SUSTAINABLE INTENSIFICATION OF MANAGEMENT PRACTICES IN CASSAVA PRODUCTION SYSTEMS OF LUAPULA PROVINCE OF ZAMBIA

By

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DECLARATION

I, Peter Kasolota Kaluba, hereby declare that all the work presented in this thesis is my own original work and has never been submitted for a degree award in any other university.

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Peter Kasolota Kaluba Date

CERTIFICATE OF APPROVAL

This thesis of Peter Kasolota Kaluba was approved as fulfilling the requirements for the award of the degree of Doctor of Philosophy in Soil Science by the University of Zambia.

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ABSTRACT

Cassava (Manihot *esculenta Crantz*) is a staple food and a main source of income for several smallholder farmers. However, its yields are low at about 6 t/ha, lower than actual yields of 20–25 t/ha in Zambia. The main objective of the study was to assess sustainable management practices in cassava production systems among smallholder farmers in Luapula Province of Zambia. A baseline study aimed at understanding cropping management practices and their effects on selected soil nutrient adequacy levels and tuber yield was carried out. Using baseline results, a field experiment was conducted aimed at assessing the performance of cassava under lime, fertilizer and grain legume intercropping on exhausted soils. Common bean being the most intercropped légumes in cassava systems with low grain yields at 0.5 t/ha partly due to leafy defoliation, an, assessesment of the effects of leaf defoliation intensity and fertilizer on growth, RUE and yield of three common bean varieties was conducted. The data generated from these experiment was analyzed using the linear mixed models at 5% levels of significance using the R software. Multiple regression analyses was performed on significantly correlated variables. The study found K and P to be highly suitable for optimal cassava production, although yields declined by 209 and 622 kg/ha at 12 and 36 for each year of cultivation without fertilizer application. Field use in the study area was limited to 8–9 years due to soil nutrient depletion. The synergistic effect of exchangeable K on growth was limited by the low to moderate availability of soil organic carbon (SOC), Ca, Mg and low N. These limited the growth and consequently reduced intercepted radiation and low yields, thus the need for routine balanced fertilizer regimes. On average, for every kg of cassava yield loss in intercropping was compensated by 0.46 kg soybean, 0.20 kg common beans and 0.26 kg of cowpea. Cassava LAI, RUE, tuber yield and grain legume yields were significantly increased by liming, fertilizing and legume species intercropping. The use of amendements achieved cassava yields obtained between 24–36 MAP under shifting cultivation at 12 MAP. The RUE reductions were higher in fertilized than unfertilized treatments. Fertilizing indeterminant growth habit common beans enhanced growth, producing optimal grain and biomass yield at 25% defoliation intensity. To promote adoption, liming, fertilizing and legume intercropping at 25% defoliation intensity in cassava production systems should be conducted on exhausted soils in farmer's field.

DEDICATION

To my wife Malama and our children Chibusa Kaluba, Ng'andwe Kaluba, Fadile Kaluba, Msinje Kaluba and Nandi Kaluba; my father Licky Kaluba and to the mothers in my life Christine, Dainess, Late Maureen, Josephine and Majory Aggie; Uncle Webby Machilika and my siblings, thank you all for your love and support. My late Mummy Edith Machilika and Late Uncle John Chanda for helping me take the first steps to school and to the entire Machilika and Kaluba families.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

ABBREVIATION AND ACRONYMS

Abbreviation	Description	Units
ZARI	Zambia Agricultural Research Institute	
RUE	Radiation Use Efficiency	g DM/MJ PAR
k	Canopy Extinction Coefficient	
DM	Dry Matter	
TDM	Total Dry Matter	
AGB	Above Ground Biomass	
BNF	Biological Nitrogen Fixation	
GLM	General linear model	
GPS	Global positioning system	
ISFM	Integrated soil fertility management	
MAP	Months after planting	
DAP	Days after planting	
SOM	Soil organic matter	
t/ha	Tons per hectare	
AAS	Atomic absorption spectrometry	
ANOVA	Analysis of variance Association	
f	Fraction of intercepted photosynthetic active radiation	%
TIPAR	Total intercepted photosynthetic active radiation	MJ/m^2
LAI	Leaf Area Index	
SSA	sub-Sahara Africa	
r	Correlation coefficient	%
AEZ	Agro-ecological region	
HI	Harvest index	
DR Congo	Democratic Republic of Congo	
C	Sole cassava/Cassava monocropping	
SB	Cassava/soybean intercropping	
CB	Cassava/common beans intercropping	
CP	Cassava/cowpea intercropping	
DI	Defoliation intensity	%
F0	No fertilizer applied	
F1	Fertilizer applied	
L0	No lime applied	
L1	Lime applied	

CHAPTER ONE

1. INTRODUCTION

1.1 Background

Cassava (*Manihot esculenta Crantz*) is a cash crop to over 700 million smallholder farmers in remote areas of Africa (Fermont, 2009; Njoku et al., 2010). It is a staple food which contributes about 30% of daily calorie requirements per person in Africa (Bennet, 2015). Cassava is mainly cultivated for its storage roots (El-Sharkawy, 2006) although its leaves are widely consumed as leafy vegetable (Latif and Müller, 2015). The cassava storage roots have a high starch content of up to 90% of dry matter, thus making it the second most important source of calories in Africa after maize. Cassava leaves are widely consumed by humans as leafy vegetable and as a source of protein (14–40% on dry weight basis), vitamins (vitamin B1, B2, B6, C), carotenes and minerals (potassium, iron, calcium, sodium) (Adewusi and Bradbury, 1993; Dada and Oworu, 2010; Latif and Müller, 2015). Africa produces more than half of the globally produced cassava. Extreme climate events inform of drought have had devastating effects on most crops, thus increasing the dependence on cassava (Roudier et al., 2011). This is manifested by an increase in cassava production to meet the increasing demand for food and fibre due to the escalating population. However, this increase in yield is due to increasing land area under production rather than increased productivity per hectare basis (FAOSTAT, 2018).

Cassava average yields in African have stagnated at about 10 t/ha which is lower than 20 t/ha and above in other continents (FAOSTAT, 2018). For example, a maximum yield of about 30 t/ha has been reported in India (FAOSTAT, 2018). However, in East Africa, tuber yields higher than the African average of 10 t/ha has been reported by several researchers under farmer field conditions. These includes; 15–40 t/ha in Uganda and Kenya (Ntawuruhunga et al., 2006), 6–17 t/ha in Kenya and Uganda without fertilizer (Fermont et al., 2010), 10.6 t/ha in Kenya and 12.0 t/ha in Uganda (FAOSTAT, 2018), 7–17 and 13–14 t/ha in farmer's field in DR Congo by Munyahali et al. (2017a) and Kintché et al. (2017) respectively. In another study, under field trials in DR Congo, Munyahali et al. (2017b) reported tuber yields of 20–25 t/ha. In Luapula Province of Zambia, cassava is the main crop grown by smallholder farmers under shifting cultivation systems under rainfed conditions

(Bennet, 2015). Recent adverse effects of climate variability and change (Roudier et al., 2011), have increased dependence on cassava production since it thrives and produces reasonable yields where other crops fail completely (Howler and Cadavid, 1983). However, the productivity of the crop is at below 6 t/ha lower than actual yields of 20–25 t/ha (Ntawuruhunga et al., 2006) under similar farming systems. This average yield of 6.0 t/ha observed in 2016 (FAOSTAT, 2018) is far below the world average yields of 11.8 t/ha and the attainable yield of over 30 t/ha, which implies a very large yield gap of 50% and over 83%, respectively.

Cassava thrives on poor soils (Howler and Cadavid, 1983) and is tolerant to drought conditions induced by climate variability and change (Roudier et al., 2011). This explains why farmers perceive cassava to be tolerant to poor soils (Leindah Devi and Choudhury, 2013; Salcedo et al., 1997; Bruun et al., 2006) and therefore it is grown on severely depleted soils. However, Asher et al. (1980) reported that at a tuberous yield of 30 t/ha cassava removes major nutrient amounts of 164 kg N/ha, 31kg P/ha and 200 kg K/ha at harvest from the soil. Overtime, such soils have become nutrient deficient in many cassava growing areas (Howler and Cadavid, 1983; Sanginga et al., 2003; Wood et al., 2016; Kintché et al., 2017; Munyahali et al., 2017b). According to Eke-Okoro et al. (1999), cassava rapidly depletes soil nutrients, unless the absorbed or lost nutrients are replenished. Cassava is mostly grown by smallholder farmers who have limited access to inorganic fertilizer because of its high cost (Njoku et al., 2010). Therefore, there is need for direct use of soil amendments in cassava production which is low to meet the higher yield potentials of various improved cassava varieties (Eke-Okoro et al., 1999; Njoku et al., 2010).

Cassava intercropping produces more than half of the cassava grown in Africa (Okigbo and Greenland, 1976) and has several advantages over sole-cropped cassava. It helps reduce soil nutrient exhaustion (Howeler, 1991) and maintenance of soil fertility (Njoku et al., 2010), ensures higher yield stability (Dapaah et al., 2003), minimizes the adverse effects of diseases, weeds and pests (Thung and Cock, 1978; Pypers et al., 2011). Cassava is intercropped with legumes or cereals under shifting cultivation systems by smallholder farmers in the tropics. These apply little or no use of inorganic fertilizer (Howeler, 1991; Leindah Devi and Choudhury, 2013). Kawano and Thung (1982) reported a minimal cassava yield reduction of 9–13% due to common bean or soybean intercropping at a plant density of

25 plants/m^2. Makinde et al. (2007) observed a 10–23% increase in cassava yield due to soybean residue incorporation, but only after two years of cassava–soybean intercropping. The evaluation of the performance of cassava under lime, fertilizer, and legume (common bean, soybeans and cowpea) intercropping on exhausted soils in Luapula Province of Zambia has rarely been assessed.

Common bean (Phaseolus *vulgaris*) is the most grown in cassava intercropping by smallholder farmers in Luapula Province (kaluba et al., 2021). Common bean is an important source of inexpensive protein, vitamins and minerals to millions of people in developed and developing countries (Ghavidel et al., 2016). However, common bean grain yields are still low at 0.5 t/ha compared to actual yield of 2.5 t/ha. The low yields of less than 0.5 t/ha in common beans among smallholder farmers are due to partial leaf defoliation for food which reduces the photosynthetic area and capacity and ultimately causes low biomass yield without substantial contribution to organic carbon build in cassava production systems and biological nitrogen fixation. Further, there is low or no use of fertilizer in common beans during the growing season (Dube and Fanadzo, 2013). When plants are defoliated, there is a reduction in green leaf area resulting in low intercepted photosynthetic active radiation (f) and thus low radiation use efficiency (RUE) (Dube and Fanadzo, 2013). Since this crop has dual purpose, the leaf defoliation effects on bean growth and yield are imperative to understand in order to maximize yields in cassava systems.

