall (mm) was recorded at Mansa Zambia Agricultural Research Station (ZARI) during two experimental seasons (2017/18 and 2018/19).

evapotranspiration varied across seasons with the 2017/18 season having a higher value than the 2018/19 season (Figure 3). This trend was in line with the amount of rainfall and radiation accumulations which also coincided with seasonal evapotranspiration.

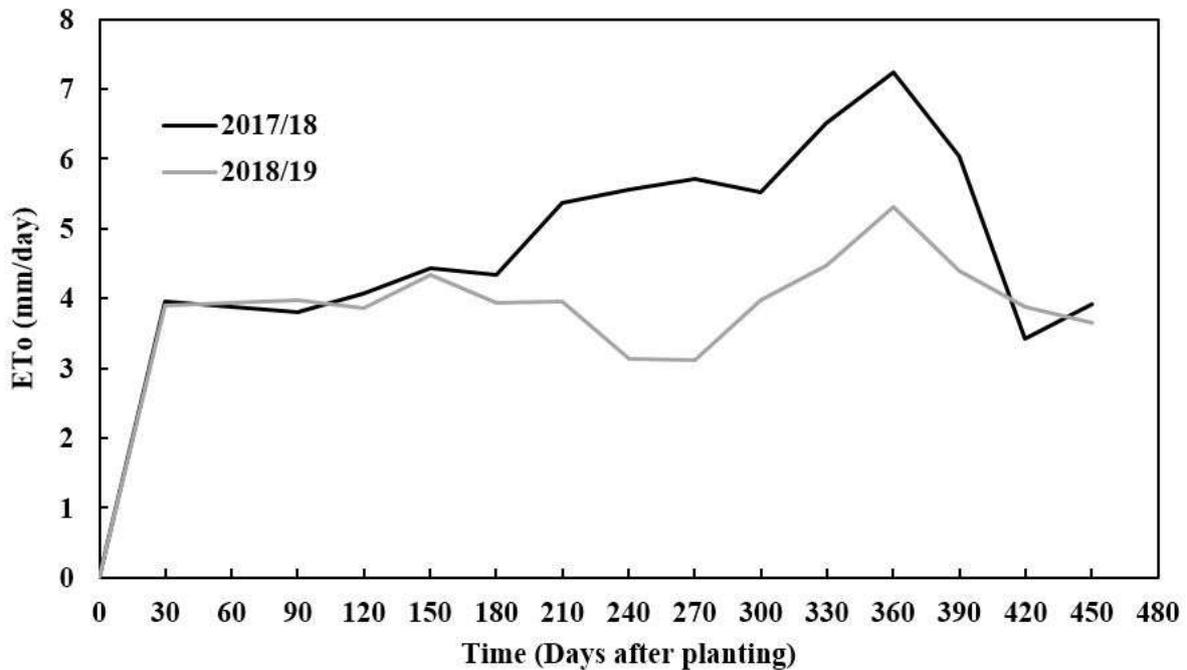


Figure 4: Evapotranspiration-ET_o (mm/day) at ZARI in Mansa during two experimental seasons (2017/18 and 2018/19 season)

4.2.2 Soil physical and chemical properties

Soil pH, total nitrogen (N), exchangeable phosphorous (P), exchangeable potassium (K), exchangeable calcium (Ca) and exchangeable magnesium (mg) were slightly higher in the second season (2018/2019) than in the first season (2017/2018), except for exchangeable sodium which was slightly lower. The variations in soil chemical properties were not significantly ($p > 0.05$) different. The soil texture classification of sandy clay loam did not vary across seasons as these fields were very close to each other

4.2.3 Effect of fertilization on yield, yield components source traits and profitability of different cassava varieties

Results showed significant differences in fertilization regimes and varieties as observed in dry root yield, biomass, harvest index, root diameter, plant height, and mean LAI, except for stem biomass, the number of tubers per plant and index of chlorophyll content in the 2017/2018 season (Table 1). In the 2018/19 season, significant differences in fertilizer and genotypic variations were observed in dry root yield, biomass, stems biomass, root diameter, plant height, mean LAI, SPAD and the number of storage roots, except for harvest index (HI) whose variations only reflected on varieties ($p = 0.05$) (Table 1). Across seasons (year) an increase in yield of 27% and 28% was observed due to fertilizer and variety, respectively. The mean root yield was higher in 2019 than in the 2018 season. Plant height and the number of storage roots showed significant variety by year effects as well as variety \times year (Table 1). Further, a yield advantage in both years of 23.9% and 27.02% in the 2018 and 2019 seasons, respectively, was attained for fertilization substitution. The interaction of the variety and the growing season was observed. Storage root yield across all treatment effects was around 7.36 % higher in 2019 than in 2018. A similar trend was observed in the whole plant biomass and stem biomass across the treatments. This was probably due to better crop establishment and consistent rainfall in the 2019 season. In addition, the

Table 1: Analysis of the variance for variety, year and fertilization effects and their interaction effects on yield, physiological and morphological plant traits using a linear mixed model during the 2017/2018 and 2018/2019 seasons (year effect).

Source	DF	Den DF	Seasonal LAI	Stem yield	Root Yield	Biomass	Harvest Index	Root Diameter	Plant height	Chlorophyll
Rep	2	22	0.007	3094	2476	3809	3.203	48	35.7	6.57
Fertility	3	22	0.024***	3954***	105472***	177858***	18.792**	325***	2444.9***	47.012**
Variety	2	22	0.0004***	647ns	124318***	150571***	86.778***	412.6***	3877.4***	90.764***
Year	1	24	0.017ns	51570***	67436***	288787***	16.392**	1270.42***	178ns	21.184*
Fert:variety	6	22	0.008***	2409***	2633ns	3685	2.173ns	61.75***	469.2**	9.379*
Fert:Year	3	24	0.024**	3553***	8702*	20090***	3.392ns	120.26*	1218.3***	43.073***
Variety:Year	2	24	0.016***	3874***	5615ns	4000ns	29.372*	361.8***	749.3**	10.83ns
Fertility:variety:Year	6	24	0.008ns	2414***	1592ns	4210ns	1.032ns	61.89ns	44.5ns	0.939ns

Significant codes: 0 ‘ ***’ 0.001 ‘ **’ 0.01 ‘ *’ 0.05 ‘ ns: not significant.

In addition, higher total daily radiation during the growth period increased aerial biomass, an indication of plant growth. The mean chlorophyll index was higher in 2018 by 2.8% than in 2019 while fertilizer \times year interaction and variety \times year interaction effect was also observed. There were no seasonal LAI differences observed across seasons across all treatments despite observing some variations in fertilization and varieties. Plant height was slightly higher in 2018 compared to 2019 across treatments while the fertilizer-by-variety interaction effect was also observed. Significant fertilizer and variety effects were observed on storage root numbers, although these differences did not reflect the year effects (Table 2). Application of NPK notably has shown to promote cassava storage root yields as reported in recent studies (Biratu, *et al.*, 2018). N is an essential yield promoter in agriculture farming.

The overall response of cassava varieties to NPK fertilization and liming (M2) showed in a significant increase in fresh and dry storage roots yield, stem dry matter, fresh biomass and dry biomass in comparison to liming only (M1) and the control (M3) (Tables 2). Similar genotypic responses were obtained with NPK fertilizer M4. However, no fertilizer by variety interaction was found. All the test varieties responded to fertiliser application.

Contradictory results were reported by Pellet and El-Sharkawy, (1997) where NPK fertilization significantly increased cassava root yield with a stronger varietal response to NPK fertilization on M Col1684 and CMC40 varieties. Moderate NPK fertilization is essential for maintaining soil fertility and yield in cassava cropping systems (Howeler, 1991). A recent study conducted in South Western Nigeria on tillage, plant density, weed control and fertilizer application in cassava also showed that fertilizer significantly increased yields even at a higher plant population of

Table 2: Cassava yield and biomass as affected by the different fertilization regimes and variety averaged across two growing seasons (2017/2018 and 2018/2019).

Treatments		Traits			
Fertilization Regimes	Variety	Fresh Root Yield (gm ⁻²)	Dry Root Yield (gm ⁻²)	Fresh Biomass (gm ⁻²)	Dry Biomass (gm ⁻²)
Control	V1	1891ab	823abc	3044abcd	1294bcd
	V2	1658ab	710ab	2766abc	1187abc
	V3	1370a	603a	2398a	1044a
Lime	V1	2072abc	818abc	3257abcd	1309bcd
	V2	1874ab	710ab	2996abcd	1206abc
	V3	1564ab	608a	2684ab	1082ab
Fertilizer only	V1	2834cd	1096de	4340e	1698fg
	V2	2242abcd	921bcd	3628cde	1509def
	V3	2363bcd	826bc	3669de	1340cde
Fertilizer + lime	V1	3012d	1162e	4504e	1768g
	V2	2401bcd	952cde	3844de	1558efg
	V3	1975abc	787abc	3363bcd	1328cde
SE(Fertilizer)		101.6 **	22.2 ***	97.7 ***	25.2 ***
SE(Variety)		73.1 ***	19.3 ***	74.3 ***	19.9 ***
SE(Fertilizer *Variety)		156.8 ns	38.6 ns	155.8 ns	41.13 ns

Significant codes: 0 ‘ ***’ 0.001 ‘ **’ 0.01 ‘ *’ 0.05, ns: not significant, V1: Bangweulu, V2: Mweru and V3: Katobamputa. Values in the column followed by the same letter are not statistically different by Tukey's honest significance test.

12,500 per hectare (Onasanya *et al.*, 2021). Varietal responses have observed for NPK fertilisation for both yield, physiological and morphological traits in cassava (Pellet and El-Sharkawy, 1997)

Treatments such as liming and the control did not show a significant response to cassava variety growth and yield parameters, compared to fertilizer + lime and fertilizer-only treatments ($p = 0.05$). Root yield and yield components did not show a significant incremental response to liming probably because liming was too short-term to produce any serious effect. The unfertilized treatment provided a baseline to which responses of all other treatments were compared. Liming, on the other hand, is thought to demonstrate the existence of genetic variations in the tolerance of acid soils among cassava cultivars (Manrique, 1987). Lime is known to increase cassava yields in soils where pH is low to neutral by offsetting soil acidity and improving the availability of plant nutrients such as Mg and Ca in low pH soils (Howeler, 2001). Although lime can be used to ameliorate soil acidity on such soils under continuous cultivation, its residual effect is short, especially in kaolinitic and oxidic soils characterized by high rainfall but sustainable in the long term (Sanchez *et al.*, 2015; Howeler, 2001). The lack of response in root yield, biomass, physiological and yield components to the lime application could be due to the highly weathered and leached soils that may require continuous liming till soil acidity is ameliorated to avail nutrients for plant growth (Tables 2). However, it is expected that long-term application of lime could help reduce soil acidity (pH 4.5-7.0) at ZARI in the northern part of the Luapula province and stabilize cassava yields in the short term as observed in our study. This could be attributed to the fact that all essential elements from our soil analysis results were below the minimum requirement thresholds for cassava productivity.

The average dry root yield increase of 31–41% for all varieties was observed from the application of NPK fertilizer + lime. The fresh root yield increase ranged from 31 to 37% across varieties with a mean of 33%. This increase in fresh root yield, in market terms, would represent an increase of US\$ 506 from the sale of additional roots, versus a total expense of USD 207(US\$ 200 from NPK fertilizer and US\$ 7 from lime expenses) on a hectare basis. This represents a gross profit of US\$ 299 per hectare. The application of fertilizer only resulted in an average yield increase in fresh root yield of 53% which translates to a US\$ 331 (531–200) gross profit. Despite this, the long-term effects of liming are likely to offset the negligible yield reduction in fresh root yield. Furthermore, it was observed that both NPK fertilizer + lime and fertilizer treatment revealed higher similar genotypic effects compared to liming and the control on yield and biomass. No fertilization regime by variety interaction effects was observed for both fresh and dry matter of root yield and biomass, respectively. However, no overall significant lime response was observed on yield and biomass (Table 2).

4.2.4 Important cassava traits for cassava yield determination

Tables 3 present the correlation matrix for two growing seasons 2018 and 2019 cassava traits for traits association. The traits used in correlations were final and averaged seasonal values at the end of the growing season. Autocorrelations were observed for total plant biomass and final root yield. Source assimilates such as mean LAI, RUE and mean chlorophyll index (SPAD), economic sinks storage root numbers and root diameter showed consistently highly significant correlations with total biomass and root yield. Plant height and leaf yields were all positively correlated to final yield and total final plant biomass.

It was evident that there were significant seasonal variations in how the various cassava varieties responded to fertilization regimes. Cassava RUE, biomass, storage root yield, and

related yield elements (plant height, LAI, SPAD (chlorophyll index), HI, stem yield, tuber number, and root diameter) were dependent on the response of the fertilization regimes and variety. Root yield was influenced by stem dry matter, mean LAI, radiation use efficiency RUE and tuber number per plant, while plant biomass was strongly influenced by root yield, SPAD (Chlorophyll index), leaf matter, HI mean LAI, tuber number and RUE. In addition, stem yield is highly influenced by reliant root yield, leaf matter, SPAD (chlorophyll), harvest index (HI), plant height (PH), root diameter, mean LAI, tuber number and RUE. These findings were supported by stepwise regression results (Table 4).

Table 3: Correlation coefficients (n = 36) for 2017/18 (1) and 2018/19 (2) growing seasons averaged across fertilizer management and variety.

Traits	Year	Leaf Yield	Stem Yield	Root yield	Biomass	HI	Tuber Number	Root Diameter	PH	SPAD	Seasonal LAI	RUE
Leaf yield	1	1										
	2	1										
Stem yield	1	0.664 ***	1									
	2	0.639 ***	1									
Root yield	1	0.731 ***	0.449 **	1								
	2	0.795 ***	0.774 ***	1								
Biomass	1	0.814 ***	0.626 ***	0.976 ***	1							
	2	0.819 ***	0.831 ***	0.993 ***	1							
HI	1	0.272 ***	-0.217ns	0.755 ***	0.599 ***	1						
	2	0.572 ***	0.499 **	0.901 ***	0.849 ***	1						
Tuber number	1	0.732 ***	0.671 ***	0.7601 **	0.831 ***	0.333 *	1					
	2	0.718 ***	0.694 ***	0.776 ***	0.799 ***	0.589 ***	1					
Root diameter	1	0.603 ***	0.595 ***	0.761 ***	0.809 ***	0.389 *	0.666 ***	1				
	2	0.653 ***	0.758 ***	0.807 ***	0.827 ***	0.648 ***	0.666 ***	1				
PH	1	0.814 ***	0.771 ***	0.662 ***	0.772 ***	0.175 ns	0.743 ***	0.752 ***	1			
	2	0.599 ***	0.556 ***	0.691 ***	0.697 ***	0.543 **	0.582 ***	0.743 ***	1			
SPAD	1	0.820 ***	0.591 ***	0.758 ***	0.815 ***	0.398 *	0.788 ***	0.683 ***	0.807 ***	1		
	2	0.668 ***	0.541 **	0.691 ***	0.703 ***	0.547 **	0.633 ***	0.715 ***	0.616 ***	1		
Seasonal LAI	1	0.696 ***	0.567 ***	0.870 ***	0.898 ***	0.558 ***	0.896 ***	0.755 ***	0.759 ***	0.826 ***	1	
	2	0.749 ***	0.807 ***	0.892 ***	0.911 ***	0.728 ***	0.839 ***	0.837 ***	0.648 ***	0.636 ***	1	
RUE	1	0.717 ***	0.609 ***	0.884 ***	0.918 ***	0.529 **	0.862 ***	0.823 ***	0.759 ***	0.772 ***	0.905 ***	1
	2	0.835 ***	0.743 ***	0.898 ***	0.909 ***	0.730 ***	0.838 ***	0.749 ***	0.603 ***	0.882 ***	0.624 ***	1

Very highly significant***, 0.001 'highly significant **', 0.01 ' *' significant 0.05

Table 4: Stepwise linear regression model for root yield, biomass and stem yield.

Response Variables	Variables	Regression Coefficient	p-Value	R²	p-Value for Regression Model
Root yield	Constant	-568.10	<0.001 ***	0.95	<0.001
	Stem Dry Matter	0.28	0.28 ns		
	Seasonal LAI	458.67	<0.001 ***		
	Tuber Number	-24.47	0.04 *		
	RUE	291.69	0.02 *		
Biomass	Constant	1492.02	<0.001 ***	0.99	<0.001
	Root yield	1.55	<0.001 ***		
	SPAD	-3.01	0.02 *		
	Leaf Matter	-0.81	0.06 ns		
	HI	-25.17	<0.001 ***		
	Mean LAI	143.66	0.001 **		
	Tuber Number	-4.71	0.15 ns		
	RUE	11.66	0.72 ns		
Stem yield	Constant	348.98	0.09 ns	0.99	<0.001
	Root yield	-0.55	0.01 *		
	SPAD	0.84	0.28 ns		
	Leaf Matter	-0.75	0.01 *		
	HI	-7.06	0.05 ns		
	Biomass	0.67	<0.001 ***		
	PH	-0.09	0.52 ns		
	Root Diameter	-0.61	0.10 ns		
	Seasonal LAI	21.52	0.44 ns		
	Tuber Number	-5.962	0.001 **		
	RUE	27.53	0.11 ns		

Significant codes: 0 '***' 0.001 ' **' 0.01 ' *' 0.05, ns: not significant.

4.2.5 Effect of fertilisation regimes on leaf area index and light interception dynamics

For each variety and growing season (year), results for the appropriate fertilizer management practices on leaf area development were assessed (Figure 5a). During the crop canopy establishment phase, which lasted one to three months, cassava LAI development was slow. Following rainfall, temperature, and leaf area longevity during the two seasons of growth, it took about 6 to 7 months to reach the maximum LAI values. Although LAI development was initially slow, it picked up speed 75 days after planting and reached its highest values at 197 and 240 DAP in the growing seasons of 2017/18 and 2018/19, which were both parallel to the rainy season. In the dry season, LAI dropped significantly. The LAI reached its highest points in the 2017/2018 and 2018/2019 seasons, respectively, at 197 and 240 DAP. At 259 and 273 DAP in the two corresponding seasons, LAI ultimately dropped quickly, and it didn't start to rise again until November in both seasons when the rainy season resumed and allowed fresh leaves to emerge (Figure 4a). These observed variations in LAI during cassava plant growth were statistically different ($P < 0.05$). The period of reduced LAI corresponded with a drier period of the year and plants responded by reducing aboveground growth, hence limiting plant transpiration. In addition, there was maximum leaf fall. In both seasons the pattern of canopy growth was similar for all fertilization regimes, although M2 and M4 had a higher LAI compared to M1 and M3 regimes. A sharp increase in LAI was observed for all fertilization regimes and varieties at 354 and 344 DAP for the 2017/18 and 2018/19 seasons till the final regrowth due to the resumption of the rainy season. It is common practice in southern Africa and particularly in Zambia's cassava growing belts to harvest cassava during the rainy season for ease of harvesting in wet soils and to avoid storage root breakage, and consequently to preserve the planting stalks (cassava cuttings)

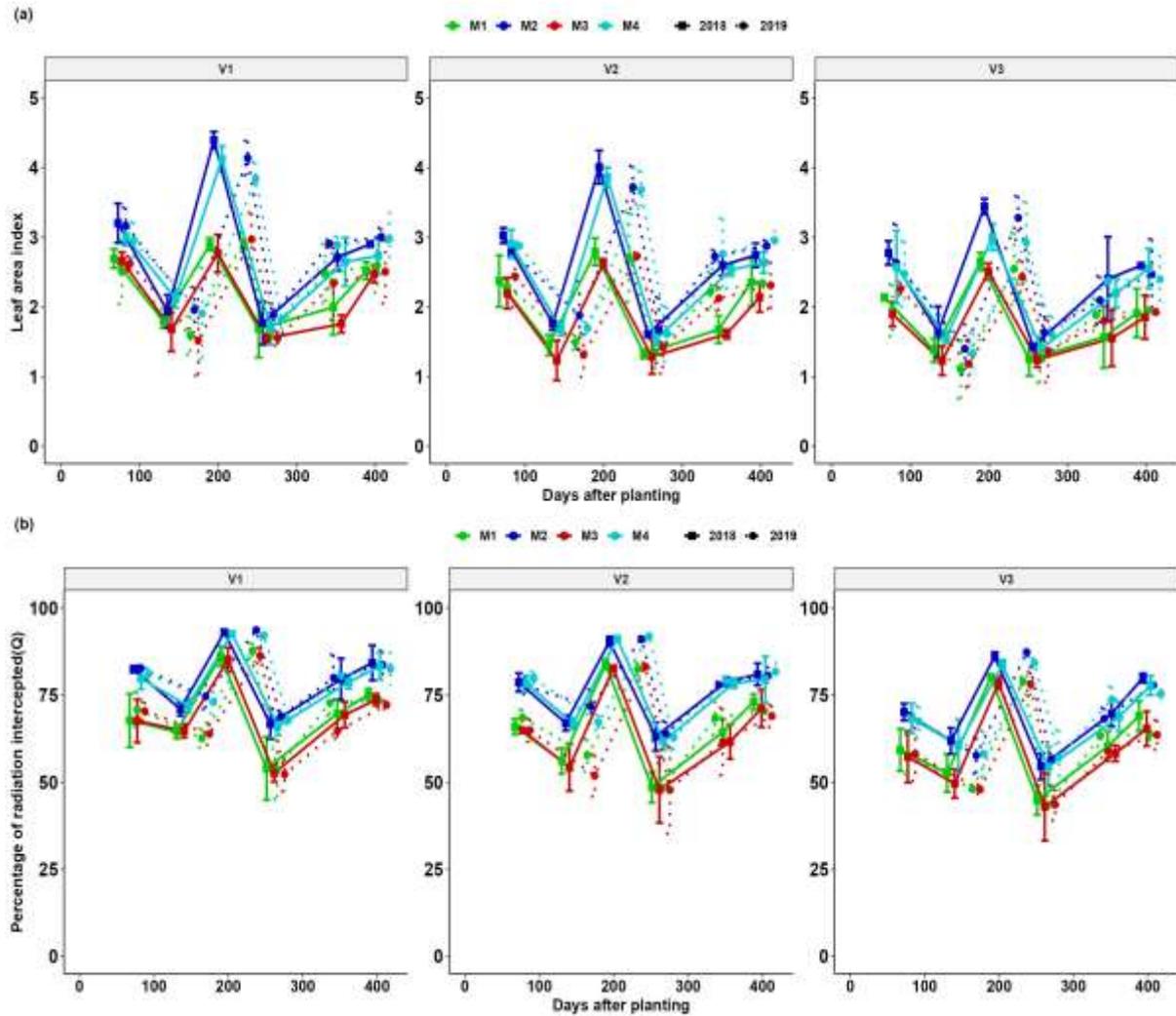


Figure 5: Leaf area index (a) and fraction light interception (b) dynamics of different cassava varieties as affected by different application fertilizer regimes. Key: M1 = lime application only, M2 = fertilizer and lime, M3 = no fertilizer and no lime (low input farmer practice) and M4 = fertilizer application. V1 = Mweru, V2 = Bangweulu and V3 = Katobamputa during the two agricultural seasons 2018 and 2019.