1.2 Statement of the Problem

Cassava is the main crop grown by smallholder farmers under shifting cultivation systems under rainfed conditions in Luapula Province of Zambia. Cassava is grown with little or no fertilizer because of its high cost. Recent adverse effects of climate variability and change have further increased the dependence on cassava production since it thrives and produces reasonable yield where other crops fail completely. Low soil fertility is prevalent in many cassava growing areas because of short fallow periods due to increasing pressure on arable land. The increase in cassava production in order to meet the increasing population and demand by the agro–industry is due to expansion of area under production rather than productivity. In the study area, current cassava yields are low at about 6 t/ha (FAOSTAT, 2018) and was confirmed by a baseline study. This yield is lower than actual yields of 20–25 t/ha and the world average yields of 11.8 t/ha under similar farming conditions. Thus it is important to understand crop management practices in cassava production systems among smallholder farmers in Luapula Province of Zambia. More than half of the cassava produced in Africa is grown under intercropping. However, the performance of cassava under lime, fertilizer and legume intercropping on exhausted soils has not been fully understood. Common bean is the most grown in cassava intercropping than soybean and cowpea by smallholder farmers in cassava production systems and grain yields is at 0.5 t/ha compared to actual yield of 2.5 t/ha. Among the causes of low yield, is the defoliation (harvesting) of leaves for leafy vegetables during the growing seasons which affects the photosynthetic capacity and results in low biomass or organic carbon in cassava production systems. Therefore, an evaluation of leaf defoliation intensities and fertilizer on the compensatory growth and yield of common beans varieties is imperative to understand both grain and biomass yield in cassava systems has rarely been addressed. The current work aimed at evaluating sustainable cropping management practices in cassava production systems among smallholder farmer's to formulate integrated soil fertility management (ISFM) measures which aimed at increasing and stabilizing cassava productivity through liming, fertilizer application and legume intercropping on exhausted soils.

1.3 Objectives and hypotheses

1.3.1 Main objective

The main objective of this study was to assess sustainable management practices in cassava production systems of Luapula Province of Zambia

1.3.2 Specific objectives

The specific objectives of this study were:

1. To evaluate cropping management practices affecting soil nutrient adequacy levels and cassava tuber yield in smallholder farming systems of Luapula Province of Zambia.
2. To assess the performance of cassava under lime, fertilizer and legume intercropping on exhausted soils of Luapula Province of Zambia.
3. To evaluate the effects of leaf defoliation intensities and fertilizer on compensatory growth and yield of common bean varieties.

1.3.3Hypotheses

The research hypotheses were:

1. Cassava management practices do not affect soil nutrient adequacy levels and tuber yield in smallholder farming systems.
2. Lime, fertilizer application and legume intercropping do not increase the performance of cassava on exhausted soils.
3. Fertilizer application and leafy defoliation do not increase the compensatory growth and yield of common beans varieties.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Overview of cassava production

Cassava (*Manihot esculenta Crantz*) is a staple food and contributes about 30% of daily calorie requirements per person in Africa (Bennet, 2015). It is a cash crop to over 700 million smallholder farmers in remote areas of Africa and plays an important role in enhancing food security (Fermont et al., 2009; Njoku et al., 2010). Cassava production only started seriously in the 20th century despite being introduced to Africa in the 16 to 18th century (Hillocks, 2002; Jones, 1959). Cassava is mainly cultivated for its storage roots (El-Sharkawy, 2006) although its leaves are widely consumed as leafy vegetable (Latif and Müller 2015). The cassava storage roots have a high starch content of up to 90% of the dry matter, thus making it the second most important source of calories in Africa after maize. It is consumed as root flours and meals, with other domestic products including snacks, starch, green leaves for human and livestock feed (FAO/IFAD, 2001). Other world market products from cassava include alcohol, starch, gari, tapioca, and dried chips (FAO/IFAD, 2001). Cassava leaves are widely consumed by humans as leafy vegetable and as a source of protein (14–40% on dry weight basis), vitamins (vitamin B1, B2, B6, C), carotenes and minerals (potassium, iron, calcium, sodium) (Adewusi and Bradbury, 1993; Dada and Oworu, 2010; Latif and Müller, 2015).

Cassava production in Africa has been steadily increasing to more than 150 million tons in 2016 (FAOSTAT, 2018). This consequently makes Africa to produce more than half of the globally produced cassava (277 million tons). Although Africa produces more than half of the global cassava production, this observed increase in yield is due to increasing land area under production rather than increased productivity per hectare basis. The continental average yields have stagnated at around 10 t/ha (FAOSTAT, 2018). According to Fermont et al. (2009) and Munyahali et al. (2017a), the observed increase in area under cassava production in Africa is a result of the declining soil fertility level in this region. Despite Africa producing more than that of the world cassava, yields are highest outside this continent where the average yield is 20 t/ha and above. For example, a maximum yield of about 30 t/ha have been reported in India (FAOSTAT, 2018). Further, in East Africa, tuber yields higher than the African average of 10 t/ha have been reported by several researchers under farmer field conditions. These include; 15–40 t/ha in Uganda and Kenya (Ntawuruhunga et al., 2006), 6–17 t/ha in Kenya and Uganda without fertilizer (Fermont et al., 2010), 10.6 t/ha in Kenya and 12.0 t/ha in Uganda (FAOSTAT, 2018), 7–17 and 13–14 t/ha in farmer's field by Munyahali et al. (2017a) and Kintché et al. (2017) in DR Congo respectively. In another study, under field trials in DR Congo, Munyahali et al. (2017b) reported tuber yields of 20–25 t/ha.

In Luapula Province of Zambia, cassava is the main crop grown by smallholder farmers under shifting cultivation systems under rainfed conditions (Bennet, 2015). Recent adverse effects of climate variability and change (Roudier et al., 2011), have increased dependence on cassava production since it thrives and produces reasonable yield where other crops fail completely (Howler and Cadavid, 1990). However, the productivity of the crop is about 6 t/ha lower than actual yields of 20–25 t/ha (Ntawuruhunga et al., 2006) under similar farming conditions. This average yield of 6.0 t/ha (FAOSTAT, 2018) is below the world average yields of 11.8 t/ha and the attainable yield of over 30 t/ha, which implies a very large yield gap of 50 % and over 83 %, respectively.

Cassava is able to thrives on poor soils where many crops fail completely (Howler and Cadavid, 1983) because of tolerances to drought conditions induced by climate variability and change (Roudier et al., 2011). This explains why farmers perceive cassava to be tolerant to poor soils (Leindah Devi and Choudhury, 2013; Salcedo et al., 1997; Bruun et al., 2006) and therefore it is grown on severely depleted soils. However, Asher et al. (1980) reported that a tuber yield of 30 t/ha removes major nutrient amounts of 164 kg N/ha, 31 kg P/ha and 200 kg K /ha at harvest from the soil. Overtime, such soils have become nutrient deficient in many cassava growing areas, since the fallow periods have shortened in response to the ever escalating food demand (Howler and Cadavid 1983; Sanginga 2003; Wood et al., 2016; Kintché et al., 2017; Munyahali et al., 2017a). According to Eke-Okoro et al. (1999), cassava rapidly depletes soil nutrients, unless the absorbed or lost nutrients are replenished. Cassava is mostly grown by smallholder farmers who have limited access to inorganic fertilizer because of its high cost (Njoku et al., 2010). Therefore, there is need for direct use of soil amendments in cassava production which is low to meet the higher yield potentials of various improved cassava varieties which is often not attained (Eke-Okoro et al., 1999; Njoku et al., 2010).

2.2 Factors affecting the production of cassava

2.2.1. Cassava growing conditions

Cassava is a perennial shrub with a height of 1 to 4 m belonging to the family of Euphorbiaceae. It produces thick roots mostly filled with starch which is harvested (Howeler, 2014) from 6 to 24 months after planting (MAP) depending on the cultivar, purpose of use and growing conditions (El-Sharkawy, 2006). It is grown under variable rain-fed conditions of less than 600 mm to more than 2000 mm per year in the semi-arid tropics (De Tafur et al., 1997) and sub-humid and humid tropics respectively (Pellet and El-Sharkawy, 1997). Cassava undergoes a physiological rest mainly in the dry seasons and cold seasons associated with stagnant growth (Fernandes et al., 2017). Cassava requires a warm climate with a mean day temperature greater than 20 °C for optimum growth and production. However, to maximize leaf photosynthesis an optimum leaf temperature of 20–25 °C is ideal (El-Sharkawy et al., 1992).

Unlike the two phase crop development pattern known for grain crops, comprising of the vegetative and reproductive phases separated by time, in cassava, shoots (stems and leaves) and roots develop simultaneously from 3–5 MAP and thus there is competition for assimilates which are partitioned between the growth of leaves and storage roots (Lahai et al., 2013). The distribution of dry matter to different organs of cassava plant is dominated by the shoot in the first 3–5 MAP and ultimately the root storage for the rest of the growth cycle (El-Sharkawy, 2004). Tuber yield is therefore, determined by both the source supply (the amount of carbohydrates available in the above ground biomass) and the sink demand (the amount of carbohydrates that can be stored in the storage roots). The source supply is related to the LAI and the net assimilatory rate while sink demand is related to the number of storage roots and their mean weight (Alves, 2002; El-Sharkawy, 2004).

2.2.2. Exchangeable potassium (K) effects on cassava yield

Exchangeable K has several functions in cassava plant growth among them is the quick reestablishment of the leaf area of the crop, which consequently improves yield (Silva and Trevizam, 2015; Umeh et al., 2015; Fernandes et al., 2017). The higher uptake of exchangeable K has been observed to have synergist effects in cassava which brings about increased uptake of other nutrients such as exchangeable Mg and Ca (Silva and Trevizam, 2015; Fernandes et al., 2017) which optimizes growth and increases yields. When exchangeable Mg is deficient, it could indicate that there is a need to include K or Mg in the fertilization regimes to increase tuber yield. Several authors have observed exchangeable K to influence the mineral nutrition of Ca and Mg (Silva and Trevizam, 2015; Umeh et al., 2015; Fernandes et al., 2017). Kintché et al. (2017) found that imbalanced K versus exchangeable Ca and Mg to be the limiting factor in most cases in the DR Congo. This nutrient imbalance has been supported by many authors who have found cassava to take up more potassium from the soil than Ca and Mg (Howeler, 1991; Putthacharoen et al., 1998). In a cassava soil suitability assessment in Nigeria, total nitrogen, exchangeable cations and phosphorus were found to be deficient and limited tuber formation (Abua, 2015). Apart from exchangeable K and Mg, Munyahali et al. (2017a) reported soil reaction (pH) to be one of the factors explaining the variability observed in cassava yields in DR Cong.

2.2.3. Fallow duration effects on exchangeable potassium in cassava systems

Although, the slash and burn method of land management works well with cassava production, the practice is not sustainable in the long run due to nutrient depletion and causes farmers shift to other places (Chase and Singh, 2014). For example, Howeler (2002) reported that exchangeable K decreased to 0.07 cmol (+)/kg below the critical level of 0.15 cmol (+)/ kg in the seventh year of continuous cassava cultivation without K fertilizer application at CIAT-Quilichao in Colombia. In India, Kabeerathumma et al. (1990) observed a yield decrease from 22 t/ha in the first year to about 6 t/ha in the tenth year without K fertilizer application. Further, den Doop (1937) reported that cassava yields declined from 15 t/ha in the first year to 4 t/ha in the third of cultivation after three consecutive plantings without applying K fertilizer. Similarly, Pellet and EL-Sharkawy (1997) reported that plant-available soil K concentration to decrease from the first to the second growing season, irrespective of the fertilizer treatment. However, Howeler, (1991) suggested that the K content of the soil and root yield could be maintained for over eight consecutive cassava cropping cycles, using a yearly application of at least 125 kg K/ha. Mansfield et al. (1975) reported 4–6 years as the land use duration for cassava cultivation in the Northern part of Zambia.

2.2.4. Effects of weeding frequency on cassava yield

Several studies have recognized poor weed management as an important constraint to cassava production (Munyahali et al., 2017a; Fermont, 2009; Leihner, 2002; Melifonwu, 1994). For example, Kintché et al. (2017) reported a twice weeding session by majority of farmers in DR Congo for the entire cassava cycle. The twice weeding frequency has been recommended to increase cassava productivity when done at the right time. According to Leihner (1983), the critical period for weed competition with cassava lasts up to 4 months after planting (MAP).

2.2.5. Tradeoffs in cassava yield in soybean, common beans and cowpea intercropping

Cassava intercropping produces more than half of the cassava grown in Africa (Okigbo and Greenland, 1976). Cassava intercropping with grain legumes has several advantages over sole-cropped cassava. It helps reduce soil nutrient exhaustion (Howeler, 1991) via maintenance of soil fertility (Njoku et al., 2010), higher yield stability (Dapaah et al., 2003) and minimizing the adverse effects of diseases, weeds and pests (Thung and Cock, 1978; Pypers et al., 2011). Leihner (1983) reported that cassava intercropping with short-duration crop to be more productive than sole-cropping of individual species. The protein content of cassava is very low thus the need for cassava grain legume mixes to satisfy dietary requirements (Thung and Cock, 1978). For example, legumes such as common beans and cowpea (*Vigna unguiculata*) can be used as dual purpose as a food crop and a soil fertility improver. The amount of N fixed by legumes and residual benefits varies with plant species, agronomic practices and environmental factors. The ranges of nitrogen fixed by various species includes 30-60 kg N/ha by soybean (Pypers et al., 2011), 88 kg N/ha by cowpea (Eke-okoro et al., 2001) and common bean fixed the least amount. The maximum benefits in intercropping systems are attainable when combined with nutrient addition (Olasantan et al., 1994).

Cassava is intercropped with legumes or cereals under shifting cultivation systems by resource poor farmers in the tropics. These apply little or none of inorganic fertilizer (Howeler, 1991; Leindah Devi and Choudhury, 2013). Recently, there is an increasing demand for cassava as a raw material by local agro and industrial markets for many products

(Bennet, 2015). This is exacerbated by the escalating population whose demand for food and fuel is on the rise (Styger et al., 2007). For instance, fresh cassava tubers contains about 4 kg K per ton (Howeler, 1981), thus a yield of 30–40 t/ha can remove about 120–160 kg K/ha (Howeler and Cadavid, 1983). Similarly, Asher et al. (1980) reported that tuber yield of 30 t/ha can remove 164 kg/N/ha, 31 kg P/ha and 200 kg K/ha from the soil. Cassava intensification under these low input systems has led to loss and degradation of agricultural land (Howeler, 1991) due to reduced fallow durations (Styger et al., 2007; Wood et al., 2016).

Cassava leaves slowly covers the ground; with complete cover occurring some 3 months after planting, therefore is highly sensitive to early competition (Cock et al., 1978). Tsay et al. (1989) reported that soybean when planted in cassava intercropping were taller than the accompanying cassava until 40 DAP in any N treatment. Most grain legumes such as common bean and cowpea develops very rapidly and often completes its growth cycle in 90 days or less (Doll and Piedrahita, 1974). The associated crop that normally matures before severe competition develops between the two species can minimize the effects on cassava growth and yield (Tsay et al., 1988a). Kawano and Thung (1982) reported that there was no significant relationship of leaf and stem weight with tuber yield ($r = 0.34$) at 3 month after planting and suggested such high-yielding cassava genotypes to be suitable for intercropping with common bean without sacrificing either common bean or cassava yield. However, some cassava varieties which were characterized by higher leaf and stem weight at early stages of growth intercepted more light than did the other types with less light interception and thus shaded common bean or soybean plants more severely. The stem and leaf weight at harvest was negatively correlated with harvest index ($r = -0.84^*$), indicating that those genotypes are strong competitors since they translocates more photosynthesized products to the aerial part than to the roots (Kawano and Thung, 1982). Also, Cenpukdee and Fukai (1992a) reported of the choice of agronomic practices which ranges from selection of cassava cultivar, height, plant density, and sowing time of the associated crop to be important in determining the yields of component crops. Preston et al. (1986) showed the relative plant heights of component crops in intercropping to determine the availability of solar radiation to each species. Further, Cenpukdee and Fukai (1992b) reported cassava canopy width, tuber growth and harvest index (HI) to greatly reduce since the pigeonpea dominated in the intercropping system. Despite this result, Cenpukdee and Fukai (1992b) concluded that canopy width was a more reliable indicator of the performance of cassava/legume intercropping rather than plant height. Leihner (1979) recommended the height increment of component crops to be taken into account in the choice of crops for intercropping.

The total average yields of the 20 cassava accessions planted at 0.93 plants/m^2 in association with common bean (27.1 t/ha) and soybeans (28.3 t/ha) intercropped at a plant density of 25 plants/m^2 were slightly less (9–13%) than in monoculture (31.0 t/ha) (Kawano and Thung, 1982). There was no significant difference in common bean yield under intercropping of 2.35 t/ha compared to monoculture at 2.34 t/ha (Kawano and Thung, 1982). However, soybeans suffered an average of 60% yield reduction when mix-planted with cassava (2.97 t vs. 1.17 t/ha). The severe effects of soybean growth were due to the aggressiveness and long-duration legume to maturity (Cenpukdee and Fukai, 1992a), which exposed it to shading by cassava plants compared to common beans (Kawano and Thung, 1982). Contrary, Borin and Frankow-Lindberg (2005) reported legume intercropping to greatly increase biomass production. Makinde et al. (2007) observed 10–23% increase in cassava yield due to soybean residue incorporation, but only after two years of cassava/soybean intercropping. Although, the contributions from biological nitrogen fixation (BNF) by the legumes cannot be expected to meet the N needs of the cassava crop, it still benefits the cassava crop.

According to Willey (1979), intercropping competition is minimized and complementary effects are maximized. For instance, Njoku et al. (2010) reported of no significant effect of cowpea planted at a density of 8 plants/m^2 on cassava plant height, number of branches, canopy diameter and leaf area index in both years in Nigeria. The highest tuber yield was obtained at the highest cowpea planting density of 80,000 in the second year of the experiment and was due to incremental nitrogen contribution from the legume. Also Cenpukdee and Fukai (1992b) reported of no significant effect on its leaf area index (LAI) when pigeonpea was intercropped at the same time as cassava. Thung and Cock (1979) suggested the variation of the relative planting time up to 5 weeks and reported almost no effect on the competitiveness of the component species in cassava/soybean and cassava/bean intercropping (Tsay et al., 1988b).

2.2.6. Effects of fertilizer on LAI and fraction of intercepted photosynthetic active radiation (f)

LAI development in cassava is slow and reaches a peak at 2–4 months after planting after which the LAI decreases rapidly (Tsay et al., 1989; Howler and Cadavid 1983). This generally corresponds to a drier period of the year and plants react by reducing top growth, which limits plant transpiration (Pellet and EL-Sharkawy, 1997). According to Cock et al. (1979), the cassava critical LAI values of 2.5–3.5 are considered as the optimum to obtain potential yield. However, Howler (2002) reported a LAI greater than 4 to indicate higher nitrogen fertilization which enhances more of vegetative growth thus partitioning less assimilates for growth of storage roots. Biratu et al. (2018a) reported a LAI of 2.7 after a combined application of 1.4 t/ha manure+150N:33P:124.5K kg/ha in Zambia which is within the ideal range considered for tuber production. Fertilizer application results in fast growing of cassava allowing the quickly covering the ground than unfertilized plants. This provides about 50% of the ground cover after two to three months (Pellet and EL-Sharkawy, 1997; Cock and El-Sharkawy, 1988). The higher LAI which corresponds to increased N application could be a result of significant increases in leaf expansion (length and breadth) resulting from cell division and cell enlargement at higher N rates (Pradhan et al., 2018). Lower LAI development in a cassava varietal response to fertilization trials in Columbia has been ascribed to the low soil fertility levels (Pellet and EL-Sharkawy, 1997). Contrary, Cock et al. (1979) observed low LAI regardless of whether the cassava was fertilized or unfertilized. However, Lahai (2013) reported that excessively larger canopies reduces yield due to shaded leaves which respire more carbon than partitioning it to the tubers.