Light interception followed a similar pattern as that of LAI for the two growing cycles. On the first date of light measurement, V1 intercepted a higher percentage of incoming PAR then followed by V2 and V3 regardless of fertilization regime (Figure 5b).

Light interception slightly decreased on 138 and 172 DAP at all treatment combinations, with V3 having the lowest light interception. The highest intercepted PAR was achieved at 197 and 240 DAP for the 2017/18 and 208/19 seasons, respectively. At 259 and 273 DAP, there was a remarkable decrease in light interception at all treatment combinations (genotypic and fertilization regimes). In addition, there was a maximum leaf fall during the dry season followed by new leaf formation as moisture conditions improved due to increased rainfall (Refer Figures 2 and 3). Varietal and fertilization regimes differences in total intercepted PAR were negligible (Figure 4 b). The range of fraction of intercepted radiation (Q) ranged from 50–90% and 43–92% across treatments for the 2017/18 and 2018/19 seasons, respectively. Both LAI and Q were slightly higher in 2018 than in the 2019 season (Figure 5a-5b). Fertilization regimes had a significant effect on all phenological and morpho-physiological stages across seasons (Figure 5). The pattern of LAI and light interception followed a pattern that corresponds to moisture availability during cassava growth (Figures 2–5 and 7). A high LAI and light interception between 90 –180 DAP were reported, which was in line with changes in evapotranspiration (Veltkamp, 1985). However, a sudden fall in LAI and light interception were observed after 200 DAP (Figure 5). Maximum canopy size and dry matter partitioning to the leaves and stems observed in this study have been reported in several other studies (Lahai and Ekanayake, 2009; Howeler and Cadavid, 1983). However, studies indicate that during drought stress, LAI, light interception and dry matter partitioning to stems and leaves reduce rapidly as photo-assimilates are mostly channelled to the growth of storage roots and only increase after the resumption of rainfall as reported in some studies (Byju and Suja, 2020; Alves and Setter, 2000).

4.2.6 Effect of fertilizer on total dry matter and root dry matter during the growing season

Total dry matter (TDM) and root dry matter (RDM) of cassava growth increased gradually after crop establishment and grew rapidly after 200 DAP in response to the rise in moisture (Figure 6). At all stages of growth and across years, biomass accumulation kept increasing and reduced in the dry season and increased rapidly after the onset of rain. At all stages, fertilization increased total biomass accumulation compared to unfertilized and limed treatments. During the growing season, TDM and RDM were determined during the six sequential plant harvests throughout the growing season. The growth of cassava TDM and RDM was slow until after 140 DAP of its growth cycle (fourth to sixth harvest). During this period, the cassava used much of its carbohydrate reserves stored in its roots to rebuild its LAI. The increase in LAI led to an increase in both TDM and RDM growth, especially between 320 and 410 DAP. Across all seasons, fertilizer + lime treatment and fertilizer-only treatment exhibited a similar trend and had significant RDM and TDM compared to lime and control treatment. It was clear that the growth dynamics curve for V1 was better than V2 followed by V3 in RDM and TDM irrespective of the fertilizer treatment. Similar findings were observed by Pellet and El-Sharkawy (1997) when LAI, RDM and TDM were higher in NPK treatments compared to the control while no dramatic varietal differences were found in LAI, RDM and TDM development. It was also observed that growth in RDM and TDM was better in 2019 than in 2018. Cassava TDM and RDM growth slightly decreased on 259 and 273 DAP at all treatment combinations with V3 having the lowest visible growth. A sharp increase in cassava varietal TDM and RDM was observed for all fertilization regimes and varieties at 354 and 344 DAP for the 2017/18 and 2018/19 seasons till the final regrowth due to the resumption of the rainy season. Fertilization treatments M2 and M4 produced comparable higher total varietal plant DTM and RDM compared to treatments M1 (lime) and M2 (control) which showed similarities in biomass production.

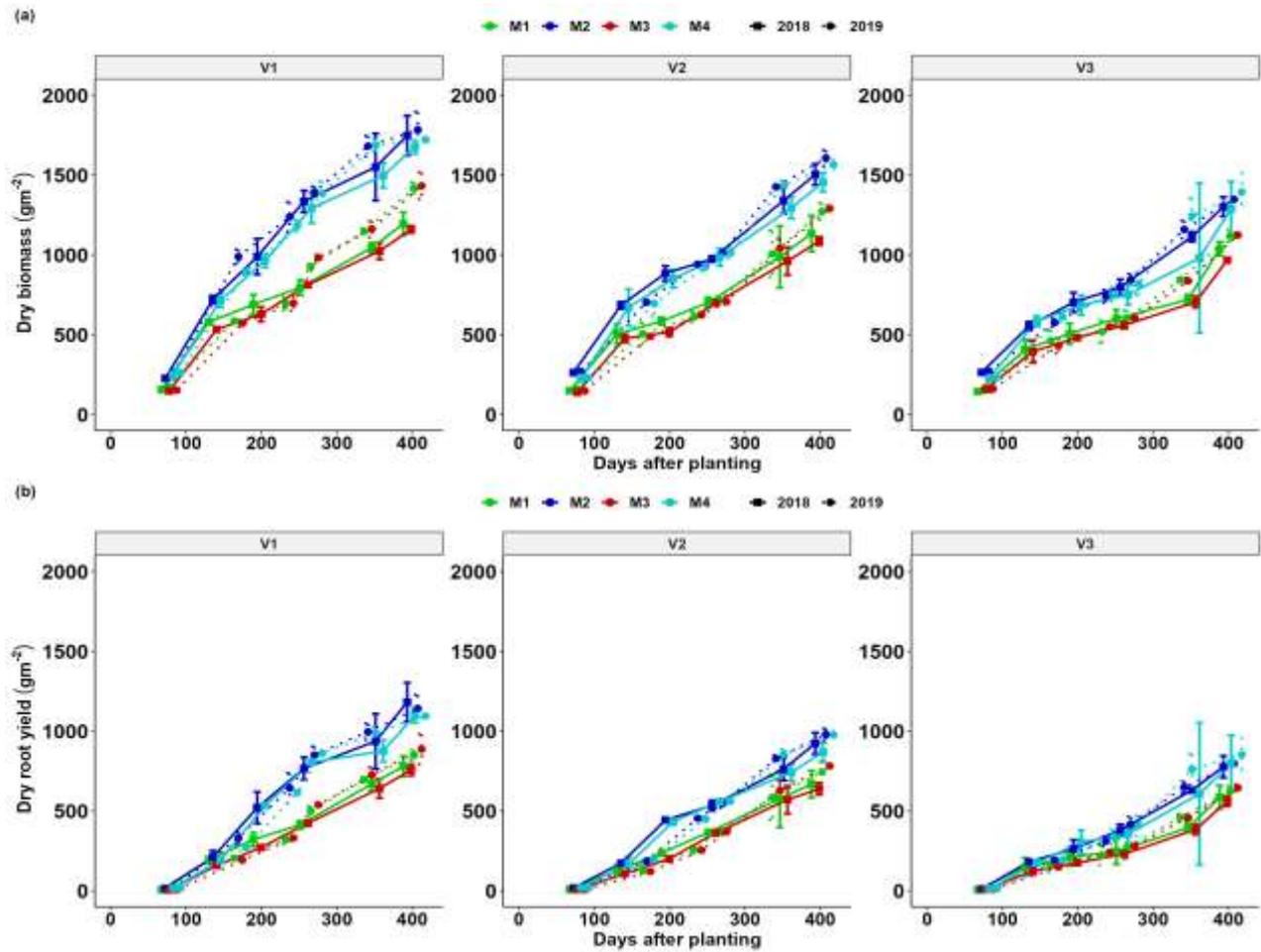


Figure 6: Biomass (TDM—total dry matter) (a) and root yield (RDM—root dry matter) (b) dynamics of different cassava varieties as affected by different fertilizer regimes. Key: M1 = lime application only, M2 = fertilizer and lime, M3 = no fertilizer and no lime (low input farmer practice) and M4 = fertilizer application only. V1 = Mweru, V2 = Bangweulu and V3 = Katobamputa during the two agricultural seasons 2018 and 2019.

4.2.7 Effect of fertilizer application regimes on light extinction coefficient and solar radiation use efficiency

The K values ranged from 0.54–0.61 and 0.52–0.61 for the 2017/18 season, respectively across varieties and fertilization regimes (Figure 7). Across all varieties, fertilization increased the K values across seasons. This was a sign that higher light interception was achieved for the same LAI because of better leaf size, branching and leaf positioning resulting from the horizontally-oriented leaf structure of varieties. The highest varietal K -values were obtained by variety Mweru (V1) followed by Bangweulu (V2) and Katobamputa (V3), respectively across all treatments. The average cassava K -value in the present study is similar to the value estimated for most crops (around = 0.60). Zhang *et al.*, (2014) estimated comparative K values among different vegetation ecosystems and found that cropland had the highest value of K (0.62), followed by broadleaf forest (0.59), shrub land (0.56), grassland (0.50) and needle leaf forest (0.45). K values obtained from this study are within the range of these suggested values.

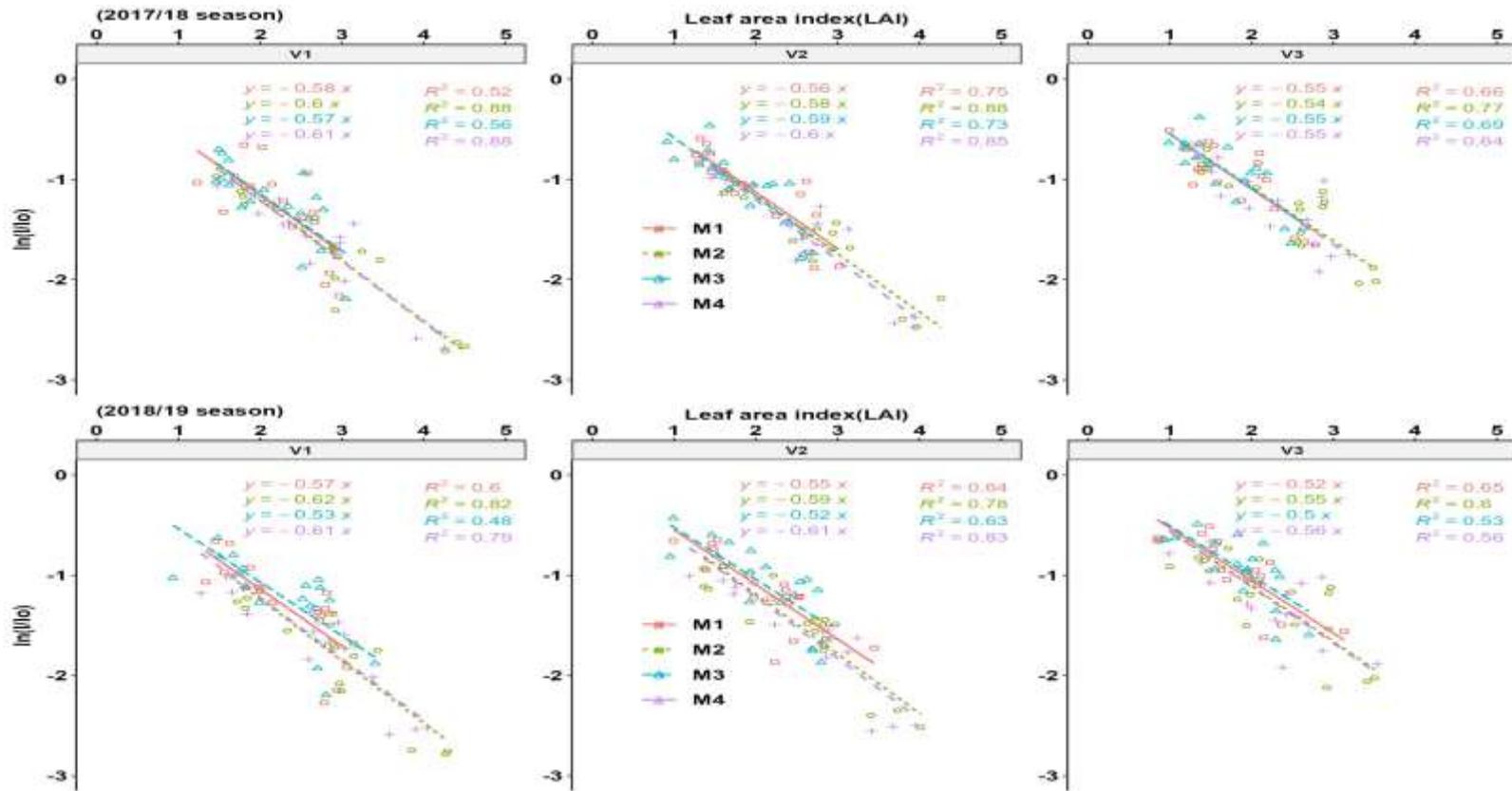


Figure 7: An illustration of cassava canopy extinction coefficients (K) of cassava varieties. Each slope corresponds to radiation use canopy extinction coefficients (K) to treatment effects for different harvesting periods for the 2017/18 and 2018/19 seasons, respectively. Key: M1 = lime application only, M2 = fertilizer and lime, M3 = no fertilizer and no lime (low input farmer practice) and M4 = fertilizer application. V1= Mweru, V2 = Bangweulu and V3 = Katobamputa, I = light received under the canopy and I_0 =incoming light above crop canopy

Data on the cumulative total biomass produced were plotted against cumulative intercepted photosynthetic active radiation (IPAR) for the different harvest times of the growing seasons. Biomass formation is a dynamic process that not only involves light interception via plant canopy but also carbon fixation by photosynthesis, and dry matter partitioning patterns among aerial and belowground organs. All varieties showed a significant increase in RUE in response to fertilization (Figure 8) due to an indirect effect of increased LAI, and a direct effect of increases in stems and storage roots with fertilization. Fertilization regimes M2 and M4 showed the highest RUE values compared to M1 and M3 across all varieties. The RUE values ranged from 1.3–2.1 and 1.5–2.2 gMJ⁻¹ PAR in the 2017/18 and 2018/19 seasons, respectively. These RUE values are within the ranges of four varieties observed under variable fertilization treatments in the sub-humid zone of Colombia, South America (Byju and Suja, 2020). Genotypic variation of RUE was observed with V1 having higher values followed by V2 in comparison to V3. Fertilization increased the RUE by 20.69% and 20.34% in the 2019 and 2018 seasons in comparison to the control (no fertilizer). Seasonal variations were not reflected in the values of RUE in the 2018 and 2019 growing cycles. The *K* values obtained in this study indicate that most of the clones had moderately horizontal leaves (planophile pattern).

In the second year, there was a better crop establishment, which led to better biomass and storage root yield as a result of better RUE. All three varieties showed significant variation in the value of *K* both in year one and year two with a strong positive response to fertilization (Figure 7). However, differential responses in *K* values did not reflect in the variation of RUE. All varieties showed a significant ($P=0.05$) increase in RUE in response to fertilization with high degree of correlation between cumulative intercepted photosynthetic radiation and total dry biomass of cassava (Figure 8). Variety V1 had the highest RUE followed by V2 and the least was V3. Pellet and El-Sharkawy (1997) observed a significant genotypic response of *K* to fertilization. The RUE ranged from 1.2–2.2 gDM MJ⁻¹ PAR intercepted across the cropping

seasons and fell within the range of 1.15–2.30 gMJ⁻¹ and the lower range of 1.4 gMJ⁻¹ obtained by Pellet and El-Sharkawy (1997) and Veltkamp, (1985) respectively. Our RUE value did not surpass the highest value of 2.3 gMJ⁻¹ obtained by Pellet and El-Sharkawy (1997) due to the reason that our short growing rainy season in Southern Africa only lasts for 150 days, followed by a drought period, which results in low biomass production due to moisture stress. Response variations in fertilization regimes were observed, NPK fertilizer in combination with lime and NPK fertilizer-only regimes increased varietal RUE. The findings showed that RUE response of varieties was also reflected and that NPK+ liming and NPK fertilizer applications only increased K with varying varietal response as opposed to lower K values for limed and unfertilized treatments. Pellet and El-Sharkawy (1997) reported significantly higher RUE and K-values in the four varieties, with noticeable variations in the varieties that had received fertilization.

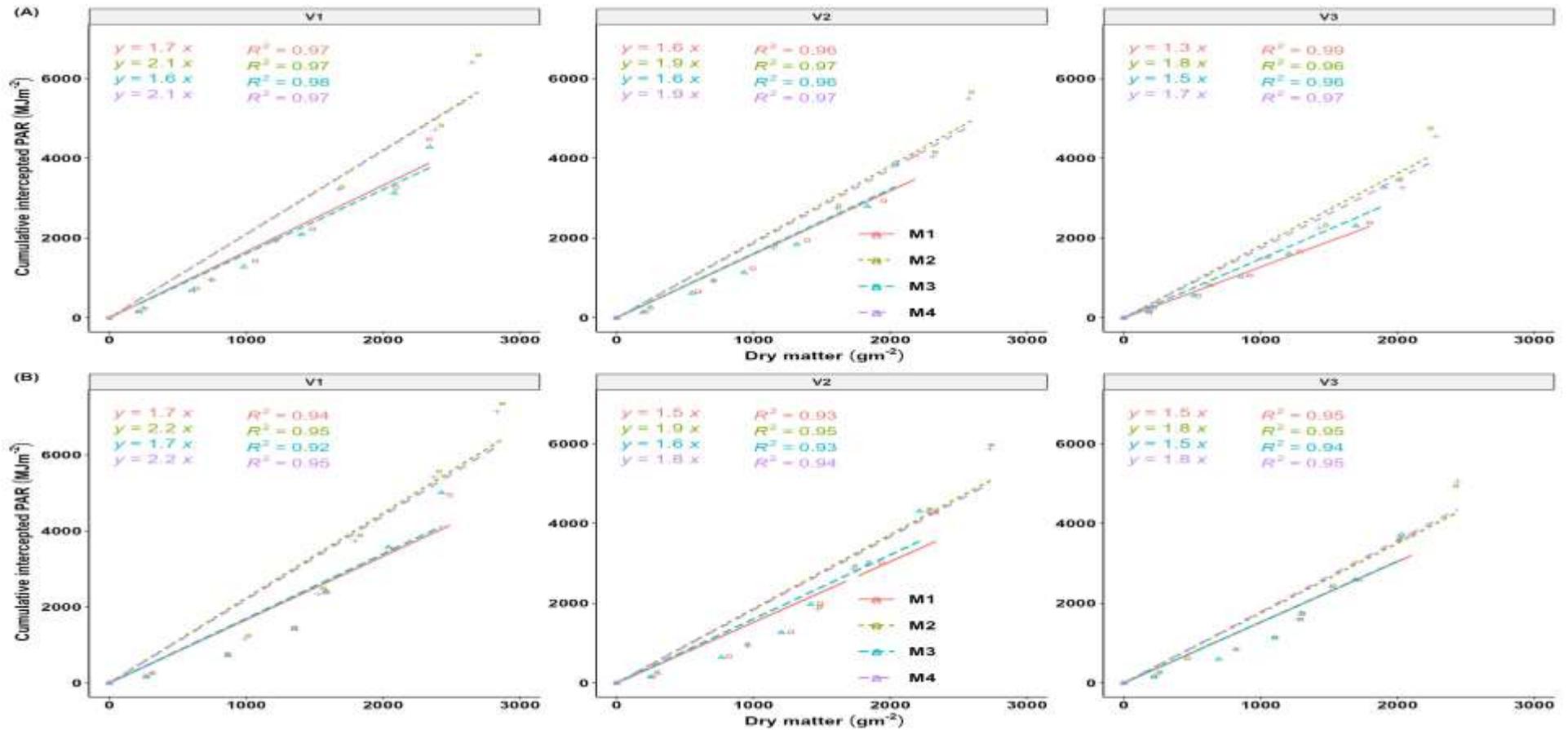


Figure 8: The relationship between the cumulative cassava biomass produced and cumulative amounts of intercepted photosynthetic radiation (IPAR) for different harvesting periods for the 2017/18 and 2018/2019 seasons, respectively (A-B) presents RUE for the 2017/2018 and 2018/2019 seasons. Each slope corresponds to radiation use efficiency (RUE) according to treatment effects. Key: M1 = lime application only, M2 = fertilizer and lime, M3 = no fertilizer and no lime (low input farmer practice) and M4 = fertilizer application. V1 = Mweru, V2 = Bangweulu and V3 = Katobamputa.