Several authors have emphasized the importance of the canopy for yield formation (Cock and El-Sharkawy, 1988b). The LAI through green leaf area duration and canopy extinction coefficient (k) influence the interception of the solar radiation throughout the crop growing period (Watiki et al., 1993; Thomson and Siddique, 1997; Jeuffroy and Ney, 1997). For example, several authors have reported of higher total intercepted photosynthetic active radiation (TIPAR) and ascribed it to the higher LAI at no water and nitrogen stress conditions (Bassu et al., 2011). Further, Pradhan et al. (2014) reported that the LAI and crop duration with greenness to increase in fertilized treatments and ascribed it to the increased interception of radiation. Bassu et al. (2011) has also observed lower TIPAR in durum wheat due to lower LAI. Similarly, Pradhan et al. (2018) reported that there was a significant higher f when nitrogen was applied at 160 kg /ha than at 40 kg /ha of 13–21% in 2013–2014 and 4–32% in 2014–2015 at almost all stages of its measurement. The lower f at 40 kg N/ha treatments was attributed to the lower LAI than at 160 kg N/ha treatments.

2.2.7. Fertilizer effects on the canopy extinction coefficient (k) of cassava and common beans

The fraction of radiation intercepted photosynthetic active radiation (f) by a crop is a function of its leaf area index (LAI) called the canopy extinction coefficient (k). The canopy extinction coefficient (k) is the efficiency with which the green leaf area intercepts solar radiation (Pengelly et al., 1999). The k depends on canopy structure, species and planting pattern of the plant and it ranges from 0.3–1.5 depending on species (Saeki, 1960; Jones, 1992). A k value below 1 is obtained for non-horizontal or clumped leaf arrangement and a k value greater than 1 occurs for horizontal or regular leaf distributions in space (Jones, 1992). Pellet and EL-Sharkawy (1997) reported k values in cassava to range between 0.5–0.58 and 0.63–0.78 for the unfertilized and fertilized cassava varieties. Other crop *k* values include *P. sativum* (0.33–0.49 - Heath and Hebblethwaite, 1985); common beans (0.4 by Gardiner et al., 1979); 0.45–0.84 for common beans, 0.63–1.02 for chickpea, 0.53–0.86 for cowpea (Tesfaye et al., 2006). Spaeth et al. (1987) and Muchow (1985) reported k values for soybean, cowpea and mungbean to range from 0.6 and 0.85.

Generally, the k values of many crops have been reported to vary and are influenced by environmental and genetic factors. Environmental conditions include air temperature and water stress which can modify leaf angle of inclination, spatial distributions (plant spacing and density) and optical properties which may occur from differences in nitrogen content (Jeuffroy and Ney, 1997). For example, several authors reported water stress effects on the k values to ranges from 0.45–0.84 for beans in Ethiopia (Tesfaye et al., 2006) and 0.42–0.5 for soybean in Nigeria (Adeboye et al., 2016). During water stress durations, low differences in the seasonal k of the crop at different stages indicate that the cultivar is tolerant to water stress (Adeboye et al., 2016). Thus the k value can be used as a factor for selecting grain legumes or crops that are capable of adjusting their canopy in response to skipping of irrigation during reproductive stage (Tesfaye et al., 2006). For example, water stress at different stages of growth has been found to affect the k (Jeuffroy and Ney 1997). However, Adeboye et al. (2016) reported water stress not to significantly affect the seasonal k in soybean. Several authors have shown fertilizer application to significantly ($p < 0.05$) affect the k values. In a water stress experiment, Tesfaye et al. (2006) reported of higher k values in the non-stressed than in the stressed treatments in legume species.

Pradhan et al. (2018) reported the k values to be significantly ($P<0.05$) lower by 16 and 9% when nitrogen was applied at a lower rate of 40 kg/ha in wheat during the 2013–2014 and 2014–2015 seasons respectively. Similarly, Pellet and EL-Sharkawy (1997) reported a 27% significant increase in k values in response to fertilization across all the cassava varieties. This was attributed to the direct effect of increased LAI with fertilization in all cassava genotypes (Pellet and EL-Sharkawy, 1997). The increase in LAI resulted in 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 genotypes (Pellet and EL-Sharkawy, 1997). The decrease in k values under low levels of nitrogen application could be explained by the fact that the leaf becomes more erect resulting in higher penetration of f into the canopy and hence lower fraction of intercepted photosynthetic active radiation (f) and radiation use efficiency (RUE) (Bassu et al., 2011; Saha et al., 2015; Pradhan et al., 2018). However, Pellet and EL-Sharkawy (1997) reported that the differences in varietal responses for k values were not reflected in variations of radiation use efficiency (RUE) especially under nitrogen stress (Bassu et al., 2011; Pradhan et al., 2018). Differences in k values may reflect differences in varieties and environment (Pengelly et al., 1999). For example, several authors reported the k values to vary among cultivars within a season and for the same cultivar between seasons (Siddique et al., 1989; Muchow et al., 1993).

2.2.8. Effects of fertilizer on the Radiation use efficiency (RUE) of cassava and common beans

Radiation-use efficiency (RUE) is defined as the amount of biomass accumulated per unit radiation intercepted. It is used as a key measure of the photosynthetic performance of field crops growing in different environments (Monteith, 1977; Muchow et al., 1993; Adeboye et al., 2016). Aboveground biomass (AGB) production can be expressed as a product of the cumulative intercepted photosynthetic active radiation (TIPAR) during the crop growth cycle and RUE (Sandańa et al., 2009). This approach is a commonly used in radiation use efficiency based crop growth models (Pengelly et al., 1999; Brisson et al., 2003; Aggarwal et al., 2004) and remote sensing estimation of biomass (Casanova et al., 1998). The cumulative total IPAR of crops is mostly controlled by fraction of the f intercepted by the canopy. The TIPAR is a function of green leaf area index (LAI) and the efficiency with which the green leaf area intercepts solar radiation, defined as the light extinction coefficient (Pengelly et al., 1999; Sandana et al., 2009). Similarly, Monteith (1977) and Russell et al., (1989) expressed yield as a function of radiation intercepted by the crop (RI), RUE and harvest index (HI) (Monteith, 1977; Russell et al., 1989).

RUE is widely considered as a stable quantity in the absence of limitations such as water deficits, inadequate nutrition and pests and diseases (Monteith and Elston, 1983; Sinclair and Muchow, 1999; Pengelly et al., 1999). This characteristic allows many applications of the RUE in agronomy. For instance, a comparison with baseline values of RUE obtained under optimal growth conditions, permits the evaluation of the extent of environmental and management limitations and the potential for yield improvement can be determined (Muchow et al., 1993). In addition, understanding the expressions of agronomic traits in response to different management practices and environment conditions particularly where the climate is variable and relatively unpredictable is vital for adaptation. Moreover, defining key physiological parameters is essential for parameterizing crop models in order to simulate cropping systems (Keating et al., 2003). Thus the RUE is a major component of the radiation-based crop growth models, which integrate several developmental, morphological, physiological, and biochemical processes at higher level of plant functions (Turner et al., 2001). Similarly, Sinclair and Muchow (1999) have used the RUE to evaluate crop performance and yield limitations under different seasonal and climatic conditions.

The use of baseline RUE values requires knowledge of how the RUE for different species varies during growth under different aerial environments (Muchow et al., 1993). RUE values may be calculated from limited biomass harvests and from either spot measurements of radiation interception or calculated interception based on extinction coefficient and leaf area index. However, to fully understand variation in RUE during growth, it is necessary to have data from frequent biomass harvests and to record intercepted radiation continuously. Further, the lack of correction for the energy content of the grain can contribute to an apparent decline in RUE during grain-filling in some species (Muchow et al., 1993). Sinclair and Horie (1989) have reported that high values of RUE can be obtained when there is high specific leaf nitrogen. For example, Shibles and Weber (1966) and Muchow (1985) reported lower RUE values of 0.72 and 0.60 g/ MJ respectively and attributed them to the low specific leaf nitrogen. A comparison of species in terms of their photosynthetic processes shows that C4 species have higher RUE than C3 species. Further, within C3 species, non-leguminous C3 species have higher RUE than leguminous species (Gosse et al., 1986).

Sinclair and Muchow (1999) reported large variation in RUE among grain legume species mainly due to a variety of environmental conditions. The RUE of many crops declines during grain-filling which is usually linked with mobilization of leaf nitrogen to the grain and also with losses of biomass due to leaf senescence (Muchow et al., 1993; Sinclair and Muchow 1999). RUE values of a species can vary with the cultivar/accession (Stutzel et al., 1994) and with crop stresses factors such as drought and disease and with the season, location, and management practices (Gregory et al., 1992). Stutzel et al. (1994) attributed yield differences of two Vicia *faba* cultivars to differences in RUE. Stutzel et al. (1994) and Muchow et al. (1993) reported low RUE values which related to the dry conditions. Contrary, Pellet and El-Sharkawy (1997) reported of high RUE values and these could partly be ascribed to the fertile soils and higher rainfall regime of 1800 mm per year in Cauca, Colombia.

2.2.9. Fertilizer effects on RUE

There are several factors which can decrease the RUE which includes water deficit, waterlogging, nutrient limitation and biotic disturbances (Muchow et al., 1993). Adeboye et al. (2016) has reported a 19.7% reduction in the average seasonal RUE of soybean during the pod initiation when compared across the seasons as affected by water stress. The RUE of fertilized crops is generally higher than that of unfertilized (Pellet and EL-Sharkawy 1997; Pradhan et al., 2018). Pradhan et al. (2018) has reported a 5–13% decrease in RUE in wheat without fertilizer application. This was attributed to the lower AGB and higher root biomass which is commonly observed under stressful environments when nitrogen applied at a lower rate of 40 kg/ha (Jamieson et al., 1995). These results are consistent with many previous research works who have reported a decrease in RUEs due to a decline in canopy photosynthetic capacity as a consequence of senescence due to water stress (Bat-Oyun et al., 2011) and nutrient deficiency (Uhart and Andrade, 1995). Pellet and EL-Sharkawy (1997) reported NPK fertilization to off-set varietal effect on yield and therefore, Howeler (1991) suggested that moderate fertilizer application can contribute to the sustainability of the cassava cropping system.