4.2.8 Response of cassava variety to Fertilization Regime

In comparison to unfertilized and limed treatments, dry matter accumulation to the root (harvest index-HI) was higher at all stages of fertilizer application (Figure 9). Nearly all harvest points showed a significant variation in how the varieties responded to fertilization. The growth curve for total HI was more related to a logistic growth function. HI is an important indicator of genotypic partitioning efficiency and followed a similar logistic trend until the last day of harvesting but there were no significant effects due to fertilization as differences were only reflected in varieties. Chlorophyll concentration index (SPAD) readings showed that chlorophyll increased with moisture and dropped drastically during the dry season (drought stress) before the rainy season but quickly increased to appreciable amounts until the last harvests.

Significant fertilizer \times variety interaction effects were observed over time and this trend was consistent across the two seasons of the experimental trial. Plant height increased with fertilization and influenced varietal plant height differentially across seasons (Figure 9). Overall observation indicated that variety Mweru had the highest fertilizer response followed by Bangweulu with the least being Katoba mputa (Local landrace).

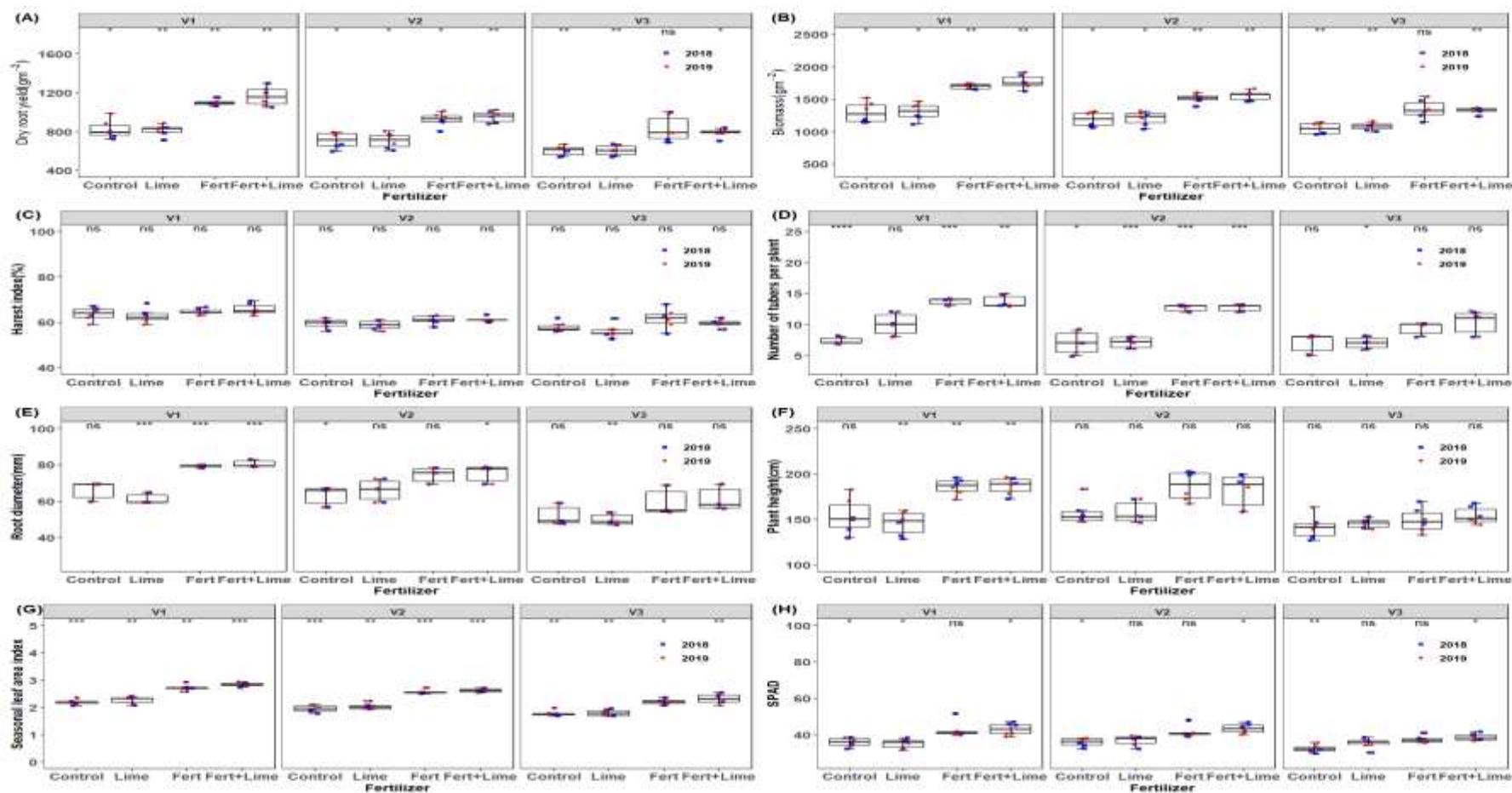


Figure 9: Box plots of (A) root yield and (B–G) are cassava yield components, and (H) is the green canopy trait of mean values per variety and season (2018 and 2019) for the different fertilization regimes (M1 = lime only, M2 = Fertilizer + Lime, M3 = no fertilizer, no lime (traditional low resource farmer management), M4 = Fertilizer only, V1 = Mweru, V2 = Bangweulu, V3 = Katobamputa. Significance codes are indicated for different treatment effects as 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05, ns: not significant above boxplots within the figure.

4.2.9 Effects of fertilization regimes on storage root yield and yield determinants of cassava varieties during the growing season

Phenotypic traits present dynamic combinations between various plant mechanisms that can easily be explained by correlations.

Fertilization had a significant net effect on the growth of cassava harvest index (HI), plant height and chlorophyll index (SPAD) across seasons and varieties (Figure 10). In addition, there was a significant increase in cassava HI, chlorophyll index (SPAD) and plant height on the fifth and sixth sampling dates with fertilization regimes of fertilizer + lime and fertilizer-only treatment indicating traits improvement in comparison to lime treatment and the control. However, with fertilization treatments M2 (NPK Fertilizer+lime) and M4 (NPK fertilizer only), V1 (Mweru variety) produced a significantly higher trait response compared to V2 (Bangweulu) followed by V3 (Katobamputa). Pellet and El-Sharkawy (1997) observed significant variation in varietal responses to fertilization for a study conducted on the hillside of Columbia under different fertilization regimes. From the results, it was observed that fertilization increased the cassava harvest index (HI), plant height and chlorophyll index (SPAD) across seasons and varieties and this indicates that cassava supplemented with NPK fertilization would increase growth and ultimate productivity of cassava.

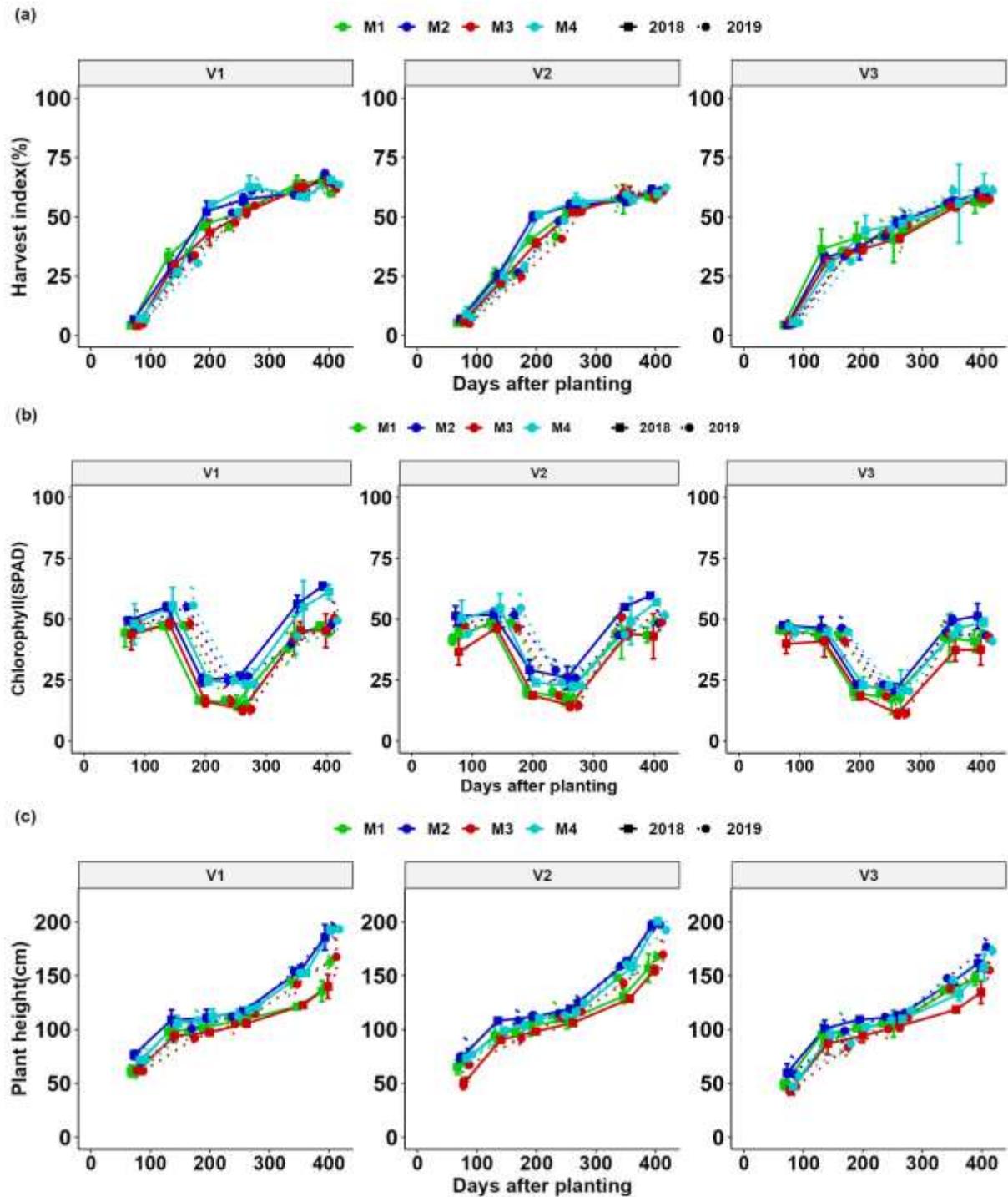


Figure 10: Line plots dynamics of (a–c) are: harvest index (%), SPAD and plant height (cm) are cassava yield components of mean values per variety at different fertilizer treatment management options. (M1 = liming only, M2 = Fertilizer + lime, M3 = no fertilizer, no lime (traditional low-resource farmer management) and M4 = fertilizer only for two seasons (2018 and 2019). V1 = Mweru, V2 = Bangweulu, V3 = Katobamputa are cassava varieties (clones).

Results indicated that HI and total plant biomass correlated strongly with storage root yield and explained more variation in storage root yield of cassava varieties regardless of fertilization regimes as indicated by the level of high accuracy of storage root yield prediction (Figure 11). In addition, plant height was positively correlated with storage root yield across fertilization regimes and varieties. The correlation was strong for plant height versus storage root yield, an indication that plant height is an indicator and a determinant of cassava storage root yield in these varieties. It was also observed that positive moderate correlation values were obtained for the number of storage roots per plant versus storage root yield. Variation across fertilization regimes and varieties are also reflected in fertilization with improved accuracy of prediction for storage root yield. In addition, we observed a consistent positive relationship across seasons for most traits and strongly correlated with cassava storage root yield (Figure 11).

Root diameter and storage root yield also revealed a stronger relationship from the positive regression curves across treatment effects (Figure 11). Storage root diameter may be used as a strong indicator (sink) in the determination of storage root yield. A strong correlation of storage root yield was observed with root diameter. A moderate correlation between the number of storage roots per plant and storage root yield was observed, an indication that varieties with a higher number of storage roots per plant will be beneficial for storage root yield increase, as suggested by Pellet and El-Sharkawy, (1993). In 2019, a weak correlation of SPAD with storage root yield was observed, while a positive and negative trend was observed in the 2018 growing season. Chlorophyll content values explained approximately up to a maximum of 4.9 % of the variation across the treatment effects in 2018 while a 9.4 % variation was observed across the treatments (Figure 11).

The application of NPK fertilizer significantly increased storage root yield, morpho-physiological traits and yield components of cassava. Significant variety responses were observed on biomass, stems biomass, HI, storage root diameter, number of storage roots per plant, plant height, seasonal LAI, light extinction coefficient (K) and SPAD to fertilization ($p = 0.05$). However, during the extended dry season, a sharp decline in SPAD, LAI and biomass production was observed (Figure 10). On average, a stronger genotypic increment in the variables studied here was associated mainly with fertilization regime: M2 (NPK fertilizer + lime) and M4 (NPK fertilizer) than M1 (lime) and (without lime nor NPK fertilizer) application.

The morphological and physiological traits were significantly and positively correlated with the storage root yield of cassava (Figure 11). For instance, fertilization increased mean LAI due to increased leaf size and resulted in a significant correlation with storage root yield across the seasons indicating the important role LAI plays in determining the storage root yield of cassava (Cock and El-Sharkawy, 1985). Cock, *et al.*, (1979) also found that the storage root dry yield of cassava was highly dependent on an incremental LAI of 3 to 4 during most of the growth period of cassava, implying that an increase in LAI improves storage root yield. In addition, our seasonal LAI was reflected in varieties V1, V2 and V3 in response to NPK fertilization, an indication that varieties responded inherently differently. It is noteworthy to underscore that the response curve follows an optimum curve, producing a decline in root yield when LAI passes beyond 4–5. Canopy structures such as leaf orientation, carbon fixation, assimilation as well as partitioning could be highly physio-genetic factors possibly influencing the storage root yield differences in varietal responses to fertilization regimes. Several other studies have identified HI as a vital trait with a stronger correlation with storage root yield in cassava, hence, recommended as a significant trait for storage root yield selection (Karim *et al.*, 2020; Omondi *et al.*, 2018; Alves, 2002; Kawano *et al.*, 1978). This implication means that

a higher yield can quickly be achieved by increasing sink storage root strength. However, in other studies modification of source characteristics such as photosynthetic capacity, LAI and RUE have been the key traits associated with an increased storage root yield (El-Sharkawy, *et al.*, 1990). This is in line with the study findings where LAI and RUE were critical for root yield (Tables 4 and 5). This study also confirms the importance of HI in root yield determination under fertilized and unfertilized conditions for cassava grown under rain-fed conditions with a high degree of accuracy (Figure 11A).

Source activity such as RUE, a carbon fixation-related trait, and storage root yield showed a significant and positive correlation in this study (see Table 3). In addition, RUE, mean LAI and tuber number strongly contributed to cassava yield, stem yield and biomass among influential traits (see Table 4). El-sharkawy and Tafur, (2014) and El-Sharkawy *et al.*, (1990) found a similar relationship between source activity (net photosynthesis) versus storage root yield in a wide range of cassava varieties grown in optimal soil conditions. In addition, positive significant correlations for the number of storage roots per plant and root diameter versus storage root yield were observed across seasons (Table 3). Fertilization had a significant positive effect on the number of storage roots and root diameter, although the factors responsible for this observation were unclear. These findings are in agreement with Pellet and El-Sharkawy. (1993), whose findings relate to this study outcome. In cassava, it appears that certain conditions can be a sink limitation where the storage root number is considered as a sink strength indicator. Sink limitation occurs at less than nine storage roots per plant, though this number is roughly lower than the ten storage roots per plant that we found to be the varietal mean in this study (Cock *et al.* 1979). This shows that the study's varietal ability to effectively use assimilates and produce the essential dry matter. Additionally, it was found that the number of storage roots per plant increased incrementally in response to fertilizer use in cassava varieties (Figure 11). This could be an indication that varietal yield responses to NPK depend

on the optimum balance between sink and source. Similar results were obtained when cassava varieties were observed in response to different P fertilizer levels (Pellet and El-Sharkawy, 1993a) Stem dry matter, mean LAI, RUE and tuber number per plant were important factors in determining the root yield of cassava . Biomass was strongly influenced by root yield, SPAD, leaf matter, HI mean LAI, tuber number and RUE ($p < 0.001$, $R^2 = 0.99$).

For Stem yield, the most significant contributing factors were root yield, leaf matter, SPAD (chlorophyll), harvest index (HI), plant height (PH), root diameter, mean LAI, tuber number and RUE ($p < 0.001$, $R^2 = 0.99$)

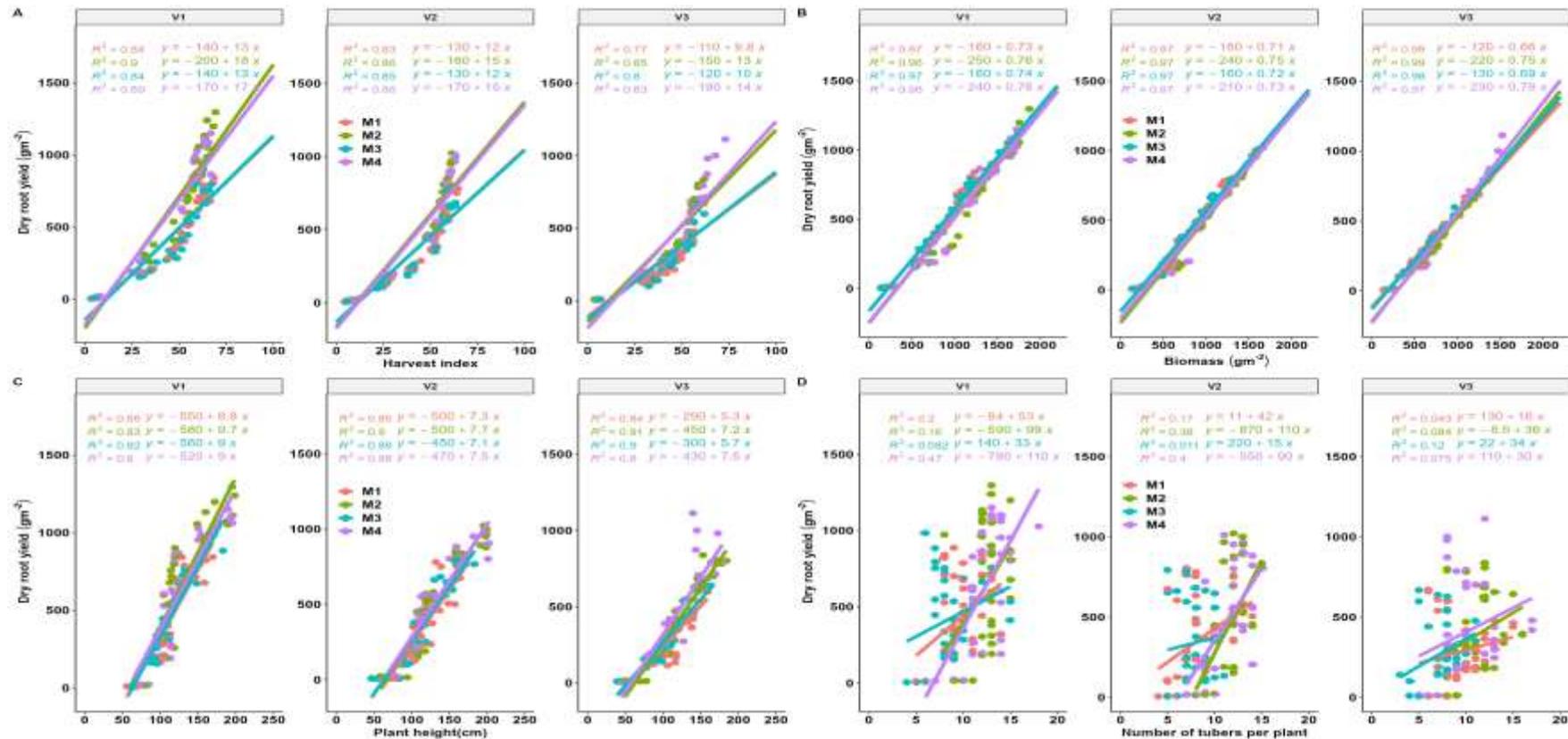


Figure 11: Regression plots between dry root yield and selected yield components (A–F) present correlations of dry root yield versus HI (harvest index), biomass, plant height, number of tubers per plant, root diameter and SPAD. M1 = lime only, M2 = fertilizer + lime, M3 = no fertilizer, no lime (traditional low resource farmer management), M4 = fertilizer only as different fertilization regimes. V1 = Mweru, V2 = Bangweulu, V3 = Katobamputa as varieties

4.3.0 CONCLUSION

This study showed that applying NPK fertilizer + lime or NPK fertilizer only treatments significantly resulted in higher yield when compared to lime or the control in cassava cropping systems. Furthermore, the study revealed that RUE, Mean LAI and number of tubers per plant were the most yield determinant factors in cassava. All varieties responded similarly to the application of NPK fertilizer + lime, NPK fertilizer, lime and the control treatments. Lime did not exhibit significant effects mainly due to high acidity and high rainfall experienced during the rainy season however long term application could be known to be effective on crop responsive. This implies that long term application could be sort in the high rainfall areas of northern Zambia.

These results show the importance of integrated soil fertility management (ISFM) in achieving higher root yield, physiology and morphological traits under rain-fed conditions in Chromic haplic Acrisol low-nutrient soils in the northern belts of Zambia. The study highlights the importance of an improved variety of use and fertilization as a way of improving cassava yields in nutrient-exhausted soils.

Further, a cassava yield advantage of 57.79%.was achieved when the highest-yielding improved variety (V1) with NPK fertilizer and lime treatment was applied compared to using low-yielding variety (V3) without fertilizer or lime. These results give hope to farmers intending to raise cassava productivity using balanced NPK fertilization and improve productivity through the use of high-yielding varieties in just 12 months after planting. The cost of fertilizer is only half of the additional revenue through increased yields, therefore the Governments are urged to support fair pricing of fertilizer and promotion of extension services on fertilizer use in cassava as they aim to reform the agricultural sectors. In addition, fertilization could help farmers harvest cassava early and increase their profitability due to

reduced time to maturity (early bulking) hence the need to consider cassava as a strategic crop in the Farmer Input Support Programme (FISP). In conclusion, NPK fertilizer + lime and NPK fertilizer treatments should be adopted to increase the response of cassava varietal yield, physiology and morphological traits in low soil nutrient conditions under high rain-fed conditions.

CHAPTER FIVE

5.0 CASSAVA VARIETAL RESPONSE TO FERTILIZATION

5.1 INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is an efficient tropical root crop in terms of the amount of energy production per unit of land (Cock, 1982), and in the absence of production constraints, it compares favourably with other major staple food and energy crops grown in the tropics (El-Sharkawy, 1993). Even, under adverse conditions (low fertility soils and prolonged water stress), cassava still yields reasonable yields where other food crops like maize (*Zea mays*) and sorghum (*Sorghum bicolor*) would likely fail (Howeler, 2017; Cock and Howeler, 1978). Due to the potential of cassava to produce under adverse edaphic and climatic conditions, increasingly more marginal land is being used for its production in Africa, Asia and Latin America (Aye and Howeler, 2017; El-sharkawy, 1993; Howeler, 1991). Cassava production is mainly dominated by resource-limited smallholder farmers on low-fertility acid soils (mainly Oxisols and Ultisols) with virtually no agrochemical inputs (Onasanya *et al.*, 2021; Cock, 1985; Howeler, 1981). Additionally, because of land pressure and sub optimal agronomic practices, farmers frequently grow cassava on the same plot of land for several years without fallow, rotation, or fertilization. These agricultural management practices lead to a gradual decline in soil fertility and yield (Howeler, 2000; Cadavid, *et al.*, 1998; Pellet and El-Sharkawy, 1993). In such circumstances, the application of chemical fertilizer, organic manure, and plant residues are desirable practices to maintain soil fertility and thereby sustain crop productivity (Biratu *et al.*, 2018b; Cadavid, *et al.*, 1998; Pellet and El-Sharkawy, 1993). Due to the heavy nutrient consumption of cassava, which removes significant amounts of nutrients from the harvested roots, particularly potassium (K) (Pellet and El-Sharkawy, 1997; Howeler, 1985), soil K would become depleted without the application of mineral fertilizers under continuous cultivation.

When cassava was grown continuously for several years in the same plots/fields, various studies have shown significant responses to K fertilization in different soils (Pellet and El-Sharkawy, 1997; Howeler, 1991) (Pellet and El-Sharkawy, 1997; Howeler, 1991). Cassava is known as a heavy nutrient feeder and removes substantial amounts of nutrients, particularly K, in the harvested roots and without application of mineral fertilizers under continuous cultivation, soil K would be depleted. Several studies have shown significant responses to K fertilization in different soils when cassava was grown continuously for several years in the same plots/fields. Furthermore, Pellet and El-Sharkawy. (1997 reported genetic differences in K use efficiency among four varieties, which implied that genetic diversity in response to K exists within cassava germplasm. Nitrogen (N) is one most important nutrients of the macro-elements in modern farming despite it's ever increasingly costly and is cannot be substituted by farmers. Nitrogen deficiency in plants is exhibited through the cessation of leaf elongation (Marschner and Marschner, 2012), inhibit photosynthesis (Gregoriou, *et al.*, 2007) reduces chloroplast size (Li *et al.*, 2013) and consequently minimizes overall growth. N has an irreplaceable role in organ construction, material metabolism, fruit yield, and the quality formation of fruit trees(Xu *et al.*, 2020). Cassava yield can be limited by phosphorus (P) supply and is for root growth, yield formation as well as overall dry matter(Pellet and El-Sharkawy, 1993). In addition, potassium also plays a critical role in plant growth. K plays a vital role in nitrogen metabolism, both elements being widely applied as fertilizers in agricultural production (Xu *et al.*, 2020). The northern part of the country is mainly dominated by soils with high Acidity and low P availability soils that possess threat to cassava yield (Kaluba *et al.*, 2021).

In light of this, it is imperative to assess and select cassava varieties that can grow in low-fertility soils with enhanced response NPK fertilizer application in Zambia. Such varieties should be used

as genomic sources in cassava breeding programmes designed to improve yield and sustain productivity without increasing pressure on the already exhausted soils (Rosa *et al.*, 2021)

The main objectives of this study were to evaluate the response of selected Zambian cassava varieties to NPK fertilization and identify those varieties that tolerate low-nutrient soils while responding to NPK fertilization.

Improve cassava productivity and yield responses in cassava-based cropping systems

Specific objectives

- i. To determine the effect of fertilization regimes on the performance of cassava varieties on physiological traits, yield, and yield components in Zambia.
- ii. To determine the effect of NPK fertilizer application on the growth of cassava growth of three different varieties in the Chromi-Haplic Acrisols Soils prevalent in the area.

Hypotheses

- i. Fertilization regimes has no effect on physiological traits, yield, and yield components of cassava varieties in Zambia
- ii. NPK fertilizer application does not increase the performance of cassava growth of three different varieties in in Chromi-Haplic Acrisols soils

5.3 RESULTS AND DISCUSSION

5.2.1 Effect of fertilization regimes on yield and yield components of selected cassava varieties

Significant differences in fertilization regimes and varieties were observed in dry root yield, biomass, root diameter, plant height, and seasonal LAI, except for the harvest index. There were significant interactions reflected in varieties for biomass, root yield, harvest index plant height, seasonal LAI and Chlorophyll index (SPAD). Additionally, significant differences were observed for fertilizer and genotypic interaction, plant height, and SPAD across the two growing cycles ($p < 0.05$) (Table 5). Across seasons (year) an increase in yield of 27 and 28% was observed due to fertilizer and variety, respectively. The mean root yield was higher in 2019 than in the 2018 season (Table 6). Further, a yield advantage in both years of 23.9 and 27.02% in the 2018 and 2019 seasons, respectively, was attained as a result of NPK fertilization. The interaction of variety and the growing season was observed for the HI. With the exception of harvest index and seasonal LAI, all traits showed interaction between fertility and year. The storage root yield in 2019 compared to 2018 was approximately 7.36% higher across all treatment effects. Better crop establishment and consistent rainfall during the 2019 season are likely factors for this difference (see Figure 2). There were no significant differences observed in the fertility \times variety \times year interaction effect. Plant height was slightly higher in 2018 compared to 2019 across treatments while the fertilizer-by-variety interaction effect was also observed. Application of NPK notably has shown to promote cassava storage root yields as reported in recent studies (Biratu *et al.*, 2018; Ezui *et al.*, 2017b). In farming and agriculture, N is a crucial yield promoter for all crops.

Table 5: Linear Mixed model ANOVA for fertilization, variety, year and their interaction effects on yield physiology and morphological traits

Source	DF	Den DF	Seasonal LAI	Stem yield	Root Yield	Biomass	Harvest Index	Root Diameter	Plant height	Chlorophyll
Rep	2	22	0.007	3094	2476	3809	3.203	48	35.7	6.57
Fertility	1	22	0.024***	3954***	105472***	177858***	18.792**	325***	2444.9***	47.012**
Variety	2	22	0.0004***	647ns	124318***	150571***	86.778***	412.6***	3877.4***	90.764***
Year	1	24	0.017ns	51570***	67436***	288787***	16.392**	1270.42***	178ns	21.184*
Fert:variety	6	22	0.008***	2409***	2633ns	3685	2.173ns	61.75***	469.2**	9.379*
Fert:Year	3	24	0.024**	3553***	8702*	20090***	3.392ns	120.26*	1218.3***	43.073***
Variety:Year	2	24	0.016***	3874***	5615ns	4000ns	29.372*	361.8***	749.3**	10.83ns
Fert:var:Year	6	24	0.008ns	2414***	1592ns	4210ns	1.032ns	61.89ns	44.5ns	0.939ns

Significant codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05, ns: not significant, V1: Bangweulu, V2: Mweru and V3: Katobamputa. Values in the column followed by the same letter are not statistically different by Tukey's honest significance test.

Table 6: Cassava yield and biomass as affected by the different fertilization regimes and variety averaged across two growing seasons (2017/2018 and 2018/2019)

Treatments		Traits			
Fertilization Regimes	Variety	Fresh Root Yield (gm ⁻²)	Dry Root Yield (gm ⁻²)	Fresh Biomass (gm ⁻²)	Dry Biomass (gm ⁻²)
Control	V1	1891ab	823ab	3044a	1297a
	V2	1658ab	711ab	2766ab	1190ab
	V3	1370b	604a	2398b	1047b
Fertilizer only	V1	2834bc	1097c	4340e	1699bc
	V2	2242cd	923bc	3628cde	1511cd
	V3	2363b	827b	3669de	1341d
SE(Fertilizer)		101.6 **	22.2 ***	97.7 ***	25.2 ***
SE(Variety)		73.1 ***	19.3 ***	74.3 ***	19.9 ***
SE(Fertilizer× Variety)		156.8 ns	38.6 ns	155.8 ns	41.13 ns

Significant codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05, ns: not significant,

V1: Bangweulu, V2: Mweru and V3: Katobamputa.

Values in the column followed by the same letter are not statistically different by Tukey's honest significance test.

5.2.2 Effect of NPK fertilization on the storage root and yield determinants of cassava varieties

Phenotypic traits present dynamic combinations between various plant mechanisms that can be explained by correlations. HI and total plant biomass correlated well with storage root yield and explained more variation in storage root yield of cassava varieties regardless of fertilization regimes as indicated by the level of high accuracy of storage root yield prediction (Figure 12). It was established that at a given HI, increasing biomass increased yield. In addition, plant height showed a high positive correlation with storage root yield across fertilization regimes and varieties. Strong correlations between plant height and storage root yield suggest that plant height in these varieties is both a predictor and an indicator of storage root yield for cassava. Additionally, it found that the majority of traits showed consistent positive relationships across seasons and were strongly correlated with cassava storage root yield (Figure 12A–D)

Furthermore, it was noted that a that NPK fertilization significantly increased all important plant traits such as root yield, plant height, chlorophyll index (SPAD), seasonal LAI, harvest index and biomass in comparison the control (Figure 13).

Plant height and storage root yield also revealed a stronger relationship from the positive regression curves across treatment effects (Figure 12C). Storage root number may be used as a strong indicator (sink) in the determination of storage root yield. A moderate correlation between the number of storage root number per plant and storage root yield was observed, an indication that varieties with a higher number of storage roots per plant will be beneficial for storage root yield increase, as suggested by Pellet and El-Sharkawy, (1993).

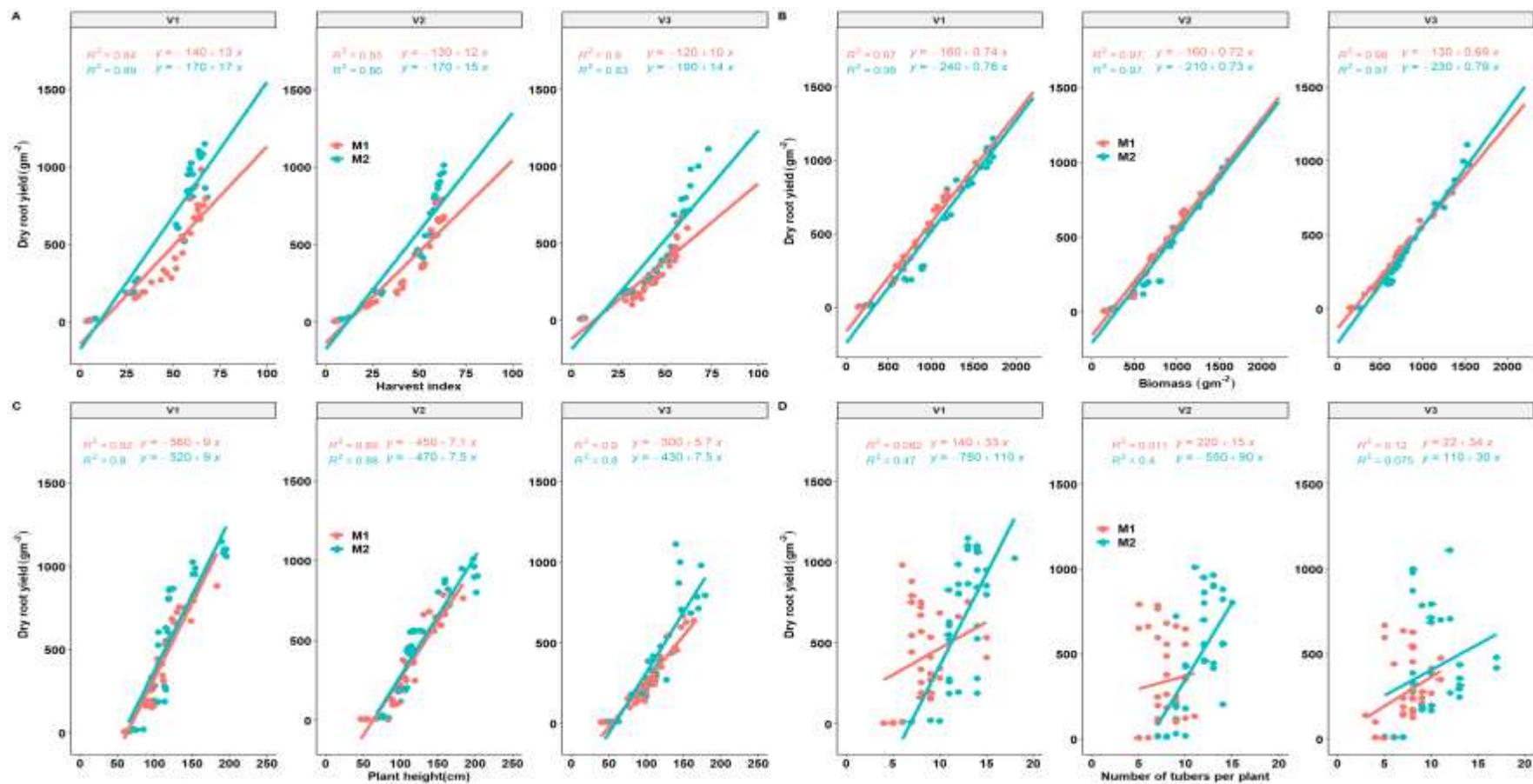


Figure 12: Regression plots between dry root yield and selected yield components (A–D) present correlations of dry root yield versus biomass, plant height, and number of tubers per plant. M1 = no lime (traditional low resource farmer management) and M2 = NPK fertilizer only fertilization regimes. V1 = Mweru, V2 = Bangweulu, V3 = Katobamputa are different varieties.

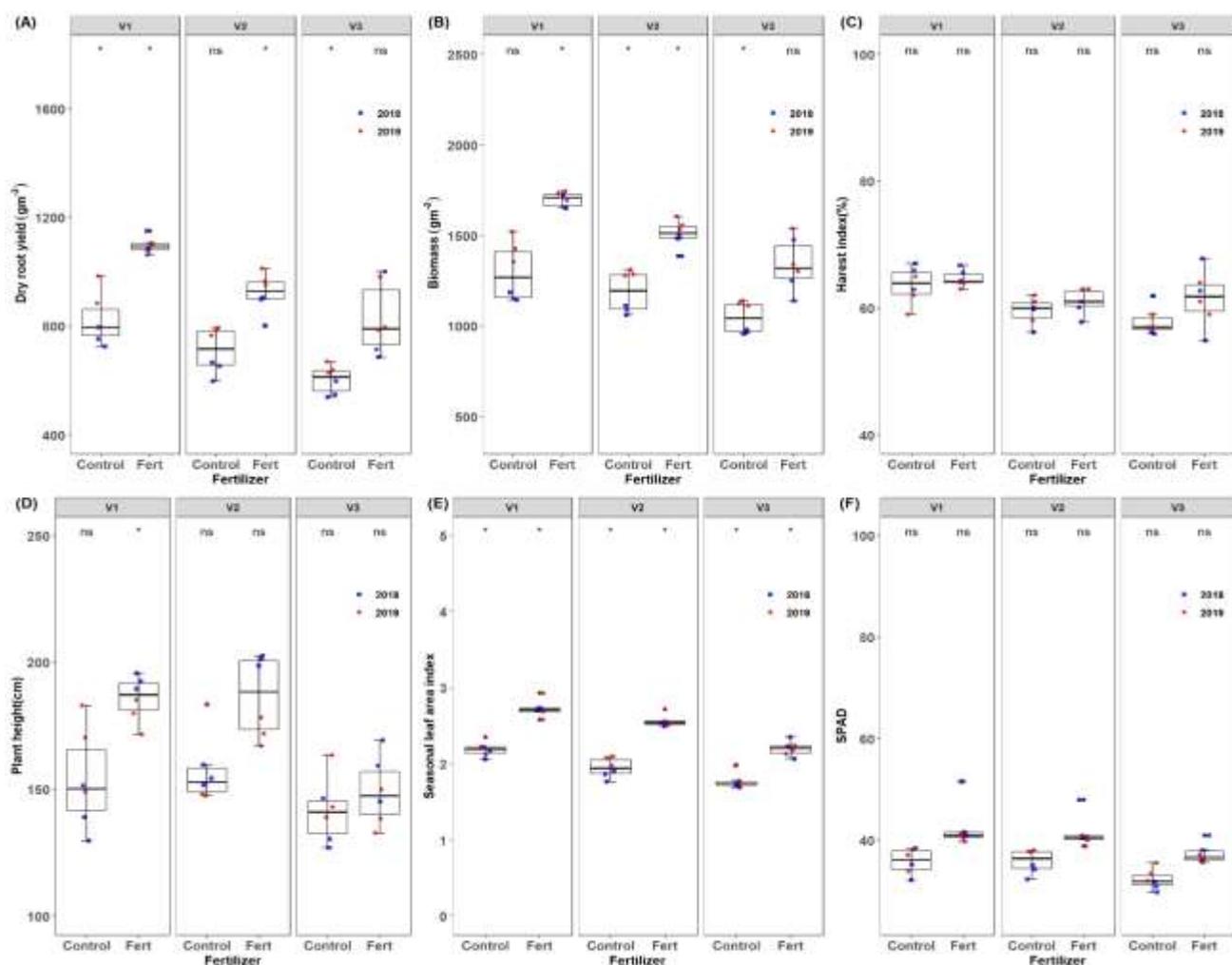


Figure 13: Box plots of (A) root yield and (B–E) are cassava yield components, and (F) is the green canopy trait of mean values per variety and season (2018 and 2019) for the two fertilization regimes (M1 = Control-no lime (traditional low resource farmer management), M2 =NPK Fertilizer M3 = no fertilizer, V1 = Mweru, V2 = Bangweulu, V3 = Katobamputa. Significance codes are indicated for different treatment effects as 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05, ns: not significant above boxplots within the figure.

5.2.3 Effect of NPK fertilization on light extinction coefficient and solar radiation use efficiency among different varieties

In both the first and second cropping cycles, fertilization only significantly increased of the value K in Mweru and Bangweulu (Table 6). This suggested better leaf positioning/exposure, possibly as a result of variations in leaf curving and leaf angles among varieties, which resulted in higher light interception for the same LAI. Variations in RUE, which demonstrates how plants convert light energy into plant biomass, did not reflect the differential varietal responses to K values. Biomass formation is a more complex process which involves not only light interception through the canopy but also net carbon fixation through photosynthesis. All varieties showed a significant increase in RUE in response to fertilization. These results are in agreement Adiele *et al.*, (2021) findings whose average fraction of light intercepted during the season was 80 %, with a light extinction coefficient of 0.67 and a RUE of 2.8 g DM MJ⁻¹ intercepted photosynthetically active radiation (IPAR). Similar findings were obtained in canopies with full ground cover and had more than 90% of the incident radiation intercepted by the top half giving light extinction (K) coefficients ranging from 0.59-0.76 (Fukai *et al.*, 1984). Ezui, *et al.* (2017) found that increased cassava yields in West Africa were achievable under rain-fed conditions through enhanced potassium management to increase RUE and water use efficiency (WUE), along with sufficient nitrogen supply for improved light interception and water transpiration by the crop.