The RUE values of cassava range from 1.15–1.48 and 1.56–2.30 g DM/MJ PAR for the unfertilized and fertilized in Cauca, Colombia (Pellet and EL-Sharkawy, 1997), 0.55–2.30 g DM/MJ by Ezui et al. (2017) in West Africa, 0.88 and 1.01 g DM /MJ PAR for cassava/soybean intercropping and sole cassava by Tsay et al. (1988a). Across all the varieties, the RUE significantly increased by 41% in response to fertilization (Pellet and EL-Sharkawy, 1997). This result was shown to be a direct effect of increased LAI with fertilization in all cassava genotypes (Pellet and EL-Sharkawy, 1997). Similarly, Ezui et al. (2017) has reported of high values of RUE in treatments with K fertilizer application at 50 and 100 kg K/ha of 1.26 and 1.29 g DM/MJ PAR respectively, and 0.92 without K application. Ezui et al. (2017) explained the poor RUEs with low K concentration in cassava due to highly deficient soil K which consequently lowers cytosol K^+ concentration. In another location, Ezui et al. (2017) observed poor RUE with large concentrations of K which declined with increasing K concentrations, with or without K fertilizer application. This was attributed to the higher exchangeable soil K content above the critical requirements for cassava. RUE values have shown an increasing trend in response to N fertilizer application which corresponds with increasing K mass fractions. This shows the complementary role of N to K resulting in high RUE and biomass production (Marschner and Marschner, 1995; Ezui et al., 2017; Fernandes et al., 2017). The lower RUE values reported by Ezui et al. (2017) despite increasing K application on K deficient soils suggests that plant tissue K concentration is more limiting for RUE than soil exchangeable K.

The RUE values of various grain legumes includes 0.49 g DM /MJ PAR in common bean under rainfed conditions in Kenya by Sennhenn et al. (2017) with 1.42 and 1.40 g DM /MJ PAR under partially and fully irrigated conditions; 1.5, 1.59 and 2.44 g DM /MJ PAR for common bean in Ethiopia under mid-season stress (MS), late season stress and non-stress water conditions by Tesfaye et al. (2006). The author attributed the much higher estimated AGB accumulation to the varieties used. Other RUE values of several grain legumes (in g DM/MJ PAR) in different locations, includes 0.30–0.93 for chickpea (Hughes et al., 1987); 0.15–0.78 for common beans (Tsubo et al., 2003); 1.09 for cowpea (Muchow et al., 1993), 0.88, 0.94, 1.05 for soybean, mungbean and cowpea respectively (Muchow et al., 1993) under well-watered conditions in tropical and subtropical environments.

2.2.10. Fertilizer effects on Cumulative intercepted photosynthetic active radiation (TIPAR)

Pradhan et al. (2018) reported a significant ($P<0.05$) increase of TIPAR in fertilized treatments than unfertilized treatments of 14.5% in wheat. The higher TIPAR at higher irrigation and nitrogen levels is attributed to the higher LAI (Bassu et al., 2011; Pradhan et al., 2018). Higher LAIs for fertilized or full irrigated treatments were reported to form large canopy thus intercepting more incident solar radiation which results in higher above ground biomass (Pellet and EL-Sharkawy, 1997; Adeboye et al., 2016; Pradhan et al., 2018). Pradhan et al. (2018) has reported of a decrease in RUE (based on AGB) among the treatments and attributed it to the variation in AGB than the variation in TIPAR. This was evident from the good correlation between the AGB of wheat with the RUE (0.84 for 2013–2014 and 0.88 for 2014–2015) than TIPAR with the RUE (0.57 for 2013–2014 and 0.61 for 2014–2015) (Pradhan et al., 2018). However, Adeboye et al. (2016) found a significant correlation between seed yield and RUE and TIPAR and concluded that RUE and TIPAR are key factors for yield formation in soybeans.

2.3 Fertilizer effects on cassava tuber yield and total dry matter (TDM)

According to Fukai et al. (1984), cassava should not be shaded by an associated crop, because tuber growth is particularly sensitive to available radiation. However, Cenpukdee and Fukai (1992a) reported the effects of pigeon pea intercropping at 6.7 plants m^{-2} on cassava total dry matter (TDM) to be generally similar to that on tuber yield. For example, pigeon pea intercropped at a high density of 25 plant/m^2 produced higher TDM of 1560 g/m^2 than sole-cropping of 1464 g/m^2. Similarly, soybean intercropping had a slight effect on cassava yield although there was no significant difference in tuber yield between the sole cassava and cassava/soybean intercropping (Cenpukdee and Fukai, 1992b). Cenpukdee and Fukai (1992b) recommended the use of low legume density so that the cassava canopy is well spread and its dry-matter growth and production is not severely affected (Cenpukdee and Fukai, 1992a).

Tsay et al. (1989) reported of reduced growth for cassava (1.23 plants /m^2) during the early growth stages due to soybean intercropping (22.2 plants/m^2). Cassava showed signs of nitrogen deficiency during the early stages of growth (Tsay et al., 1988b) which was attributed to the high nitrogen uptake by the soybean (Tsay et al., 1988a). This result was confirmed by the severely reduced nitrogen uptake by cassava up to 85 DAP when soybean was harvested. However, the sole cassava had significantly higher nitrogen concentration than cassava in intercropping. According to Keating (1981), this trend of reduced N uptake in intercropped cassava during the early growth stages contributed to the high harvest index via preferential distribution of assimilate to tubers under low rates of N applications. After soybean maturity, the cassava had sufficient time to attain full light interception and to produce high total biomass. During the later stages of growth, the cassava enhanced dry-matter partitioning to tubers resulting in high harvest index compared to sole cassava. Thus the final cassava yield was not significantly affected by the intercropped soybean. However, the gross TDM of cassava was significantly reduced by the intercropped soybean throughout the whole growth period for each N treatment.

The intercropped cassava produced almost no branches but had significantly larger leaves than the sole cassava (Tsay et al., 1989). However, the number of branches in cassava in sole-cropping without N fertilizer at planting was only about half of that when N was provided at planting. According to Tsay et al. (1989), intercropping soybean in cassava affected growth of cassava in a manner similar to not applying fertilizer. Without fertilizer application, the intercropped cassava had lower LAI and TDM than the sole cassava and this difference was solely due to N supply. For example, the intercropped soybean reduced the N available to cassava by an amount which exceeded the applied 80 kg N/ha (Tsay et al., 1989). Further, the shading effects on cassava by the intercropped soybean partly contributed to their suppression. Similarly Pradhan et al. (2018) has reported a 23.5% higher AGB in wheat when nitrogen fertilizer was applied at 160 kg/ha than 40 kg/ha. During the early growth stages (before 85 DAP), leaf area and dry-matter production of cassava were significantly increased by N application at planting, but reduced by intercropped soybean (Cenpukdee and Fukai, 1993).

Hunt et al. (1977) have suggested that branch production is related to the light environment. The harvest index has been reported to decrease with increased N application. Thus Tsay et al. (1988a, b) have suggested that soybean intercropping with cassava appears to be a particularly productive system under high N availability in the soil. Nitrogen application at planting significantly enhanced TDM at 85 DAP, and the weight was about 20% greater than in the control on 155 DAP, in both sole-cropping and intercropping (Tsay et al., 1989). The effects of soybean intercropping were greater than no-N application at any time of growth. Lateral branches and leaves production even in sole-cropping was affected without N application. Without N application, the reduction in cassava growth in intercropping was minimum thus resulting in only relatively small further improvement in distribution ratio (slope of tuber yield to TDM) and hence HI. Thus maximizing of cassava intercropping with quick-maturing soybean is limited when N supply is low (Tsay et al., 1988a, b).

2.4 The effect of cassava intercropping on selected legume yield and total dry matter (TDM)

Cassava adversely affected pigeonpea TDM although intercropping had no effect on 100-seed weight and HI of pigeonpea (Cenpukdee and Fukai, 1992a). Across seasons and cassava varieties, pigeonpea-seed yield was significantly negatively correlated (r=-0.81**) with tuber yield and TDM (r=-0.84**). Tsay et al. (1989) has reported of total N accumulation by soybean in cassava intercropping not to be significantly affected by N treatments of 135 kg/ha compared to 22 kg/ha. This was manifested by the fact that N fertilizer application at planting had no effect on any characteristics of growth and yield of intercropped soybean (Tsay et al., 1989). The mean TDM of soybean of all N treatments was 3.76 t/ha at maturity.

2.5 Common beans in cassava intercropping systems

Common bean is an important source of inexpensive protein, vitamins and minerals to millions of people in developed and developing countries. It is consumed as leaves, pods and grains depending on the location in the world (Broughton et al., 2003; Ghavidel et al., 2016). Common bean is grown in cassava intercropping by smallholder farmers and grain yields are still low at 0.5 t/ha (Kumar and Abbo, 2001). Among the causes of low yields are limited land available, low soil fertility (Kushwaha et al., 2016), aluminium toxicity (Minella and Sorellis, 1992; Kushwaha et al., 2017), lack of improved varieties and poor agronomic practices (Kumar and Abbo, 2001). Leaf defoliation is another form of disturbance similar to injury inflicted by insects, in which farmers harvest the youngest leaves or tender shoots as leafy vegetable (Dube and Fanadzo, 2013).

2.6 Leaf defoliation intensity effects on compensatory growth and yield of common beans varieties

Depending on the timing of defoliation and intensity, several authors have reported different defoliation effects such as suppressing total plant biomass, seed yield, seed number per pod and number of pods per plant (Bubenheim et al., 1990; Ibrahim et al., 2010; Dube and Fanadzo, 2013). Matikiti et al. (2012) reported a fortnight leaf harvesting of cowpea to allow compensatory growth in leaf size than weekly harvests. Ali et al. (2013) reported that a 25% defoliation intensity as the optimal level and had non-significant effects on AGB and seed yield in soybean. Ibrahim et al. (2010) concluded that 50% was the optimal defoliation intensity in cowpea as it resulted in reasonable yields at podding stage. Vieira (1981) observed a 66% defoliation intensity to be very detrimental to yield when done during flowering and pod formation compared to the 0 and 33% DI. Waddill et al. (1984) reported repeated weekly defoliation of 50% to cause a 34% yield losses. Capinera et al. (1987) found that late-season defoliation intensity of up to 19% in common bean as the tolerable defoliation levels. Other studies have reported that legumes tolerate considerable defoliation of up to 20 – 66% before yield is significantly reduced (Kogan and Turnipseed, 1980; Vieira, 1981). Matikiti et al. (2012) observed greater reductions in grain yield on sandy soil than on the rich clay soil caused by leaf harvesting. Li et al. (2005) has suggested that higher levels of soil nutrients increased the ability of plants to maintain high leaf area under severe defoliation. However, Bubenheim et al. (1990) and Malone (2001) reported of slightly defoliated plants to produce more new leaves than controls, showing that compensatory growth occurs when leaves are harvested.

When plants are defoliated, there is a reduction in green leaf area which intercepts low f and thus low RUE (Dube and Fanadzo, 2013). However, the RUE is constant in non-stressful environments (Jeuffroy and Ney, 1997; Sinclair and Muchow, 1999). Therefore, defoliation reduces the LAI thus affecting the f consequently affected the canopy extinction coefficient and RUE (Ayaz et al., 2004; Pradham et al., 2018).