5.2.4 Effect of NPK fertilization on leaf area index and light interception dynamics

For each variety and growing season, LAI development and light interception were slow, taking up to four to six months to reach maximum values, parallel with the first rain peak between December and January then decreasing rapidly (Figure 14). This corresponded to a drier period of the year and plants reacted by reducing aerial growth, thus limiting plant transpiration. In the second growing season particularly between six and eight months after planting, some leaf

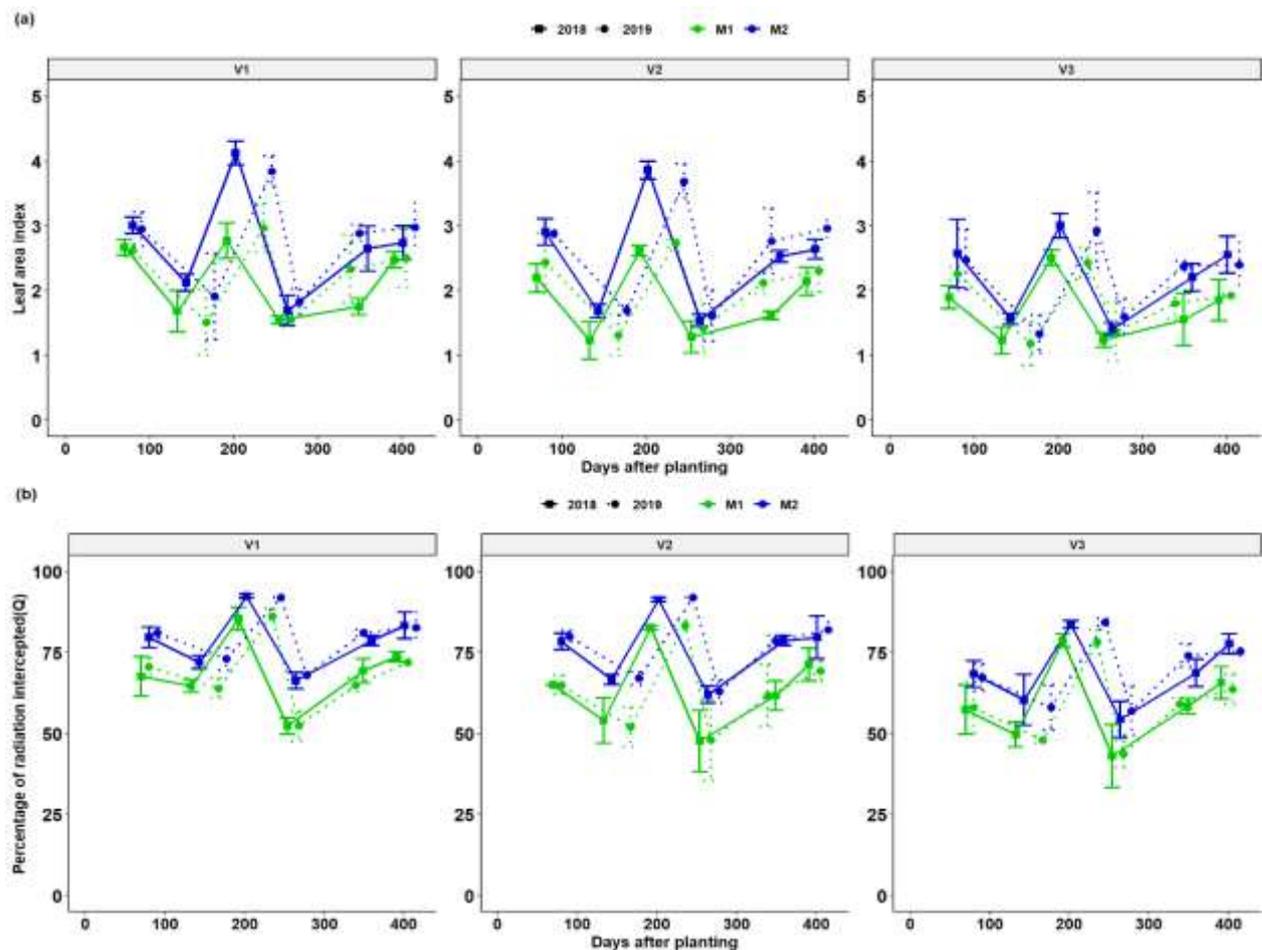


Figure 14: Leaf area index (a) and fraction light interception (b) dynamics of different cassava varieties as affected by two different fertilizer regimes. Key: M1 = Control- no lime (traditional low resource farmer management), M2 = NPK fertilizer = V1 = Mweru, V2 = Bangweulu and V3 = Katobamputa during the two agricultural seasons 2018 and 2019.

regrowth was observed making use of the second short rainy period, mainly in fertilized plants of Mweru and Bangweulu. Although unfertilized cassava plants developed a smaller LAI and captured low light interception in comparison to fertilized plants, particularly in the first growing season (2018), all varieties exhibited a similar pattern of canopy growth and a light interception with a high value after a few months of growth, a sharp decrease and final regrowth. This finding corresponded with the general pattern described by (Cock, 1985) and this approves the well-known trend for balanced fertilization to stimulate LAI growth (El-Sharkawy *et al.*, 1990a; Cock and El-Sharkawy, 1988). In cassava, the importance of the

canopy for yield formation has been demonstrated by many authors (Cock *et al.*, 1979; Cock and El-Sharkawy, 1988; Pellet and El-Sharkawy, 1993). LAI values observed in the present studies remained suboptimal for sustaining the cassava yield potential (Cock *et al.*, 1979), including those under NPK fertilization. No Varietal differences in LAI development were observed in response to fertilization except in seasonal LAI differences were significant. Light interception development did not vary among varieties for fertilization. This is because varieties responded similarly in LAI and light interception along the growth path as each season only varying in seasonal performance. Mweru and Bangwelu have close plant architecture except for katoba mputa which is slightly open. Pellet and El-Sharkawy. (1997) found that there were no significant variations in leaf area index (LAI) development among contrasting cassava varieties and this tallies with the study finding. .

5.2.5 Effect of NPK fertilization on total dry matter (TDM) and root dry matter (RDM) during the growing season

In contrast to canopy development, storage root biomass was almost non-existent in the first two months after planting, and root growth was limited to the fibrous root system (Figure 15). Four months after planting when canopy development had almost reached its maximum, the dry weight of the storage root was only about 20-30% of the final yield in fertilized plants. Effects of fertilization were obvious at six months after planting in the first growth cycle and at four months after planting in the second cycle. With fertilization, Mweru and Bangweulu produced significantly higher final root yields than Katoba mputa (Mwamba *et al.*, 2021)). These two varieties also had the strongest response to NPK fertilization, differences being almost three-fold between fertilized and non-fertilized plants across seasons. Over the two years, fertilized plants of each variety produced comparable final yields, but much higher yields than that of unfertilized plants indicating that judicious fertilization is necessary to maintain soil fertility and yield in cassava-based cropping systems (Howeler, 1991).

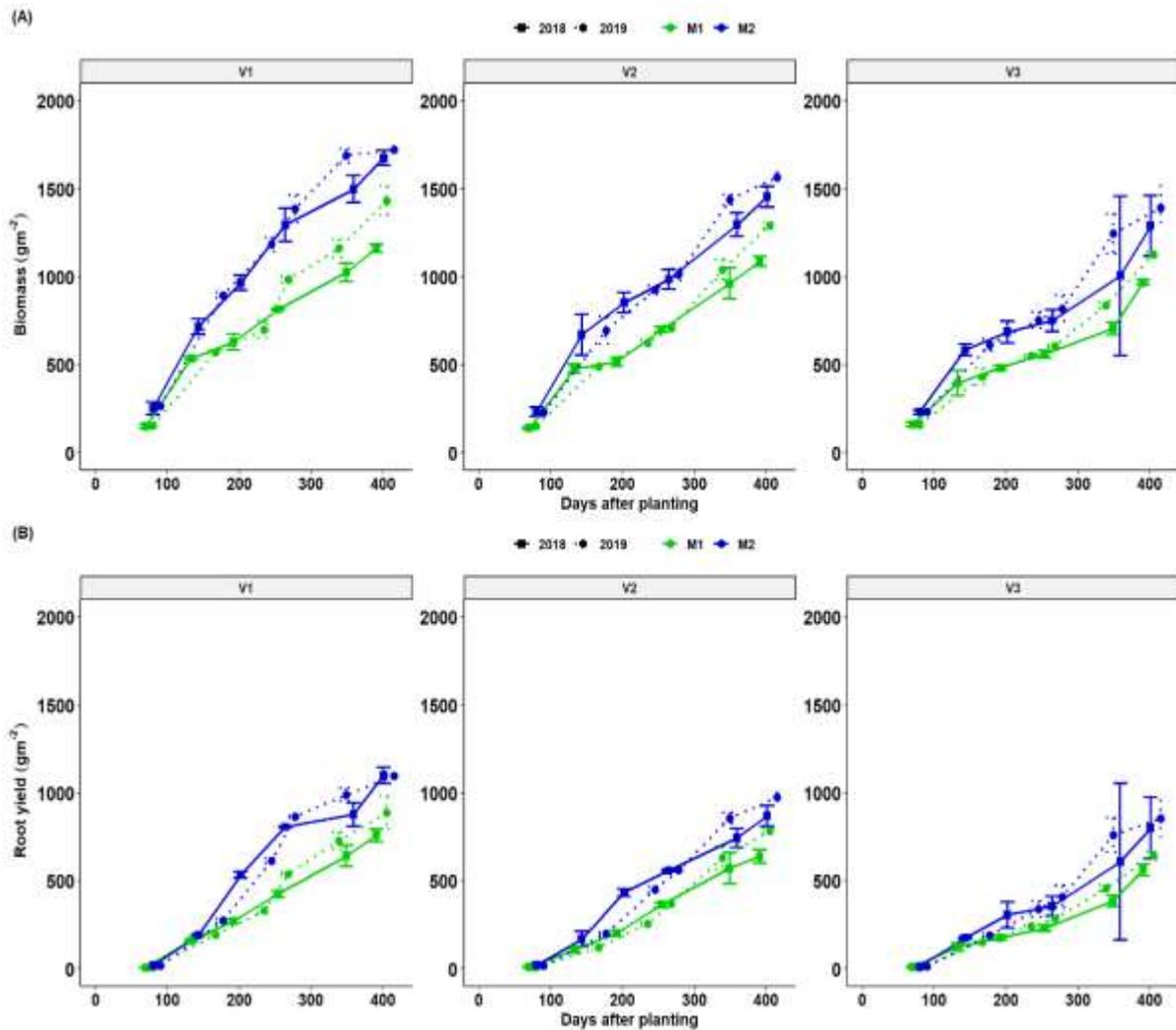


Figure 15: Biomass (TDM-total dry matter) (a) and root yield (RDM-root dry matter) (b) dynamics of different cassava varieties as affected by two different fertilization regimes. Key: M1= no fertilizer and no lime (low input farmer practice) M2 = NPK fertilizer application only. V1 = Mweru, V2 = Bangweulu and V3 = Katobamputa during the two agricultural seasons 2018 and 2019.

5.2.6 Effect of NPK fertilization on the extinction coefficient and solar radiation use efficiency in three cassava varieties

In the first crop cycle, fertilization significantly raised the value of the light extinction coefficient in the Mweru and Bangweulu varieties (Table 7). This showed higher light interception for the same LAI because of better leaf positioning, possibly as a result of differences in leaf curving and leaf angles among varieties. These differential varietal responses for light extinction coefficient (K) values were not reflected in variations of radiation use efficiency (RUE), an indication of how plants transform light energy into plant biomass. Biomass formation is a more complex process which involves not only light interception through the canopy but also net carbon fixation through photosynthesis. All varieties showed a significant increase in RUE in response to fertilization (Table 7), as a direct effect of increased LAI with fertilization. Fertilized plants of Mweru and Bangweulu showed the highest RUE values, compared with Katoba mputa the local landrace. As observed by Pellet and El-Sharkawy. (1993) CM 489-1 had the highest single-leaf photosynthesis compared with the other three varieties, and also responded positively to fertilization. This could explain why the variety Mweru could offset its comparatively low light extinction coefficient and have high radiation use efficiency.

Table 7: Effect of fertilization on the extinction coefficient (K) and solar radiation use efficiency (RUE) in three cassava varieties as a direct effect of increased LAI with fertilization.

Treatments									
Fertilization Regime	Variety	RUE (2018)	RUE (2019)	Mean RUE	K	K	Mean K	R^2	R^2
		(gMJ-1)	(gMJ-1)	(gMJ-1)	2018	2019		2018	2019
M1(Control)	V1	1.6	1.7	1.65	0.57	0.53	0.55	0.98	0.92
	V2	1.6	1.6	1.6	0.59	0.52	0.555	0.96	0.93
	V3	1.5	1.5	1.5	0.55	0.5	0.525	0.96	0.94
M2(Fertilizer)	V1	2.1	2.2	2.15	0.61	0.61	0.61	0.97	0.95
	V2	1.9	1.8	1.85	0.6	0.61	0.605	0.97	0.94
	V3	1.7	1.8	1.75	0.55	0.56	0.555	0.97	0.95
Min		1.5	1.5	1.5	0.55	0.5	0.525	0.96	0.92
Mean		1.7	1.73	1.715	0.57	0.55	0.56	0.97	0.94
Max		2.1	2.2	2.15	0.61	0.61	0.61	0.98	0.95

Fertilized plants of Mweru and Bangweulu showed the highest RUE values, compared with Katobamputa. As observed by Pellet and El-Sharkawy, 1993b, CM 489 had the highest single-leaf photosynthesis compared with the other three varieties, and also responded positively to fertilization. This could explain why Mweru could offset its relatively low light extinction coefficient and have high radiation use efficiency.

5.3 CONCLUSION

Cassava-based cropping systems can affect soil fertility through heavy nutrient export through continuous cultivation. The current study demonstrates how varieties do respond to low-nutrient soils and with an improved variety response to fertilization. Parameters related to aerial growth showed that in improved varieties, differences in canopy growth were reflected in soil fertility. Additionally, the use of NPK fertiliser revealed notable differences in performance between improved varieties bred for high yield and conventional landrace varieties. The improved varieties exhibited a much superior response compared to the landrace variety. The enhanced traits and increased adaptability of improved varieties have consequential advantages, including higher responsiveness to NPK fertilisation and reduced time required for crop maturation. Hence, it is imperative to take into account the genetic variability and significant physiological features in the selection of cassava varieties that exhibit enhanced production responses aligned with diverse cropping practises in Zambia.

CHAPTER SIX

6.0 THE EFFECT OF FERTILIZATION AND LEAF HARVESTING ON GROWTH, YIELD, PHYSIOLOGY AND YIELD COMPONENTS OF ZAMBIAN CASSAVA VARIETIES

6.1 INTRODUCTION

Cassava (*Manihot esculenta*) is an important calorie-rich food crop in the tropics after cereals rice and maize feeding millions of people from Asia, Africa and Latin America (Prakash, 2013). According to FAO 2018, world production of cassava was around 292 million tonnes in 2018. Cassava is ranked as the second staple food crop in Zambia after Maize with >75% of farm households growing cassava in the Agro-Ecological Region 3 (AER3) and 15% of overall cultivation at the country level (Alamu, *et al.*, 2019, Kabwe, 2014, Arega *et al.*, 2013 Haggblade and Nyembe, 2007 and Barratt *et al.*, 2006). Its ability to thrive under wide edapho-climatic stresses makes cassava to be cultivated in poor soils with minimal or no inputs of fertilizer and pesticides, resulting in very low yields (< 12 ton ha⁻¹ fresh storage roots), as compared to its high potential productivity (> 80 ton ha⁻¹) attainable in a favourable environment (El-Sharkawy, 2006, Howeler, 2001, El-Sharkawy, 1993 and Howeler, 1991). This makes cassava a more suitable pro-poor crop for the over 250 million population for food consumption and production in Sub-Saharan Africa (Philips *et al.*, 2006). According to FAOSTAT (2019), the average cassava storage root yield in Zambia from 2013 to 2017 was projected to be 5.8 ton ha⁻¹ is significantly lower than the experimental yields of 15.5 ton ha⁻¹ achieved without the use of fertiliser by Biratu. (2018).

In Luapula province, cassava production predominantly follows a shifting cultivation practise, commonly known as ‘slash and burn’. This practise may exert significant stress on land resources and has adverse effects on the environment due to prolonged time required for natural vegetation to regenerate, resulting in soil erosion. This ultimately results in a decrease in critical mineral elements, especially potassium (K), which is a necessary element for cassava growth

and this trend. Crop yields of cassava in the Northern and Luapula Provinces of Zambia are adversely affected from decreased K (Sumithra, *et al.*, 2013; Howeler, 2012 and Howeler, 1991). In cassava production K is a key fertilizer element and a determinant of storage root yield by playing a role in root bulking in cassava productivity (Howeler, 2009). In addition, farmers harvest cassava storage roots by uprooting the whole plant materials (stems, leaves and roots) from the ground and either throwing away stems and leaves or burning them after drying. This method of harvesting cassava results in serious soil nutrient mining and the destruction of soil's physical properties (Howeler, 2012; 1991). Despite all this, cassava is continuously grown with minimum or no inputs such as fertilizers of Nitrogen (N), Phosphorous (P) and Potassium (K) in Luapula Province. To increase cassava yields, mineral fertilizers may be required for optimal cassava yield in the AER3 of Zambia where Nitrogen, Potassium and Phosphorous are in short supply (Biratu, 2018).

Cassava storage roots are a potential valuable energy source, while their leaves offer significant nutritional benefits in the form of protein, vitamins, and minerals for both humans and livestock (Montagnac *et al.*, 2009). Due to their high crude protein content (29.3% to 32.4% of dry weight), cassava leaves contribute significantly to human nutrition. Additionally, they provide a valuable source of energy, as well as vitamins A, B1, B2, and C.(GRZ, 2009; Montagnac *et al.*, 2009; Awoyinka *et al.*, 1995; Lancaster and Brooks, 1983). Although most African countries consume cassava in their daily diets, little is known about its leaf vegetable usage in Africa, except for the Democratic Republic of the Congo (DRC). (Munyahali *et al.*, 2017 and Liu *et al.*, 2014). In Zambia cassava is mostly consumed for its leaves, as a snack and as flour for preparing meals such as nshima (Alamu *et al.*, 2019).

Leaf harvesting for cassava vegetables in Luapula province is done throughout the cassava cropping season once the plants form a considerable leaf canopy. The leaf harvesting is done

at high intensity especially off-season when the demand for vegetables is high as other rain-fed seasonal vegetables are not available. Recent studies indicate that leaf harvesting increases cassava vulnerability to cassava mosaic disease (CMD) which negatively affects the yield of storage root tubers (Ariyo, *et al.*, 2003).

Munyahali *et al.*, 2017, reported that harvesting of tender leaves resulted in minimal effects on cassava growth and yield while NPK fertilization increased both growth and yields regardless of leaf harvesting frequency. Other reports about leaf harvesting frequencies have been documented on the intensity and frequency of leaf harvesting (Phengvichith, *et al.*, 2006; Lutaladio and Ezumah, 1981; Dahniya and Leone, 1974) and reported a decrease in yield regardless of cassava variety. Consequently, a 2-3-month interval of leaf harvesting was recommended for the attainment of optimal yields. In addition, leaf harvesting reduces plant canopy and negatively affects the leaf area index (LAI). A higher LAI is key to achieving the potential yield of cassava and has been shown to have a high positive correlation with total dry biomass, above-ground biomass, and storage root yield (El-Sharkawy *et al.*,1992, El-Sharkawy and de Tafur, 2010; Pellet, 1992). The consequences of reduced LAI result in reduced light interception and could lead to low crop productivity emanating from low radiation use efficiency (De Souza *et al.*, 2017; Pellet and El-Sharkawy, 1993, 1997).

In Zambia, frequent leaf harvesting is a common practice in cassava fields on randomly selected plants implying that the effects could be minimal per plant since not all plants are targeted during defoliation. Cassava leaves are in high demand in the dry season because seasonal African indigenous vegetables like amaranth, cleome, and pumpkin leaves are only grown in the wet season. So, leaf harvesting intervals may vary by season and demand. It is therefore unclear whether this indiscriminate approach to leaf harvesting and the low levels of

nutrient status of the soils in the region have also contributed to the already low yield averages reported in Luapula Province.

Luapula Province is characterized by highly weathered, leached soils with extreme acidity and hence requires liming before mineral fertilizer application for optimal crop production and efficient phosphorous utilization (Tsuji *et al.*, 2005; Chinene, 1991; Haynes, 1982). Cassava fertilisation will likely reduce the yield gap between potential yield and actual production in smallholder farms and any detrimental influence of leaf harvesting on yield.(Kabwe, 2014, Fermont, 2009, Fermont *et al.*, 2010). Insufficient information exist on how fertilisation and leaf harvesting affect varietal responses, storage root yield, growth, radiation use efficiency and canopy features in Zambia's cassava production systems. The study investigated whether leaf harvesting intervals affect growth and storage root yield, light interception, radiation use efficiency (RUE), plant growth, root yield, and variety dependant and fertiliser regime-modulated effects.

Specific Objectives were to:

- i. Assess the effects of leaf harvesting frequency and fertilizer management on the growth and yield of cassava varieties.
- ii. Determine the effects of leaf harvesting frequency and NPK fertilizer application on light interception, radiation use efficiency (RUE) and yield components of cassava varieties.

Hypotheses

- i. Leaf harvesting frequency and fertilizer management regimes does not affect the growth and yield of cassava

- ii. NPK fertilizer application and leaf harvesting frequency does not affect cassava light interception, radiation use efficiency (RUE) and yield components

6.2 RESULTS AND DISCUSSION

6.2.1 Biophysical characteristics of the study site

Season variation of rainfall was observed with more precipitation of about 400mm in 2017/2018 compared to 2018/2019. (see Figure 2). The 2017/18 season had better rainfall distribution compared to the 2018/19 growing season, monthly. Despite the low monthly precipitation distribution at the beginning of the 2018/2019 season, two times more precipitation fell in March than in 2017/2018 growing season.

Reference evapotranspiration in 2017/2018 was higher compared to 2018/2019 season, mainly attributed to more rainfall and radiation accumulations. Soil pH, total nitrogen, exchangeable phosphorous (P), exchangeable potassium (K), exchangeable calcium (Ca), and exchangeable magnesium (mg) were slightly higher in the second season (2018/2019) than in the first season (2017/2018), except for exchangeable sodium which was slightly lower. However, N P K soil analysis showed that soil samples from the study region were below the critical averages of nutrients required for cassava production (Table 1). The variation in soil chemical properties was not significantly ($P > 0.05$) different. The soil texture classification of sandy clay loam did not vary across seasons as these fields were very close to each other.

6.2.2 Effect of fertilization regimes and leaf harvesting on root yield, total dry matter and yield components of cassava

Cassava storage root yields were significantly different for varieties, fertilizer and leaf harvesting interval ($P < 0.05$) (Table 8). An application of fertilizer and lime resulted in a significant increase in storage root yields, and total dry matter ($P < 0.05$) while the increase in the frequency of leaf harvesting decreased cassava root yields (Table 9). There were significant ($P < 0.05$) variety effects with Mweru yielding the highest compared to Bangweulu and

Katobamputa a local common landrace (Table 8) in the 2017/2018 season. Additionally, root yield reduction was observed at different leaf harvest intervals with harvesting every after two weeks (D2) having the lowest yield followed by a three weeks' interval (D3) compared to the control (D1) where no leaves were harvested. Two cassava varieties Mweru and Bangweulu reacted similarly to leaf harvesting interval for dry storage root yields in comparison with Katobamputa a local landrace. Katobamputa a traditional landrace had the highest reduction in root yield due to leaf harvesting and the yields reduction increased with the frequency of leaf harvesting. The other two varieties produced a much higher leaf area index which highly correlated to root yield. Dry matter partitioning to the roots (HI) was significantly affected by fertility \times variety and fertility \times intensity in the 2018/2019 season while plant height was significantly affected by fertility \times intensity 2017/2018 respectively.

Table 8: Linear Mixed model ANOVA Type III (Mean Sq.) for variety and different defoliation levels averaged across 2017/2018 and 2018/2019 seasons respectively

Source	DF	Den DF	Seasonal LAI	Dry Shoot yield	Dry Root Yield	Total biomass	Harvest Index	Root Diameter	Plant height	SPAD
Rep	2	11	0.003	366	6443	3035	5.54	10.06	377.4	0.01
Fertility	1	11	0.586***	26225*	688331***	826142***	412.05***	486.96.	6615.9**	624.37***
Intensity	2	60	1.033***	77477***	998032***	1631592***	189.04***	1074.85***	6656.4***	108.55***
Year	1	60	0.459***	100701***	317959***	776537***	4.16ns	249.53ns	3272.4*	12.29ns
variety	2	11	0.250***	1060ns	450399***	411255***	649.38***	366.7*	7454***	336.23***
Fertility: Intensity	2	60	0.0008ns	6197ns	44968ns	24680ns	103.39**	383.15*	810.8**	17.07ns
Fertility: Year	1	60	0.059**	62ns	28033ns	30731ns	7.18ns	114.64ns	69.2ns	7.56ns
Intensity: Year	2	60	0.080***	809ns	14740ns	19063ns	5.86ns	22.14ns	25ns	12.18ns
Fertility: Variety	2	11	0.003ns	6401ns	9564ns	12354ns	92.5*	46.01ns	59ns	11.86ns
Intensity: Variety	4	60	0.005ns	398ns	17772ns	16718ns	15.61ns	165.17ns	25.8ns	22.87ns
Year: Variety	2	60	0.002ns	603ns	3912ns	7556ns	1.35ns	15.51ns	563.9*	9.22ns
Fertility: Inten: Year	2	60	0.001ns	419ns	10353ns	13497ns	1.47ns	33.41ns	42.3ns	0.77ns
Fertility: Inten: var	4	60	0.006ns	469ns	8084ns	21809ns	11.58ns	22.7ns	84.2ns	8.86ns
Fert: Year: Variety	2	60	0.044**	1258ns	2103ns	2787ns	4.14ns	37.81ns	359.5ns	0.65ns
Intensity: Year: Var	4	60	0.001ns	831ns	2184ns	2766ns	5.59ns	37.13ns	294.4ns	26.09ns
Fert: Inten: Year: Var	4	60	0.001ns	1282ns	1806ns	3415ns	3.99ns	29.52ns	153.3ns	5.89ns

Sig. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1, ns: not significant

No significant ($p>0.05$) treatment mean effects were observed for shoot dry yield in the 2018 and 2019 seasons on variety, fertilizer management and leaf harvest interval. However, an application of fertilizer and lime increased shoot yield in both treatments (varietal level and leaf harvest interval) respectively compared to the control (Table 9). Harvesting of leaves contributed to slight differences observed for both fertilizer management practices and varietal levels. An application of a fertilizer-lime combination treatment resulted in an average of 8.89% increase in stem biomass (yield) in comparison to the control.

The total dry matter at final harvest Katobamputa (V3) produced low dry matter compared to varieties Mweru (V2) and Bangweulu (V1) as leaf harvesting frequency increased.

Regardless of fertilization regime, a bi-weekly (D2) and three-week harvest interval (D3) produced considerably more total dry matter than no leaf harvesting (control-D1). Regardless of the period between leaf harvests, varieties V2 (Mweru) generated more dry matter than V1 (Bangweulu) and V3 (Katobamputa); however, the differences were only statistically significant when comparison was done with V3 (Katobamputa) ($p>0.05$). Application of fertilizer and lime (M2) increased cassava tuber yields by 23.96% a difference of (235gm^{-2}) for the first crop cycle, while the second crop cycle recorded 27.02% with a yield difference of 273gm^{-2} (Table 9). The allocation of dry matter between storage roots and the shoot was calculated to determine the distribution patterns of dry matter to the tubers from the total biomass as harvest index (HI). Variety V3 (Katobamputa) HI decreased with the increasing frequency of leaf harvesting especially during two weeks harvest interval (Table 9). Varietal dry matter allocation (HI) to the roots for V1 (Bangweulu), V2 (Mweru) and V3 (Katobamputa) was 67.3%, 70.6%, 61.3% and 66.8%, 69.8% and 61.6% for 2017/2018 and 2018/2019 seasons respectively.

Table 9: Cassava yield and yield components as affected by fertilizer management practices, variety and leaf harvesting interval in Mansa in 2017/18 and 2018/19

Fertility	Variety	Harvest interval	Year	Seasonal LAI	Root Yield (gm ⁻²)	Shoot biomass (gm ⁻²)	Total biomass (gm ⁻²)	HI (%)	Plant (cm)	SPAD	Root diameter (mm)
M1	-	-		1.71	699	376	1075	64.1	132	39.5	48.8
M2	-	-		1.96	940	425	1364	68.3	149	48.1	55.1
-	V1	-		1.8	846	404	1250	67.1	148	44.8	52.4
-	V2	-		1.99	973	406	1379	70.2	150	46.2	54.9
-	V3	-		1.72	639	391	1030	61.3	124	40.3	48.5
-	-	D1		2.02	982	446	1427	68.2	156	45.7	58.2
-	-	D2		1.68	649	353	1002	63.7	130	42.4	48
-	-	D3		1.82	828	402	1229	66.7	136	43.2	49.7
			2018	1.9	765	370	1135	66.4	125	43.2	49.7
			2019	1.77	874	431	1304	66	156	44.4	54.2
SE(Fertility)				0.021***	27.4***	14.1*	38.3***	0.593***	3.23**	0.82***	2.01ns
SE(Variety)				0.026***	33.6***	17.3ns	46.9***	0.726***	3.38***	0.74 **	1.98*
SE(Intensity)				0.019***	26.6***	13.5***	35.7***	0.697***	3.38***	0.74***	1.98***
SE(Year)				0.017***	23.3***	11.9***	31.7***	0.575ns	4.25*	0.82ns	2.03ns

Fig. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1, ns: not significant, M1: without fertilizer and no lime, M2: fertilizer and lime, V1: Bangweulu, V2: Mweru and V3:Katobamputa, D1: no harvesting, D2: leaf harvesting at 2 weeks intervals and D3 leaf harvesting at 3 weeks intervals, -: without treatment respectively.

However, HI reduced with increasing frequency of leaf harvesting across all three varieties and with similarity in both growing seasons (Table 9). Mweru variety was found to respond better followed by Bangweulu and Katobamputa in tolerating different leaf harvesting frequencies.

Plant height also varied significantly for fertilizer management practices, varieties and leaf harvest intervals while significant interaction between fertilizer management practice and leaf harvest interval was observed ($P<0.05$) in the 2017/18 season only. Responses of plant height to fertilizer management practices were stronger with the NPK+ lime combination than with the control (no NPK fertilizer and non-limed treatments). NPK+ lime combination treatment had a significant effect on plant height ($P<0.05$) in the 2017/2018 season. Similarly, the application of lime and NPK fertilizer increased plant height by 17.8% in comparison with the unfertilized and non-limed treatment (control). Plant height also varied significantly with leaf harvest intervals with cassava height decreasing with the increase in the intensity of leaf harvesting (Table 8). There were significant differences in varietal response on the final plant height, however, such variations were mainly observed when V1 (Bangweulu) and V2 (Mweru) varieties were compared to V3 (Katobamputa).

Responses of seasonal LAI to fertilizer management regimes were significant but effects observed due to leaf harvest interval and within varieties were stronger than fertilization effects (Tables 9). Application of NPK fertilizer and lime to cassava increased seasonal LAI compared to traditional low-input practices (unfertilized and non-limed treatments) during the two growing seasons. However, the LAI in the first year was slightly higher than in the second but was non-significant. There was improved productivity observed under NPK fertilizer + lime treatments could be attributed to balanced nutrition compared to unfertilized treatments (Table 9).

It was also observed that chlorophyll profiles varied significantly with fertilizer management practices, within varieties and leaf harvest interval, while no interaction effect was observed among the treatments. Fertilizer treatment M2 (NPK fertilizer + lime) significantly increased chlorophyll index, irrespective of leaf harvesting interval compared to non - fertilized and non-limed treatment (M1). Additionally, it was observed that root diameter response to fertilizer management practices and leaf harvest interval were strong whilst no significant cassava clonal variations were observed.

The variation in root diameter due to fertilization was observed in the 2017/2018 season only while the variation due to intensity was observed in both growing seasons. The traditional low-input method of not fertilizing cassava without leaf harvesting produced similar storage root yields in the two experimental cycles. Similarly, an application of NPK and lime treatment showed comparable storage dry root yields in the 2017/2018 and 2018/2019 seasons for the traditional low input method (no-leaf harvesting treatment-D1). Leaf harvesting interval of 2 weeks negatively affected storage dry root yield of cassava varieties more than 3 weeks' interval. On the other hand, the root yield of the 3week leaf harvesting frequency was similar to the root yield at no leaf harvesting in both seasons. This indicates that the lower frequency of leaf harvesting (3 weeks' intervals) allowed cassava to regenerate and allow for compensatory growth of new leaves. The yields reported of 765 gm⁻² (7.7 ton- ha⁻¹) and 880 gm⁻² (8.8tonha) in Mansa in Luapula Province for two consecutive seasons (see data in Tables 2 and 3) were higher than those reported for Zambia (average of 5.8 ton ha⁻¹) and also higher than the average of 10.9 t ha⁻¹ fresh storage root yield obtained in Africa (Chikoti, *et al.*, 2016, Legg *et al.*, 2015, FAOSTAT, 2009). These results are in line with other similar findings where improved varieties /varieties, disease-free cuttings, improved fertilization management and enough rainfall resulted in higher yields than the low-input farmer practice in Kenya (Fermont, 2009). Cassava leaf harvesting is known to have negative effects on root yields by reducing

leaf canopy since the harvested leaves are usually the fully expanded young leaves from the upper canopy which possess the highest photosynthetic rates (El-Sharkawy and De Tafur, 2007). Moreover, leaf harvesting results in the partitioning of more photo-assimilates towards the shoots to rebuild the plant canopy as a leaf compensatory mechanism due to leaf harvesting. This plant partitioning comes at the expense of dry matter diversion to shoots instead of storage root bulking, hence the reduction in storage root yield. In this study storage root yields were significantly affected by leaf harvesting intervals with or without the application of fertilizer and liming (Tables 9). This is because of the high intensity of leaf harvesting and the quantity of leaf removal (5 to 7 leaves per plant) and the response of different cassava varieties applied in our study. However, we observed that bi-weekly removal of leaves significantly reduced cassava varietal yields in the 2018 season although in 2019 the effects were much reflected in both (fertilized and limed) and the control treatments. A three-weekly leaf collection did not cause a significant reduction in root storage yield and was comparable to no leaf harvesting treatment when fertilizer and liming were applied to cassava in both the 2018 and 2019 growing seasons. This implies that farmers harvesting cassava leaves should consider limiting harvest frequency to a 3-week interval or even longer, and limited to collecting up to 7 leaves per plant. Excessive removal of leaves is expected to significantly reduce storage root yield, regardless of the frequency of leaf harvesting, as observed by Lutaladio and Ezumah (1980). Lutaladio and Ezumah (1980) reported a reduction in storage root yields when leaves were collected only at a 4-week interval, because of the high number of leaves harvested compared to the number of leaves harvested in our study. Older studies by observed yield reductions in storage root yields when cassava leaves were harvested at the 1-month interval (4 weeks interval). From our study we observed that the higher frequency of leaf harvesting resulted in root yield reduction of 33% -34% compared to the no leaf harvesting treatments of cassava across the seasons. In contrast to earlier research by Lockard *et al.*(1985) which found yield reductions in

storage root yields when cassava leaves were harvested at 1-month intervals (4 weeks apart), our study found that a higher frequency of leaf harvesting led to a reduction in root yield of 33%–34% when compared to cassava treatments that did not involve leaf harvesting throughout the seasons.

Munyahali *et al.* (2017) observed reductions in storage root yields of (49-66%) in a more frequent leaf collection interval of 2- weeks relative to the unharvested treatment. Dahniya *et al.* (1981) also observed yield reductions of 76%, 62% and 15% when cassava leaves were harvested at intervals of 1, 2 and 3 months respectively. Present results show that cassava leaf harvesting has a significant negative effect on the root yield of cassava varieties regardless of fertilization management practice. Our results are in agreement with Dahniya *et al.* (1981) who found a differential varietal response to leaf harvesting frequencies on storage root yield reduction perhaps due to leaf production capacity variations. The effect of leaf harvest interval on storage root yield could be explained by the harvesting frequency and quantity of leaves removed per plant (5-8) compared to Munyahali *et al.* (2017) who only removed 3-5 tender leaves. Moreover, harvesting leaves every 2 weeks resulted in a significant reduction in shoot dry yield in comparison to 3 weeks' leaf harvest interval with and without NPK fertilizer and liming. In this AER 3 of Zambia, tender leaves can be harvested on 3 weekly basis provided the quantity of leaves harvested is minimal. Similar recommendations were suggested by adopting an optimal leaf harvesting interval to minimise negative effects on storage root yield (Dahniya *et al.*, 1981)

6.2.3 Correlation effects of cassava traits

Correlation analysis was performed to derive a correlation matrix for two cropping seasons and showed strong associations among cassava traits (Table 10). The final total plant biomass was very much related (closest) to dry root yield, an indication of autocorrelation. Mean LAI

(source-sink) and economic sink size (root diameter) showed consistently stable significant relations with total dry biomass and root yield. Shoot yield was negatively correlated to harvest index whilst chlorophyll index as a source activity was significantly and strongly correlated to root yield, total dry matter, root diameter, plant height and harvest index. Generally, the strength of the correlation was similar in the two seasons for most of the traits. HI was positively and strongly correlated to dry root yield, total plant biomass and seasonal LAI. However, the highest positive correlation was observed between total dry biomass and dry root yield ($R^2=0.98$) in both seasons (Table 10). Shoot dry matter was negatively correlated to HI in both seasons

Table 10: Correlation coefficients (n=54) for 2017/18 (1) and 2018/19 (2) growing season averaged across fertilizer management, variety and leaf harvesting interval

Parameters	Season	Seasonal LAI	Chlorophyll index	Plant height	Root diameter	Total Dry biomass	Dry root yield	Shoot dry matter	dry HI
Mean LAI	1	1							
	2	1							
Chlorophyll index	1	0.702***	1						
	2	0.725***	1						
Plant Height	1	0.789***	0.671***	1					
	2	0.674***	0.567***	1					
Root diameter	1	0.584***	0.447***	0.490***	1				
	2	0.464***	0.189ns	0.457***	1				
Total Dry biomass	1	0.694***	0.514***	0.679***	0.679***	1			
	2	0.844***	0.678***	0.685***	0.456***	1			
Dry root yield	1	0.744***	0.540***	0.699***	0.499***	0.975***	1		
	2	0.851***	0.710***	0.693***	0.453***	0.981***	1		
Shoot dry matter	1	0.302*	0.257ns	0.386**	0.296*	0.733***	0.565***	1	
	2	0.389**	0.200ns	0.304*	0.239ns	0.577***	0.406**	1	
HI	1	0.669***	0.492***	0.574***	0.331*	0.584***	0.738***	-0.089ns	1
	2	0.646***	0.613***	0.519***	0.299*	0.664***	0.789***	-0.192ns	1

Sig. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1, ns: not significant

6.2.4 Effect of Fertilizer Management Regimes on Cassava Root Yields and Yield Components

The application of NPK fertilizer and lime increased both storage root yield and related yield components in the two seasons of our study. The increase in yield was a result of the increase in root diameter, leaf area index, plant height, chlorophyll and harvest index (Tables 9). Pellet and El-Sharkawy, (1997) found similar results in the studies conducted in the hillside areas of Colombia. Another important yield component, i. e. root number per plant, is positively affected by the application of NPK (Pellet and El-Sharkawy, 1993). Biratu *et al.*, (2018) reported an increase in storage root yield and associated yield components owing to NPK fertilizer and manure application in the Kabangwe area of Lusaka and Mansa areas in Lusaka and Luapula Provinces of Zambia. In addition, fertilizer application played positive impact on root yield of cassava by compensating for leaf harvesting across all varieties. However, the combination of fertilizer and lime showed a more significant cassava yield response than control regardless of the leaf harvesting frequency (Figure 16). This was clear when the assumed NPK combination showed that yield increased with fertilizer application which was assumed as maximum value 100 Kg Ha⁻¹ in comparison to the control (No fertilizer application).

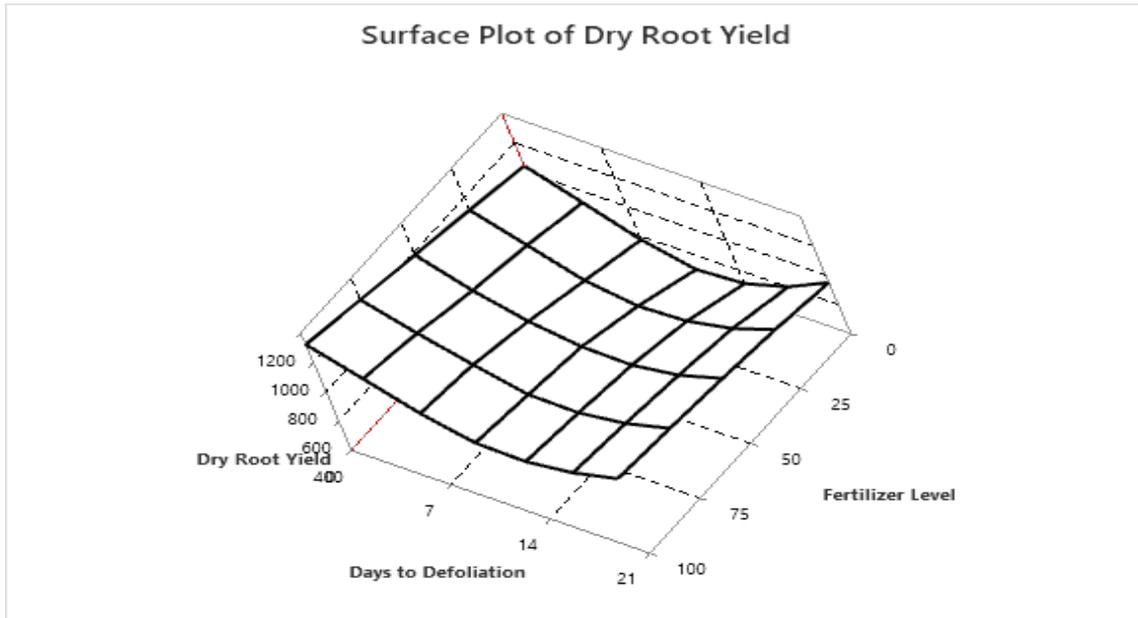


Figure 16: Simulated 3D surface plot depicting the effect of fertilizer and leaf harvesting (days to defoliation) on cassava root yield

In this study, fertilizer was combined with lime due to the high acidity of the study area in Mansa district of Luapula province. Study findings are in line with Pypers. (2011, 2012) who observed significant responses of cassava root yield to fertilization in the Democratic Republic of Congo (DRC). Nevertheless, the research conducted by Carsky and Toukourou (2005) in Southern Benin revealed that the initial year of cultivating cassava in the field did not have a noteworthy impact on the cassava's reaction to the application of mineral NPK in Ferralsols, which contradicts the findings of our study. Similarly, Lema *et al.*, (2005) found no significant effects of NPK fertilization on both storage root yield and associated yield components when both improved and local landraces were used in a study carried out in DRC. Furthermore, Omondi *et al.*, (2018), in their study carried out at the IITA Lusaka, station in Zambia, found that excess nitrogen (N) fertilization in cassava had led to a reduction in leaf photosynthetic rate and storage root yield. These effects were attributed to a reduction in the harvest index. These results also contradict our findings perhaps because our application rate of NPK and lime used in this study were optimally different. Similarly, Omondi *et al.* (2018) using a semi-hydroponic fertigation system found that there was storage root yield stagnation at an early stage of growth when too much nitrogen was used. However, it is well documented that cassava fertilisation notably 7 is known to increase the storage root yield of cassava under different soil conditions(Pellet and El-Sharkawy, 1997).