2.7 Effects of leaf defoliation and growth habit on common bean yield

Genetic differences exist among legume cultivars' in response to defoliation intensity. For instance, the seed yield of leafy indeterminate cowpea and soybeans types have been shown to be more tolerant to defoliation than determinate types (Li et al., 2005; Dube and Fanadzo, 2013). Also, Madamba (2000) has concluded that indeterminate cowpea types are better able to compensate for leaf harvest losses than determinate types. This is attributed to the mechanisms in determinate cultivars, where they allocate a greater proportion of biomass to reproductive organs after defoliation, which results in less leaf regrowth and delayed senescence of remaining leaves. In indeterminate cultivars, there is increased biomass partitioning to leaves therefore delaying reproductive development, which allows defoliated plants to produce more new leaves (Li et al., 2005). HI varies with the ability of a genotype to partition current assimilate to the seed (Turner et al., 2001; Tesfaye et al., 2006). If the length to maturity of indeterminant variety is long, this allows the defoliated variety enough time to compensatory growth thus reducing effects on seed and aboveground biomass (Madamba, 2000; Li et al., 2005; Dube and Fanadzo, 2013).

2.8 Summary of review and conclusions

This review has established that cassava yields in Zambia are low at below 6 t/ha compared to actual yields of 20–25 t/ha under similar farming conditions. The farmers grow cassava with little or without inorganic fertilizer application due to the high cost. Consequently, land degradation characterizes farmer's field with declining yields after growing cassava for a certain period of time. A good understanding of sustainable crop management practices in cassava production systems among smallholder farmers is imperative to sustain the intensification of cassava production systems in Luapula Province of Zambia. The common identified constraints in most cassava production systems across Africa were limited nitrogen, low potassium, soil acidity, reduced fallow period, and weed pressure and nutrient imbalance. Further, the review identified cassava to be intercropped mostly with common beans, cowpea and maize under shifting cultivation systems. Thus, it was important to evaluate the performance of cassava under lime, NPK fertilizer with common bean, soybeans and cowpea intercropping systems on exhausted soils. The radiation use efficiency (RUE) of cassava in intercropping is rarely established in Zambia. Since, the RUE is widely considered as a stable quantity thus comparing other experimental RUE results with baseline values of RUE obtained under optimal growth conditions, allows for the evaluation of the extent of environmental limitation and management practices and the potential for yield improvement be determined. More than half of the cassava in Africa is grown under intercropping systems with legumes. Common bean is the most intercropped legume with cassava. Common bean is a dual purpose consumed crop as leafy vegetable and grain thus affecting both grain (0.5 t/ha) and biomass yield. Defoliation limits the photosynthetic capacity and thus reduces nitrogen fixation and biomass contribution to organic carbon which is low in cassava production systems. Therefore, the need to evaluate the effects of defoliation intensity and fertilizer application on the compensatory growth, yield and radiation use efficiency of common beans varieties.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Description of study sites

This study was accomplished in three phases comprising of a survey in smallholder farmer's fields in Nchelenge District and two field experiments at Mansa Agricultural Research Institute (ZARI) of Luapula Province of Zambia. The Field surveys were conducted as a baseline study to understand the effects of crop management practice on soil adequacy levels and tuber yield in cassava production systems of Luapula Province of Zambia. Based on preliminary results of the baseline study, an experiment was conducted to investigate the performance of cassava under lime, fertilizer, and grain legume intercropping on exhausted soils at Mansa ZARI station. The exhausted soils were similar to abandoned fields under shifting cultivation in Nchelenge District. Since common beans is the most prevalent legume in cassava intercropping, the last experiment was conducted to improve our understanding of the effects of leaf defoliation intensities and fertilizer levels on the compensatory growth and yield of common beans varieties. The baseline study was conducted in Mantampala Camp of Nchelenge District in Luapula Province (Figure 1), of Zambia (9°19.028'59"S, 28°50'44'E, and at an elevation of 959 m above sea level).

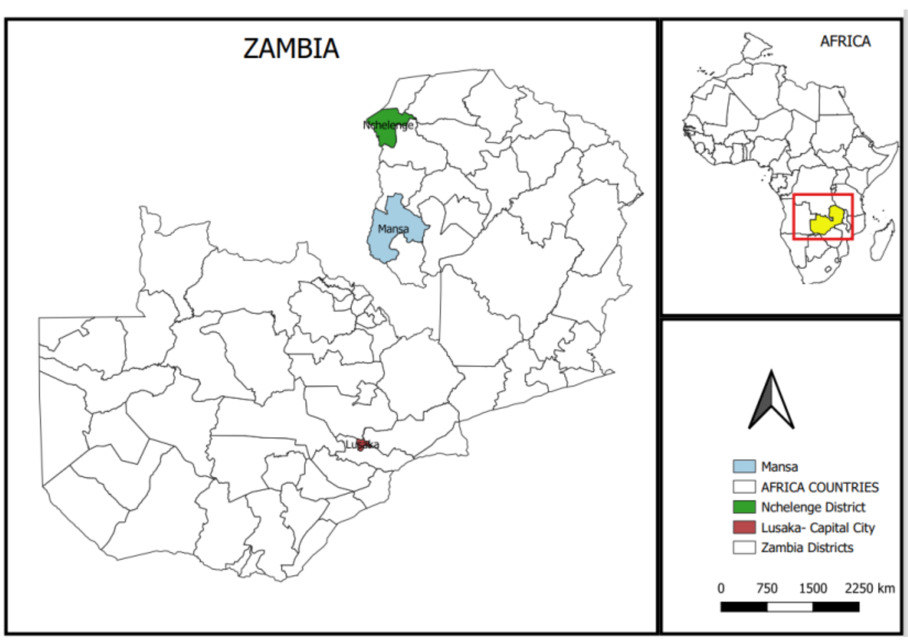

Figure 1: Location of the two study sites in Luapula Province of Zambia

The area lies in an agro-ecological region III which is characterized by an average annual rainfall of above 1,000 mm and an average annual temperature of 23.1 °C (Figure 2) and experiences a tropical savannah climate with three seasons, namely winter (May–August), dry (September–October) and rainy season (November–April).

The main soil types in the region include Ferric and Orthic Acrisols formed from underlying acid igneous or siliceous sedimentary rocks (Mansfield et al., 1975). Agriculture is the main livelihood activity in Mantampala with cassava being the staple crop and source of income. Other crops interplanted with cassava include maize, groundnuts, beans, sweet potato, rice and millet. Cassava is grown under shifting cultivation (Chitemene system) which involves slashing grass and burning of lopped tree branches as a source of nutrients and fuel. After two to three cycles of cropping the land is exhausted and cannot provide sufficient nutrients to meet crop demand. Thereafter, the land is left to regenerate via fallowing (Leindah et al., 2013; Mertz et al., 2009). Fallowing is a prerequisite for maintaining long-term plant-available nutrient pools and crop yields in many tropical cultivation systems (Bruun et al., 2006). The shifting cultivation system is only sustainable where there is a low population density and abundant land (Styger et al., 2007; Mansfield et al., 1975).

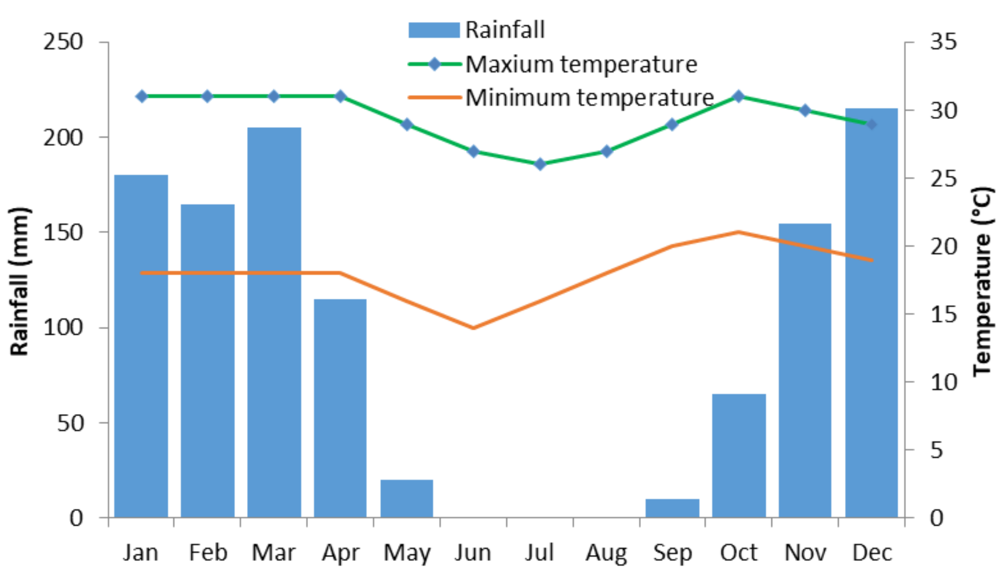

Figure 2: Mean monthly maximum and minimum temperatures with total monthly rainfall during 2017–2018 survey period. Bar graphs show the total monthly rainfall and the line graphs show the mean maximum and minimum temperature.

3.2 Cassava management practices affecting soil nutrient adequacy levels and tuber yield among smallholder farmers in Luapula Province of Zambia

3.2.1 Farmer sampling design

Ten villages where randomly selected for this study in Mantampala Camp with variable number of inhabitants and ease of access to and from the District. In each village, 3 to 7 farmers were randomly selected each with three fields of cassava at different stages of growth: 12, 24 and 36 months after planting (MAP). These farmers were chosen so that their fields would cover the largest possible variation in soil characteristics. For each farmer, information for all the three fields was obtained using semi-structured interviews. In total, the dataset comprised of 40 farmers and 120 fields. The Fieldwork was conducted between October – December 2017 and a follow up in 2018 to fill up on the necessary information which was missing.

3.2.2 Data collection

3.2.2.1 Management and biophysical data

In all the farmer fields, semi-structured interviews were conducted in situ with the farmer that owned the field or other members of the household. Interviews were focused on the previous use of the fields and on its current management. In each farmer's field, the coordinates were obtained using GPS to calculate the field sizes in Arc GIS 10.

In order to assess the cassava cropping practices, basic information on age of the field and cassava, land clearing, preparation, planting times, weeding frequency and cassava varieties planted and legumes intercropped with cassava and period of cropping before fallow were recorded. Other information obtained included input use (fertilizer, pesticides and fungicides) and leaf harvesting frequency.