6.2.5 Effect of fertilizer management practices and leaf harvesting on the fresh and dry matter yields of cassava during the growing season

The average leaf weight gathered per plant was calculated during the growing season for various leaf harvesting intervals and fertilizer management regimes, including NPK + Lime (M2) and unfertilized and non-limed treatments (M1). The collected leaves, both fresh and dry, showed significant differences between the two harvesting intervals (D2 and D3) for the 2017/2018 and 2018/2019 seasons (Table 11). The leaves were higher in yield when harvested every two weeks compared to when harvested every three weeks ($P < 0.05$). This information is presented in. The average leaf weight was strongly influenced by the interval at which the leaves were harvested ($P < 0.05$). Harvesting leaves at a two-week interval (D2) resulted in a higher amount of leaf biomass removed per plant compared to harvesting leaves at three-week intervals (D3) over the course of two growth cycles.

Furthermore, the use of lime and fertilizer resulted in a substantial increase of both the fresh weights of leaves and the amount of dry matter accumulated throughout the growing season (Table 11). Differences in both fresh biomass and dry biomass were seen for leaves taken every two weeks (D2), suggesting a more gradual loss of leaves from the plant compared to leaves harvested every three weeks. Similar results were obtained by Munyahali *et al.*, (2017) in South Kivu, DRC where the harvesting of young leaves resulted in small or negligible effects on cassava growth and yields compared to the mineral fertilizers which increased both cassava growth and yields.

Table 11: Cassava leaves harvested for the 2017/18 and 2018/19 seasons for three varieties harvested at two intervals during the growing season

Treatments			Traits			
Fertility	Variety	Harvest interval	Fresh leaves (g plant ⁻¹) 2017/18	Fresh leaves (g plant ⁻¹) 2018/19	DM leaves (g plant ⁻¹) 2017/18	DM leaves (g plant ⁻¹) 2018/19
M1	-	-	320	378	75.4	87
M2	-	-	405	456	98.5	125
-	V1	-	326	379	78.6	89
-	V2	-	348	369	87	107
-	V3	-	413	409	95.3	126
-	-	D2	416	490	97.3	137
-	-	D3	309	356	76.6	87
M1	V1	-	288	321	66.3	82
M1	V2	-	314	367	79.6	89
M1	V3	-	359	389	80.4	112
M2	V1	-	365	402	90.9	135
M2	V2	-	382	421	94.3	125
M2	V3	-	466	489	110.2	121
M1	-	D2	373	412	84	98
M2	-	D2	460	512	110.6	123
M1	-	D3	268	312	66.9	81
M2	-	D3	350	389	86.4	98
-	V1	D2	376	391	88.1	103
-	V2	D2	408	456	93.7	112
-	V3	D2	465	501	110.1	123
-	V1	D3	277	322	69.2	78
-	V2	D3	288	344	80.3	103
-	V3	D3	361	398	80.5	106
SE(Fertility)			4.75**	4.98***	2.1 **	3.12***
SE(Variety)			5.82**	5.21***	2.53 ***	3.23***
SE(Intensity)			4.75***	4.29**	4.75***	5.32***

Sig. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1, ns: not significant, M1: without fertilizer and without lime, M2: fertilizer and lime, V1: Bangweulu, V2: Mweru and V3:Katobamputa, D1: no harvesting, D2: leaf harvesting at 2 weeks interval and D3 leaf harvesting at 3 weeks intervals, -: without treatment respectively.

6.2.6 Effect of fertilizer management regimes and leaf harvesting on leaf area index (LAI) dynamics, light interception, canopy extinction coefficient and radiation use efficiency of cassava

Variations in LAI were observed across seasons in response to fertilization, varieties and leaf harvesting intervals (Figure 17). From leaf sprouting to 75 days after planting (DAP) LAI for varieties, significantly increased at both fertilization regimes. However, LAI was negatively affected by the leaf harvesting interval. From 75 to 138 DAP a decrease in LAI was attained and this time significant clonal variations across seasons were observed. This period coincided with the dry period and low temperatures during the two seasons of crop growth. During the growth period, fertilizer management response and leaf harvest interval on LAI resulted in the highest clonal average LAI of 3.68 for V1 (Bangweulu), 3.92 for V2 (Mweru) and 3.14 for V3 (Katobamputa) at 197 DAP in 2017/18 season. In the 2018/19 season, LAI was similar although slightly lower compared to the first cycle, with maximum average LAIs of 3.45 for V2 (Mweru), 3.17 for V1 (Bangweulu) and 2.87 for V3 (Katobamputa) achieved under fertilizer and lime combination under the same period. This period in July coincided with the formation of new leaves and leaf growth before cassava began shading off leaves up to the end of August for both seasons. At 259 DAP all varieties decreased in LAI regardless of fertilization regimes and leaf harvesting intervals, nevertheless, a leaf harvesting interval of 2 weeks under low input farmer management resulted in the lowest LAI.

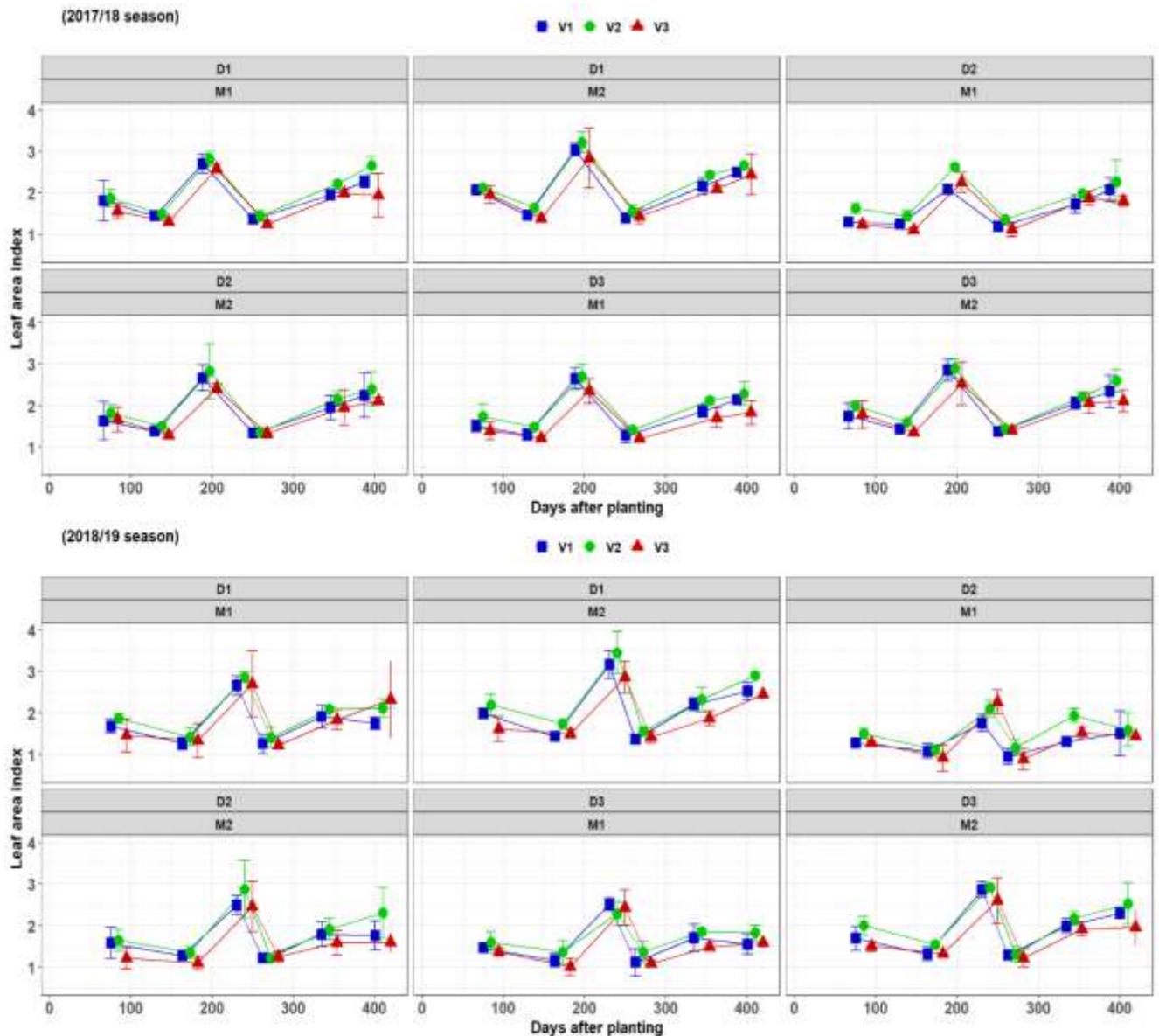


Figure 17: Leaf area index of several cassava varieties at different defoliation frequencies under two fertility management options during the growing seasons. Key: D1= Control (No leaf harvesting), D2=Leaf harvesting at 2weeks intervals, D3= Leaf harvesting at 3weeks intervals, V1=Bangweulu, V2=Mweru and V3=Katobamputa, M1= No fertilizer without lime (low input farmer practice) and M2= Fertilizer + lime (Optimal cassava management).

During this period cassava growth had the highest leaf fall and coincided with serious drought and low temperatures. From 259 to 354 DAP there was an increase in LAI till the last sampling harvest in the first and second growing cycles respectively (Figure 17). This period was marked by the beginning of rainfall activities and a new planting season with remarkably good precipitation.

During the second cycle, the clonal response of LAI to leaf harvesting interval and fertilizer management regime was significant and followed a similar pattern as in the first cycle. In general, LAI response to fertilizer management practice and leaf harvest interval response was significantly different among varieties in the first season while no significant clonal variations were observed in the second season (Figure 17).

The patterns of light interception for different cassava varieties varied with fertilizer management regimes and leaf harvesting intervals (Figure 18.)

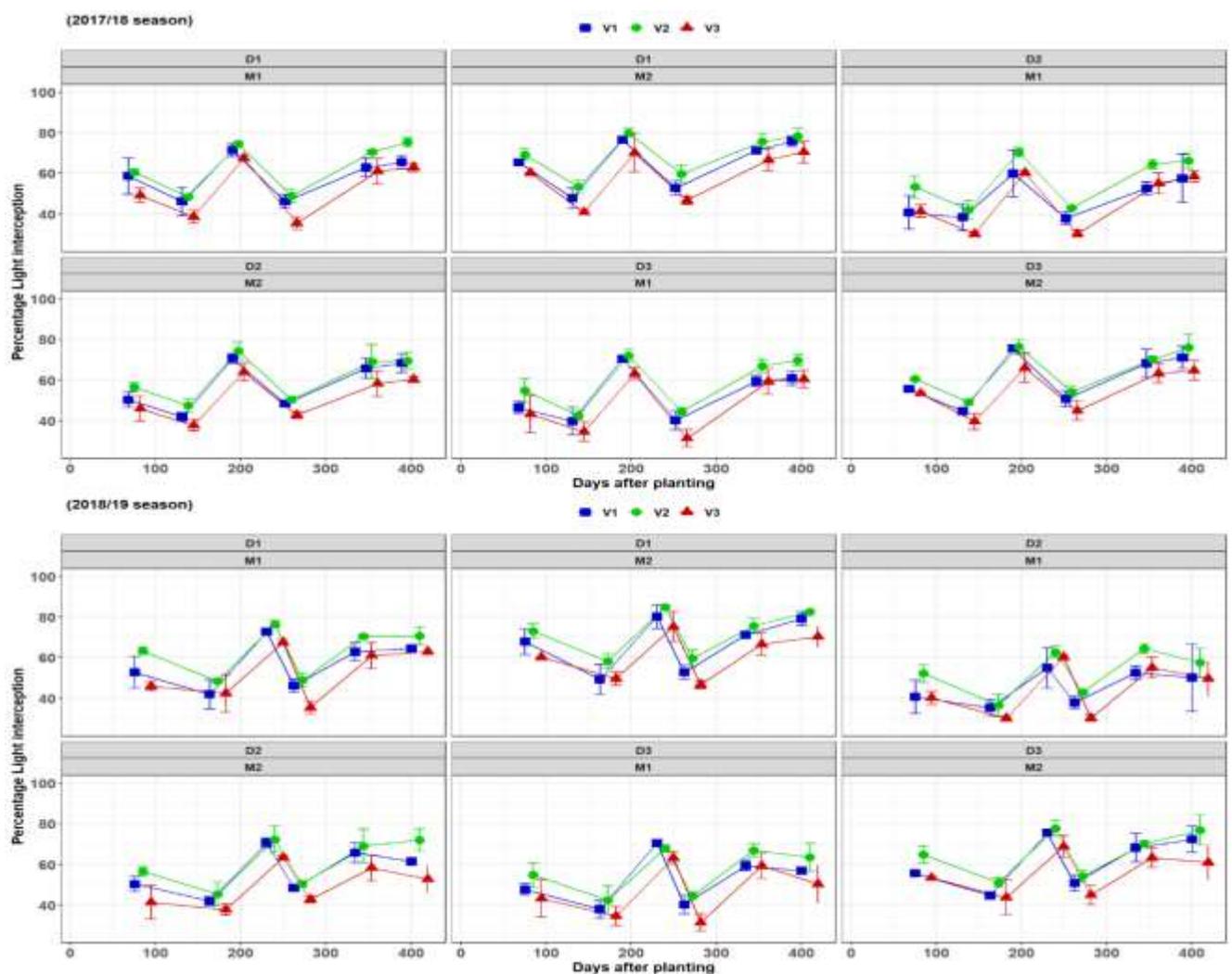


Figure 18: Percentage light interception (Q) of different cassava varieties at different defoliation intervals under two fertility management options during the growing seasons. Key: D1= Control (No leaf harvesting), D2=Leaf harvesting at 2weeks interval and D3= Leaf harvesting at 3weeks interval, V1=Bangweulu, V2=Mweru and V3=Katobamputa, M1= No fertilizer without lime (low input farmer practice), M2= Fertilizer +lime (Optimal cassava management)

On the first date of light measurement, V2 (Mweru) intercepted more PAR followed by V1 (Bangweulu) and V3 (Katobamputa). This pattern was observed for all the treatments till the last date of measurements. Fertilizer treatment M2 (fertilizer + lime) resulted in higher clonal PAR interception compared to non-fertilized treatment (M1: No fertilizer no lime) across varieties regardless of leaf harvesting interval. However, the interception was slightly higher in the first cropping cycle compared to the second cropping cycle. In all sampling dates' leaf harvesting interval negatively affected light interception. The lowest interception was observed when the leaf harvesting intensity was increased to two weeks harvesting intervals (D2) compared to three weeks harvesting intervals (D3) and the no-leaf harvesting treatment (D1) (Figure 6). The highest light interception of 89.27%, 88.8% and 80.2% was reached at LAIs of 3.92 for Mweru, 3.68 for Bangweulu and 3.14 for Katobamputa varieties in the 2017/2018 growing season respectively. In the second year, we observed slight a decline in light interception where 84.7%, 80.3% and 75.3% of V2 (Mweru), 3.17 for V1 (Bangweulu) and 2.87 for V3 (Katobamputa) varieties were recorded corresponding to LAIs of 3.45, 3.17 and 2.87 2018/2019 under improved fertilization (fertilizer + lime regime) respectively.

Significant varietal differences in radiation use efficiencies (RUE) were observed among treatments. All varieties showed a significant increase in RUE as LAI increased in response to improved fertilization. However, the response of RUE and LAI was dependent on fertilization regimes and leaf harvesting intervals. The highest RUE was observed under fertilizer management- M2 (NPK + lime) without zero leaf harvesting across varieties in comparison to no fertilization (control) under the same conditions (Table 8). Pellet and El-Sharkawy, 1997 also observed varietal greater response to fertilization in terms of RUE, this could explain why V2 (Mweru) under mineral fertilizer and liming had a higher RUE due to higher light interception and LAI where no leaf harvesting was done. A leaf harvesting interval of two weeks resulted in reduced light interception and LAI that consequently affected yield negatively. Studies have

shown that increase in LAI has been shown to stimulate yield positively and has a positive correlation to the storage of root dry matter and total dry matter (Cock *et al.*, 1979, El-Sharkawy, 2006, El-Sharkawy and deTafur, 2010). In this study, it was observed that moderate soil fertilization resulted in an increase of LAI and total dry matter across all the treatments compared to a non-fertilized treatment a practice mostly associated with low-input smallholder farmers.

6.2.7 Effect of fertilization on varietal light extinction coefficient (K), LAI and light interception

LAI was studied to understand the effect of fertilizer management and leaf harvesting interval on cassava canopy development. The K values for the 2017/18 season ranged from 0.42-0.54 while the 2018/19 season had a slightly higher range of 0.41-0.57 for different varieties across leaf harvesting intervals and fertilization.

The highest clonal K -values were obtained by Mweru followed by Bangweulu and Katobamputa varieties respectively. However, higher K -values were associated with improved fertilization (NPK+Lime) compared to low input management (no fertilizer no lime) practised by farmers. K values were higher in the second season compared to the first growing season. Leaf harvesting at a high intensity of 2-week intervals negatively affected the value of K compared to that of weeks 3-week and no leaf harvesting regimes (Figure 17). In this study, NPK mineral fertilizer and liming increased LAI, light interception, K (light extinction coefficient) and radiation use efficiency of cassava varieties irrespective of leaf harvest interval (Figures 2, 8, 9 and 10).

The increment in the LAI was highly attributed to fertilizer and lime application in comparison to the control (Table 8). The seasonal LAI has highly correlated with storage root yield over the 2 years of study an indication of the importance of LAI in yield determination (Cock and El - Sharkawy, 1988, Pellet and El-Sharkawy, 1993, El-Sharkawy 2006, El-Sharkawy and de Tafur, 2010). Cock *et al.* (1979) also found that the root dry yield of cassava was highly dependent on an incremental LAI of 3 to 4 during most of the growth period of cassava. Nevertheless, Pellet and

El-Sharkawy (1993) found that beyond four months after planting (MAP), no apparent changes occurred in root number irrespective of soil fertility levels. In addition, the highest LAI values were observed at 4 MAP time, irrespective of soil fertility level, with large varietal differences (Pellet and El-Sharkawy, 1993). In Pellet and El-Sharkawy, (1993) LAI was greater in the four varieties tested with NPK applications than in absence of fertilization. This scenario could be associated with a varietal response to NPK fertilizer. In our study, we also observed the response of seasonal LAI and storage dry root yield increase to NPK fertilization thus giving an opportunity and avenue for further genetic improvements for nutrient use efficiency among cassava varieties. Recent studies also indicate that responses of LAI to fertilizer applications were stronger with NPK application, especially with N and K for studies carried out in West Africa (Ezui *et al.*, 2017).

A significant increase in the value of the light extinction coefficient (K) was observed across variety and leaf harvesting due to fertilization during the two years of study. This was mainly an indication of higher light interception for similar LAI due to better leaf angles and positioning among cassava varieties (Figure 19). A better supply of N was found to improve leaf canopy and consequently improved light interception according to Ezui *et al.* (2017). Our study indicates that K varied with varieties and leaf harvesting intervals with a more frequent leaf removal having reduced K values in response to fertilization regimes. The values of K indicate that most of the clones used in this study had moderately horizontal leaves. In addition, the study found that the application of NPK fertilizer and lime increased the mean value of K across all treatments. Pellet and El-Sharkawy (1997) reported significantly greater K values in four cassava varieties with the application of NPK fertilizer, with notable differences among varieties.