3.2.2.2 Soil sampling in farmer's field and analysis

In each farmer's field, the topsoil (0–30 cm) samples were randomly collected at five points using an auger and thoroughly mixed to make one composite sample per field (120 composite samples). The depth of soil sampling was in accordance with the farmer's practices of ridges of 30 cm height. The soils were dried, sieved through a 2 mm sieve before being analysed for selected soil chemical and physical properties as described below.

3.2.2.3 Soil Reaction

Ten grams of air-dry soil was equilibrated in 25 mL of distilled water for 30 minutes. The soil reaction was measured in the supernatant solution using a pH glass electrode according to van Reeuwijk (1992) fitted to a pH meter (pH 3110, WTW82362, Weilheim, Germany).

3.2.2.4 Determination of exchangeable acidity

Exchangeable acidity was determined according to the approach by Hendershot et al. (1993). Ten grams of air dry soil (passed through 2 mm sieve) was weighed into 250 mL Erlenmeyer flask to which 100 mL of 1M KCl was added and shaken for 1 hour. After shaking, the samples were filtered using Whitman No. 42 filter paper and the filtrate collected in the beaker. For each sample, 25 mL of the filtrate was then pipetted into conical flasks followed by the addition of 100 mL of distilled water and 5 drops phenolphthalein indicator. This was titrated with 0.01M NaOH solution to a pink end point.

3.2.2.5 Determination of exchangeable bases

Ten grams of air dry soil was placed into 100 mL plastic bottle, to which 50 ml of NH_4OAc buffered at pH 7 was added. After shaking for 30 minutes, the mixture was filtered through Whitman No. 42 filter paper after which the concentration of K and Na were read directly from the filtrate on the flame photometer. Meanwhile, to determine the concentration of Ca and Mg, 2 mL of the filtrate was added to a 25 mL volumetric flask to which 10 mL of 5000 mg/L strontium chloride was added. The volumetric flask was then filled to the mark with 1 M ammonium acetate and thereafter Ca and Mg were read using on the Atomic absorption spectrophotometer (AAS) (Analyst 400, PerkinElmer Life and Analytical Sciences, Shelton, USA) (Van Ranst et al., 1999).

3.2.2.6 Particle Size Distribution

The particle size distribution was determined using the hydrometer method (Day, 1965). Fifty grams of air–dried soil was placed into a dispensing cup to which 50 mL of 5 % sodium hexametaphosphate (calgon) was added as a soil dispersing agent. The cup was then half filled with tap water and continuously stirred for 5 minutes using a mechanical stirrer. The suspension was quantitatively transferred to a sedimentation cylinder using a stream of distilled water and then filled the cylinder to 1000 mL. A blank was also prepared by adding 50 mL of calgon into a 1000 mL cylinder and then filled to the mark with distilled water. The temperature of the suspension in the sample and the blank were measured using mercury glass thermometer. A plunger was then used to thoroughly mix the soil suspension in the cylinder. After 20 seconds, a hydrometer was lowered into the soil suspension and the density was read at 40 seconds to determine the silt and clay content. This was repeated three times to obtain an average value. The suspension was then allowed to settle for 2 hours before taking the final density and temperature readings to allow clay content determination. The percentages of clay, silt and sand were calculated as outlined by van Ranst et al. (1999). The textural class was determined using the USDA textural triangle.

3.2.2.7 Determination of total nitrogen

One gram of air dried soil sample was weighed in triplicates into 500 mL Kjedahl flasks and digested with10 ml of concentrated H_2SO_4 and 3 g of the catalyst mixture. After digestion, the mixture was allowed to cool and then diluted with 100 mL of distilled water. Ten millilitres of 10 M NaoH was added to 10 mL of the digested sample and the ammonia which was produced from the reaction was trapped in 20 mL of boric acid-indicator (H_3BO_3) solution. The boric acid indicator mixture was then titrated with 0.05 M HCl to a pink end point (Bremner, 1969).

3.2.2.8 Plant available phosphorus

Three grams of air dry-dried soil was equilibrated with 21 mL of Bray I (Bray and Kurtz, 1945) for 1 minute and then filtered through Whitman No. 42 filter paper. Five millilitres of the filtrate was pipetted into a 25 mL volumetric flask and diluted with 10 mL of distilled water. Thereafter, 4 mL of 2% ascorbic acid was also added and filled up to the mark using distilled water. The mixture was allowed to stand for 15 minutes in order for the colour to develop. Phosphorus content was determined using the spectrophotometry at 882 nm.

3.2.2.9 Soil organic matter

Soil organic matter was determined using the wet oxidation method of walkley and black (1934). One gram of air-dried soil was completely oxidized in 10 mL of 1 N $K_2CR_2O_7$ in an acid medium containing 20 mL of concentrated H_2SO_4. The digestion was equilibrated for 30 minutes, after which 150 mL of distilled water and 10 mL of concentrated phosphoric

(H_3PO_4) acid were added. Thereafter, 10 drops of diphenylamine indicator were added to the digestion mixture which was then titrated with iron (II) sulphate solution to a green end point.

3.2.2.10 Micronutrients

The micronutrients comprising of copper, zinc, iron and manganese were extracted using diethylenetriaminepentaacetic acid (DTPA) according to the procedure by Lindsay and Norvell (1978). Twenty grams of air-dried soil was placed into a 50 mL container and to which 40 mL of DTPA was added and shaken for 2 hours. The mixture was filtered through Whitman No. 42 filter paper and the concentration of copper, zinc, iron and manganese were read using appropriate standards after calibration on the atomic absorption spectrophotometry.

3.2.2.11 **Cassava leaf area index, light interception and tuber yield**

Leaf area index (LAI) was measured in established cassava fields at three locations using the canopy analyzer (LAI–2200, plant canopy analyzer, LICOR Inc., Lincoln, NE, USA). Similarly, the intercepted photosynthetically active radiation (f) was measured at each of three locations in the field using the line quantum sensor and LI COR 190R (LICOR Inc., Lincoln, NE, USA). The relationship between intercepted light and LAI was calculated using equation 1 as done by Veltkamp (1985):

$$Ln\left(\frac{I}{Io}\right) = -kLAI \qquad (1)$$

where I = light received beneath the canopy (three positions per plot)

I_0 = incoming light just above the crop canopy (one measurement per plot)

k= extinction coefficient.

The average values for k per cassava maturity group at the time of the survey were calculated as the slope of a regression line of ln (light absorption) as a function of LAI, according to Veltkamp (1983).

Since the planting patterns were not orderly in some fields, harvesting of cassava was done based on the number of plants after the LAI and light interception were measured. The plant population in each field was obtained by counting the cassava stands in a 3 m by 3 m portion; thereafter the tubers were dug, counted before weighing for each of the 120 fields. Total fresh yield weight of each field and number of plants in a 3 m by 3 m area were used to calculate fresh cassava yield (t/ha) and to convert to dry matter tuber per ha, a factor of 0.34 was used similar to Alves (2002).

3.2.3 Statistical Data Analysis

Descriptive statistics were applied to analyse cropping management practices in cassava fields at 12, 24 and 36 months after planting. Nutrient levels in crop fields were evaluated for soil adequacy for cassava production by comparing values to known critical nutrient levels and sufficiency ranges recommended for optimal cassava growth for each soil type (Hillocks, 2002; Imakumbili et al., 2019). An analysis of variance (ANOVA) was conducted on the data to compare the management effects of cassava management practices on soil properties for each cassava maturity group and on the all dataset. Effects of management practice and soil properties on cassava yield within each maturity group were obtained by separating each group into high and low yields using the median. The low and high yielding farmer's ranged from 2.7–5.6 and 5.7–12 t/ha at 12 MAP. At 24 MAP, the low and high yield categories were 9–20 and 20–34 t/ha respectively. The low and high yield categories were 7–23 and 24–35 t/ha respectively at 36 MAP. These were analyzed using non-parametric tests for one independent sample using the Kruskal Wallis test or linear model. Statistical analyses were conducted in R-3.5.2 (R Core Team, 2019).

Cassava tuber yield determining factors were identified and estimated using stepwise regression models according to the maturity group at 12, 24 and 36 MAP. The variables considered to be yield determining factors were social, management, cassava LAI, f, plant density and soil properties. Correlation analysis was performed on all the variables and explanatory variables that had a significant relationship with cassava tuber yield were selected for multiple regression analysis ($P < 0.05$). The omitted variables were not correlated with those included in the regression to avoid biasness. All variables were further scaled to ensure standardization of the different variables in the model. Explanatory variables that had a significant correlation coefficient (r) with yield and/or exhibited a pattern of co-variation with cassava tuber yields were selected for further analysis. The significance of the different factors on the yield were evaluated at p-value < 0.05 significance level.

3.3 Assessing the performance of cassava under lime, fertilizer and legume intercropping on exhausted soils

Based on the preliminary results from the survey conducted, it was established that after continuous cassava cultivation for 9 years, smallholder farmers abandon fields due to nutrient mining (exhausted soils) and decline in yields. This trend is not sustainable in the future since the demand for cassava will keeps increasing in response to the escalating population and agro industries. This is exacerbated by the frequent extreme climate change events which have resulted in substantial yield loss of other crops thus increasing dependence on cassava. Thus the use of lime, fertilizer and legume intercropping on cassava performance on exhausted soils is imperative to allow production without causing deforestation.

3.3.1 Description of study sites in Mansa Agricultural Research Institute

The two experiments were conducted at the Zambia Agricultural Research Institute (ZARI), in Mansa, Luapula Province. The study site is located at a longitude of 28.9508 °E and latitude of 11.2414 °S at 1249 m above sea level. The area is located in agro-ecological region (AEZ) III which receives above 1000 mm of rainfall annually and the rainfall pattern is unimodal (Figure 3). According to the Köppen climate classification, Zambia is dominated by a humid subtropical climate (Zifan, 2016). The area experiences a humid to sub-humid climate with growing periods varying from 120 to 150 days in AEZ III (Saasa, 2003).