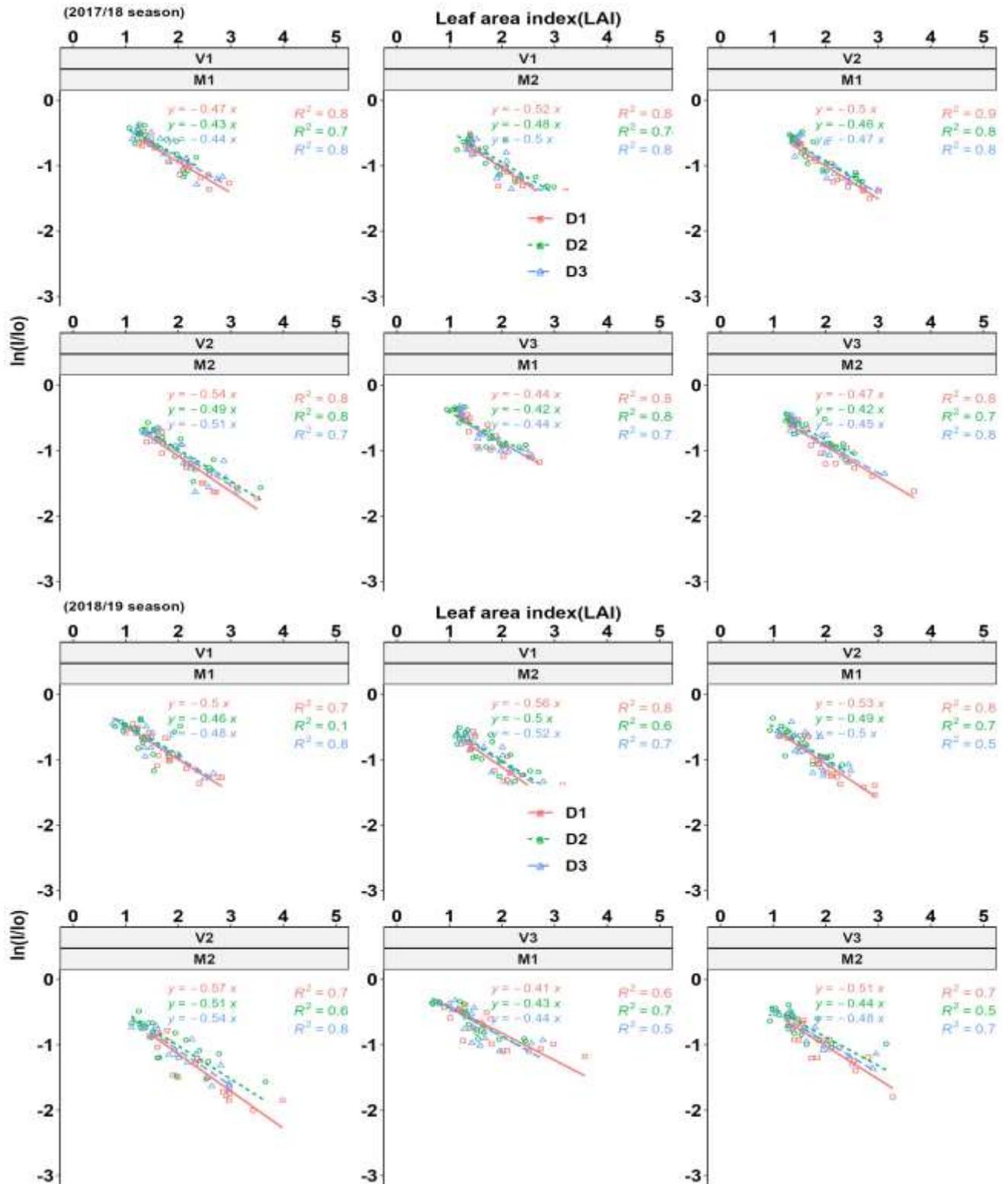


Figure 19: Percentage light interception ($Q - \ln(I/I_0)$) of different cassava varieties at different defoliation intervals under two fertility management options during the growing seasons. Key: D1= Control (No leaf harvesting), D2=Leaf harvesting at 2weeks interval and D3= Leaf harvesting at 3weeks interval, V1=Bangweulu, V2=Mweru and V3=Katobamputa, M1= No fertilizer without lime (low input farmer practice), M2= Fertilizer +lime (Optimal cassava management)

6.2.8 Effect of fertilization management regimes and leaf harvesting on varietal radiation use efficiency

Data on cumulative total dry matter of different cassava varieties was plotted against cumulative IPAR for different treatments and the relationships were nearly linear (Figure 20). A strong correlation between cumulative total dry matter and IPAR was established. Seasonal specific radiation use efficiency (RUE) ranges were 1.2 -2.1 gMJ⁻¹ and 1.4-2.2 gMJ⁻¹ for the first and second seasons respectively. These values for cassava varieties were averaged across treatment effects for a period of utmost 13 months. All varieties showed a significant increase in RUE in response to fertilization regardless of the interval of leaf harvesting resulting from a direct effect resulting from the increase in LAI, and better leaf canopy photosynthesis. It is notable in this study that all varieties showed a significant increase in radiation use efficiency (RUE) in response to fertilization regardless of leaf harvest intensity in comparison to the control. RUE is the ability of how plants to transform light energy into plant biomass and involves net carbon fixation by the process of photosynthesis.

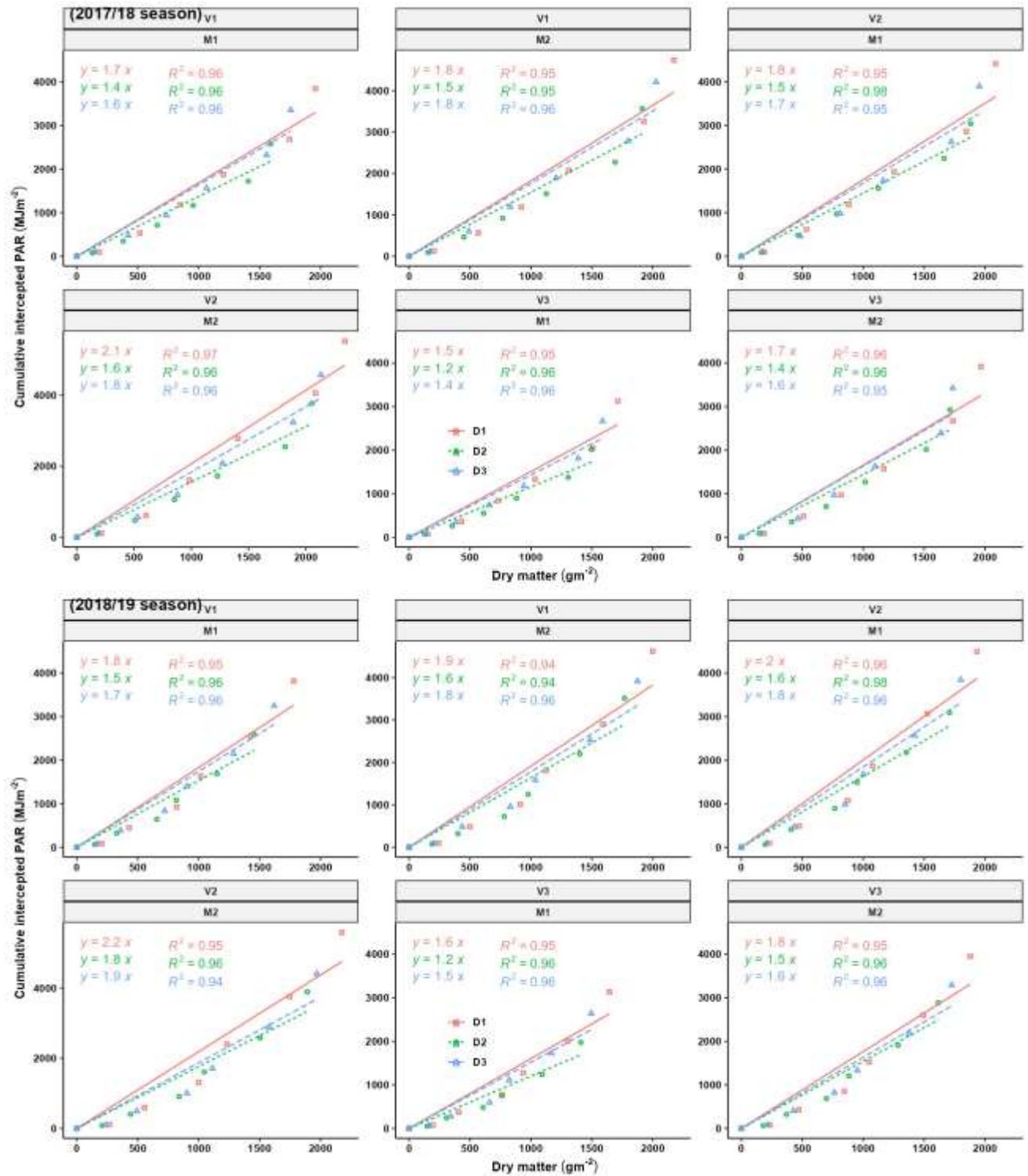


Figure 20: Radiation use efficiency of several cassava varieties at different defoliation frequencies under two fertility management options during the growing seasons. Key: D1= Control (No leaf harvesting), D2=Leaf harvesting at 2weeks intervals and D3= Leaf harvesting at 3weeks intervals, V1=Bangweulu, V2=Mweru Fertilizer + lime (Optimal cassava management and V3=Katobamputa, M1= No fertilizer without lime (low input farmer practice), M2= Fertilizer +lime (Optimal cassava management)

The RUE ranged between 1.2gMJ^{-1} - 2.2gMJ^{-1} across varieties and leaf harvest intervals in response to fertilization regimes (Figure 20). Current RUE values for two seasons are consistent and fall within the lower and higher bracket of the RUE range of $1.15\text{-}2.30\text{ gMJ}^{-1}$ obtained by Pellet and El-Sharkawy (1997). However, in other studies conducted by Ezui *et al.* (2017) a seasonal RUE value of 1.16 was obtained in similar studies in West Africa, a value close to our lowest RUE. These findings could be attributed to the fact that in current-studies and both seasons, the study site received adequate rainfall to support cassava growth of 1919mm and 1859mm in the 2018 and 2019 seasons respectively (Figure 2) compared to low rainfall of 574 to 736 mm for their study. Increased varietal RUE and total dry biomass of cassava varied differently in response to NPK fertilizer and liming and leaf harvesting intensity. Similar findings were observed by Pellet and El-Sharkawy (1997) whose results showed a significant increase in varietal RUE in response to fertilization compared to unfertilized treatments. However, the current RUE was affected by the leaf harvesting interval where the lowest values observed were associated with a biweekly leaf harvesting frequency

6.3 CONCLUSION

This study established that harvesting 5-8 young leaves per plant may not affect cassava yield at low harvesting frequency (3 weeks intervals). Cassava growth, root yield and radiation use efficiency are affected when leaf harvesting is done at short intervals of 2 weeks or shorter. Harvesting of cassava leaves needs to be well timed with a strict selection of varieties as leaf harvesting impacts negatively on LAI and RUE, consequently affecting crop productivity. Improved fertilization for cassava can greatly reduce the negative impact of leaf harvesting through the increase in leaf formation, enhanced photosynthesis, improvements in sugar levels and translocation of resources to the roots compared to unfertilized treatments. These results imply a strict recommendation for small-scale farmers regarding leaf harvesting and storage root production. In this case, varietal selection and fertilization are key to the success of such an

undertaking. For as long as leaf harvesting frequency does not exceed our recommended regimes applied in this study, cassava growth, root yield and ability of biomass production (RUE) may rarely be affected. The improved high-yielding cassava varieties such as Mweru and Bangweulu ought to be promoted for both root and leaf vegetable production for nutrition security.

It may be noted here that more studies ought to be done with more competitive leaf harvesting intervals with more varieties. Improved cassava varieties such as Mweru and Bangweulu should be adopted in the design of a more realistic recommendation for farmers intending to use cassava as a leaf vegetable with minimal effects on growth and root yield production. In this study application of NPK fertilizer and the liming combination resulted in a significant increase in varietal yield components (Seasonal LAI, plant height, root diameter, leaf chlorophyll, stem diameter and harvest index) and root yield regardless of the leaf harvesting interval. It can therefore be recommended that the application of NPK fertilizer and lime in cassava cropping systems with low soil fertility and high acidity will likely lead to larger responses of mineral fertilizers and lime and result in serious economic farmer benefits. More studies and information on fertilizer responses under different agro-ecologies are needed to develop suitability and well-tailored production systems that are more resilient and cost-reflective to smallholder farmers.

CHAPTER SEVEN

7.0 GENERAL CONCLUSION

Relative to study objectives, the following general conclusions were drawn from this study:

7.1 Evaluation of selected cassava varieties for morphological and physiological responses to fertilization regimes

- All test varieties responded similarly to the application of NPK fertilizer + lime, NPK fertilizer, lime and the control treatments.
- applying NPK fertilizer + lime or NPK fertilizer only treatments significantly resulted in higher yield when compared to lime or the no fertiliser control in cassava cropping systems. Furthermore, the study revealed that RUE, Mean LAI and number of tubers per plant were the most yield determinant factors in cassava.
- The improved variety Mweru was the best in terms of what followed by Bangweulu while the local landrace Katoba mputa was outperformed at all fertilization regimes. Landrace does not respond to improved fertiliser regime.
- The study suggests within study limits of only 2 varieties, that selection of appropriate cassava LAI during development and storage root accumulation stages with a high light interception and RUE could be used as a criterion for selecting varieties in breeding programs.

7.2 Varietal response to NPK fertilization

- The study demonstrated how varieties do respond to low-nutrient soils and with greater response to fertilization varieties Mweru and Bangweulu out-yielded the traditional variety Katobamputa.

7.3. Effect of fertilization and leaf harvesting on cassava growth, yield, physiology and yield components

- The study revealed that frequent leaf harvesting such as harvesting of cassava leaves every after two reduces cassava root yield in comparison to three weeks' leaf harvesting.
- Application of NPK fertilizer and the lime increased root yield and yield components (Seasonal LAI, plant height, root diameter, leaf chlorophyll, stem diameter and harvest index) regardless of the leaf harvesting interval applied.
- The findings reveal that the positive effects on cassava growth and yields and economic benefits from fertilizer are larger with variety choice.

CHAPTER EIGHT

8.0 RECOMMENDATIONS

Therefore, it is concluded that the development of agricultural technology packages that include improved, high yielding and disease-resistant cassava varieties, improved agricultural practices and the use of NPK fertilizers will considerably reduce the yield gaps between the actual and attainable yields of cassava at a small scale and thereby significantly contribute to improving the livelihoods of smallholder cassava farmers.

Our results show the importance of integrated soil fertility management (ISFM) in achieving higher root yield, physiology and morphological traits under rain-fed conditions in Chromehaplic Acrisol low-nutrient soils in the northern belts of Zambia. The study highlights the importance of an improved variety of use and fertilization as a way of improving cassava yields in nutrient-exhausted soils.

The indirect advantages of enhanced cultivars with superior adaptability entail enhanced responsiveness to NPK fertilization and reduced time to harvest. Hence, it is crucial to utilize genetic variety in cassava to choose varieties that exhibit enhanced production responses, aligned with diverse cropping strategies. More studies and information on specific NPK fertilizer rates responses under different agro-ecologies need to be conducted to help develop cassava soil suitability and well-tailored production systems that are more resilient and cost-reflective to smallholder farmers. Furthermore, cassava varieties ought to be studied for dual purposes especially when cassava leaves in Zambia form part of a nutritious leaf vegetable apart from the uses of meal for Nsima as well as in starch and ethanol production for industrial purposes.

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10.0 APPENDICES

APPENDIX A: SOILS DATA, PRODUCTION COSTS AND PRODUCTION TREND

A1: Selected physio-chemical properties of the topsoil (0-20cm depth) of the experimental site at Zambia Agricultural Research Institute (ZARI) Mansa

Parameter	Unit	Mean 2018		Cassava suitability production levels
			Mean 2019	
pH(CaCl ₂)	-	4.47	4.48	4.5-7.0
Total N	%	0.21	0.25	0.20-0.50
Org C	%	0.23	0.29	2.0-4.0
Exchangeable P	mg kg ⁻¹	2.5	2.8	10 - 14
Exchangeable K	(cmol kg ⁻¹)	0.07	0.09	0.15-2.5
Exchangeable Ca	(cmol kg ⁻¹)	0.87	0.94	1.0-5.0
Exchangeable Mg	(cmol kg ⁻¹)	0.17	0.21	0.4-1.0
Exchangeable Na	(cmol kg ⁻¹)	0.004	0.002	
Micronutrients				
Zn	(mg kg ⁻¹)	0.61	0.58	0.5-1.0
Cu	(mg kg ⁻¹)	5.12	4.89	0.1-0.3
Mn	(mg kg ⁻¹)	50	48	10 - 100
Fe	(mg kg ⁻¹)	72	71	10 - 100
Particle size(%)				
Sand		74	73	
clay		4.3	4.2	
Silt		20.7	20.6	
Textural class		sandy clay loam	Sandy clay loam	Sandy loam

Source: CIAT

A.2: Cassava production costs for a hectare (Without fertilizer)

Cassava production costs for a hectare(Without fertilizer)		Unit cost	Total
S/N	Control Costs Activity	unit	Amount (ZMK) Amount (ZMK)
1	Making ridges		800
2	Planting material		960
3	Planting		320
4	Weeding K400 x 2		800
5	Harvesting		560
6	Supervision		600
	Total Costs		4040
	Revenue(price cassava K3/kg dried*Yield)	6029.0 3	18087
	Profit		17305
	Yield Kg/ha for highest yielding variety		11,616
	Yield Kg/ha for lowest yielding variety		6029.0

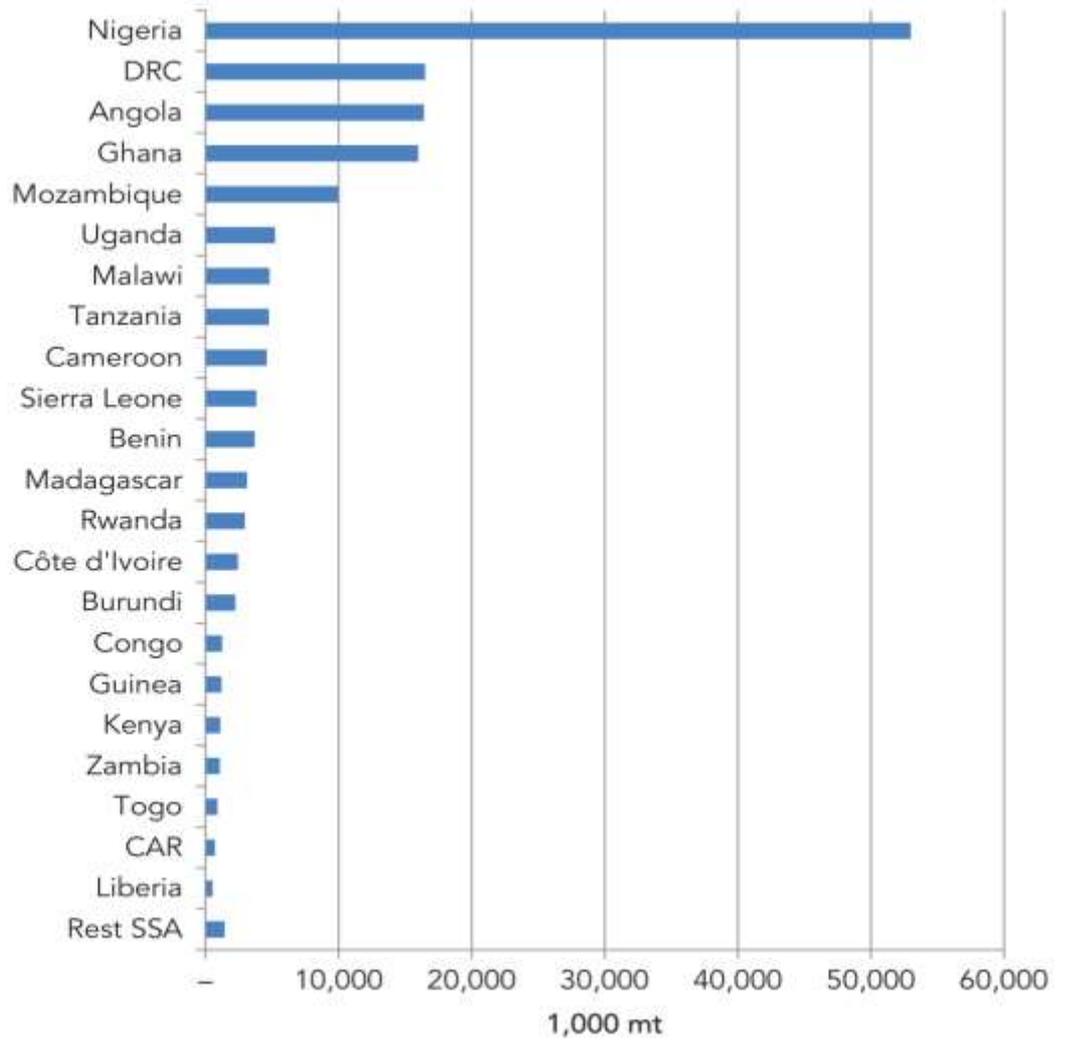
1USD=21.11 (August 2021)
Profit in USD=17305/21.11
819.75 USD

A.3 Production costs with Fertilizer and Lime per Ha of Cassava

A.3. Cassava production costs for a hectare with fertilizer and lime				
S/N	Fertilizer and lime regime costs Activity	Unit	Unit Cost AmountZMK	Total AmountZMK
1	Making ridges			800
2	Planting material			960
3	Planting			320
4	Weeding K400 x 2			800
5	Harvesting			560
6	Supervision			600
	Subtotal			4040
	Fertilizer costs per Ha			
7	Fertilizer Urea(N)50kg bag	4	400	1600
8	Fertilizer Triple superphosphate 50kg bag	3	400	1200
9	Fertilizer Muriate of Potash(K) 50kg bag	3	400	1200
10	lime 300/Kgs	1	135	135
	Subtotal			4135
	Total Costs			8135
	Revenue(price cassava K3/kg dried chips*Yield)	11,616 3		34848
	Profit			26713

1USD=21.11(August 2021)
Profit in USD = 26713/21.11 =**1265.42 USD**

A.4 Cassava production by country in sub-Saharan Africa, 2013. Source: FAOSTAT, 2/12/2015



APPENDIX

B: PUBLICATIONS SEMINARS AND CONFERENCES

Publications

Mwamba, S.; Kaluba, P.; Moualeu-Ngangue, D.; Winter, E.; Chiona, M.; Chishala, B.H.; Munyinda, K.; Stützel, H. Physiological and Morphological Responses of Cassava Genotypes to Fertilization Regimes in Chromi-Haplic Acrisols Soils. *Agronomy* 2021, *11*, 1757. <https://doi.org/10.3390/agronomy11091757>

B2 Conferences

1. **14th Symposium International Society of Tropical Root Crops-Africa Branch (ISTRC-AB) 2021 held in Lusaka, Zambia (20-24th September 2021).** Genetic Response of Cassava Varieties to Fertilization Regimes in the Northern part of Luapula Province in Zambia.