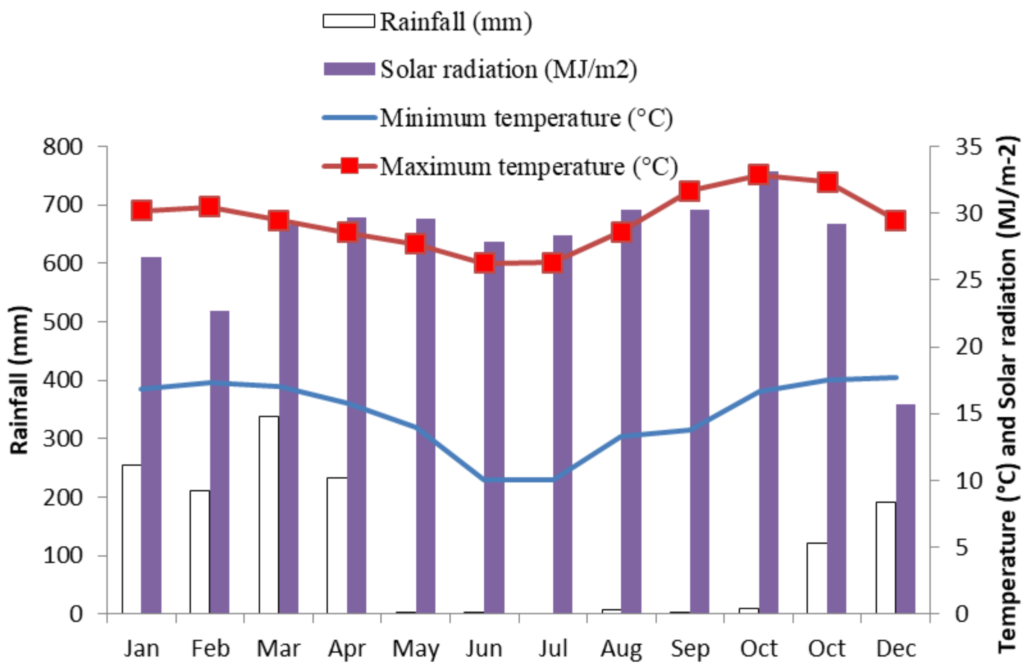

Figure 3: Mean monthly maximum, minimum temperature, monthly rainfall and solar radiation for the 2017–2018 and 2018–2019 seasons. Bar graphs show the total monthly rainfall, solar radiation and the line graphs show the mean maximum and minimum temperature.

3.3.2 Trial establishment

The experimental site was abandoned after continuous cassava cultivation for about 9 years. Prior to the trial establishment, 10 soil samples were collected using a soil auger at 0–30 cm and thoroughly mixed to make a composite soil sample. The depth of soil sampling was in accordance with the farmer's practices of ridges height of between 0–30 cm. The soil sample were dried, sieved using a 2 mm sieve before being analysed for selected soil chemical and physical properties. Soil reaction (pH), soil texture, exchangeable acidity, soil carbon, total nitrogen, exchangeable cations and phosphorus were determined using methods as highlighted in the farm survey study and the results are presented in (Table 7). Daily rainfall was measured on each site using manual rain gauges. Daily solar radiation, daily minimum and maximum temperatures, air humidity, and wind speed data were provided by the nearest weather station.

3.3.3 Experimental design and treatment description

The field experiments were conducted for two consecutive growing seasons of 2017/18 and 2018/19 rain-seasons and that all trials were planted in early December. The experimental design was a split-split plot design in a randomized completely block (RCBD). The experiment was laid out as a 2 by 2 by 4 design comprising of two levels of lime 0 and 300 kg/ha, two levels of compound fertilizer 0 and 100N: 23P:80K kg/ ha with three legumes (common beans, cowpea and soybean) intercropped in cassava and sole cassava. These were replicated three times giving a total of 48 plots. Fertilizer rates of 0 and 100 N: 23 P: 80 K kg N/ha were applied per plot prior to planting in early December of each year. The individual nutrient requirement from straight fertilizers of urea 46% (N) give 217 kg of urea per ha was calculated to meet 100 kg/ha of N, triple superphosphate 46% (P_2O_5) giving 150 kg/ha to achieve the above phosphorous application rate of 23 kg/ha and 50% muriate of Potash (K_2O) amounting to 160 kg/ha to meet 80 kg/ha of potassium. The lime application was done using the recommended rate in Agroecological region III of Zambia following a lime requirement of 1.5 × Al (cmol/kg). The plot size was 4 m by 7 m with cassava planted at a spacing of 1 m by 1 m. The cassava variety Mweru which matures in 12 months after planting was used in the study due to its dominance among smallholder farmers. The common beans, cowpea and soybeans varieties were Luangeni, Lutembwe and Magoye which are an indeterminate growth habit. The common beans and cowpea had the earliest maturing period of 80–90 days compared to soybeans at 120 days. Three grain legume seeds were sown by interplanting on the ridge at a spacing of 0.10 m within the 1 m cassava intra row spacing according to the farmers practice. At two weeks after sowing, the plants were thinned targeting 100,000 plants/ha. At six weeks after sowing, the crop was sprayed with Karate (Lamda-cyhalothrin) 2.5 E.C to control aphids. Weed control was achieved by traditional methods with the hand hoe through re-ridging and banking, to achieve a weed free seedbed.

3.3.4 Data collection

Data on grain legumes phenology included days to 50% flowering which were recorded by counting the total number of days required for 50% of the total population to flower. Days to physiological maturity were recorded when 90% of the pods were dry (Sennhenn et al., 2017). For the grain weight, 10 of the mature and ripened beans pods from each randomly selected individual plant within two middle rows were harvested for assessment. These samples were oven-dried at 60 to 65 °C until constant dry mass. The number of pods/plant, seed/pod, pod length, 100 seed weight per plant were recorded. To obtain grain yield, pods were dried in the sunlight before threshing and drying. For simplicity, only data on grain weight at harvest was used in the analysis.

Cassava growth characteristics were measured on 5 tagged plants located in the middle of the plot. The readings were averaged over the growing cycle. Six sequential harvests were done at 85, 173, 240, 272, 344, and final harvests were done up to 410 days after planting (DAP) and in a 3 m × 3 m portion in the middle of the whole plots for sequential and final harvests per plot. Plant parts were separated into storage roots and shoots (leaves + stems), before determining the fresh weights using the digital balance. For the roots and stems 300 g, and 200 g of leaves, were sampled for dry weight determination. The materials were oven dried to constant weight under 80 ℃ for 48 hours. Dry matter was determined as a ratio of dry to fresh weight of the samples, while the harvest index (HI) was calculated as ratio of storage root dry weight to total plant dry weight at harvest.

In each plot, the leaf area index and fraction of intercepted photosynthetically active radiation (f) were measured starting at 3 months after planting, thereafter 2 months interval up to 6 measurements. The LAI and f were measured using the canopy analyser (LI–3000, LICOR Inc., Lincoln, NE, USA) and line quantum sensor and LI COR 190R (LICOR Inc., Lincoln, NE, USA). For each plot, the daily fractional intercepted photosynthetically active radiation (f) was calculated on the basis of the ratio daily incident solar radiation (I_0) and solar radiation transmitted (I). All sets of measurements were taken under clear-sky conditions during a period of constant irradiance. Meteorological data including precipitation, air temperature and other relevant parameters were recorded daily at the study site. The radiation extinction coefficient (k) being the effectiveness with which canopy intercepts radiation was calculated as the slope of the relationship between the daily fractional intercepted solar radiation and leaf area index (LAI) according to Veltkamp (1985) using equation 1:

The radiation-use efficiency (RUE) was estimated as the regression between the accumulated total above-ground biomass and cumulative intercepted photosynthetically active radiation (Pellet and El-Sharkawy, 1997). RUE represents the effectiveness with which the common bean converts the intercepted radiation into dry matter. The photosynthetically active radiation (f) was assumed to be 45% solar radiation in this study.

3.3.5 Statistical analysis

A linear mixed model with year as a random factor was performed to assess the treatment effect of lime and fertilizer rates and legume species intercropping (common bean, cowpea and soybean) on plant growth characteristics, RUE and selected yield components. Lime and fertilizer rates and legume species intercropping were assigned as main, sub- and sub-sub treatments, respectively. Where treatments differed statistically, the least significant differences (LSD) were used to separate the means at $p \leq 0.05$. For parameters were the “year x treatment” interaction was not significant, data were combined over years, and means were presented. Mean values were separated according to LSD test at $p = 0.05$. Correlation analysis was done using Pearson’s simple correlation coefficients to test the strength relationship of variables and their strength of association. Statistical analyses were conducted in R-3.5.2 (R Core Team, 2019).

3.4 Effects of fertilizer and leaf defoliation intensity on compensatory growth and radiation use efficiency of common bean

Common bean is an important source of inexpensive protein, vitamins and minerals to millions of peoples in developed and developing countries (Ghavidel et al., 2016). Common bean is the most grown in cassava intercropping by smallholder farmers in Luapula Province (kaluba et al., 2021) and grain yields are still low at 0.5 t/ha compared to potential yield of 2.5 t/ha. These low yields of common beans among smallholder farmers are due to partial leaf defoliation for food which reduces the photosynthetic area and capacity and ultimately causes low biomass yield without substantial build up of organic carbon in cassava production systems and biological nitrogen fixation. Further, there is low or no use of fertilizer in common beans during the growing season. When plants are defoliated, there is a reduction in green leaf area resulting in low intercepted photosynthetic active radiation (f) and thus low radiation use efficiency (RUE). Since this crop has dual purpose, the leaf defoliation effect on common bean growth and yield is imperative to understand in order to maximize crop production yields in cassava systems.

3.4.1 Description of study site

The study was conducted in the 2018 and 2019 growing seasons under rainfed at the Zambia Agricultural Research Institute (ZARI), in Mansa, Luapula Province. The longitude, latitude and altitude of the experimental site is 28°.158′ E, 11° 40′ S, 1249 m asl. The area is located in agro-ecological region III which receives above 1000 mm (Figure 13) of rainfall annually (Aregheore, 2009). According to the Köppen climate classification, Zambia is dominated by a humid subtropical climate (Zifan, 2016). The area experiences a humid to sub-humid climate with growing periods varying from 120 to 150 days in AEZ III (Saasa, 2003). The rainfall follows a unimodal pattern (Figure 13) from November to April. Depending on the rainfall distribution, mostly common bean is planted in January. The rainfall pattern is unimodal (Figure 13) and that common bean is planted in December or January depending on the rainfall distribution. The soils at the experimental site were sampled and analyzed for soil acidity, total nitrogen, available phosphorus, exchangeable cations, soil organic carbon and particle size distribution using the methods as described in the earlier sections on the baseline study.

3.4.3 Field experiments

The experiments were laid out in a split split plot arranged in randomized complete block design. The main plot treatments were fertilizer management (no fertilizer, NPK fertilizer), and subplots were variety and defoliation intensities were sub sub plot. The experiment comprised of a 2 by 3 by 4 factorial combinations giving 24 treatments. These were two rates of 0 and compound NPK fertilizer supplying 20 kg N, 40 Kg P_2O_5, 20 kg K_2O per ha with three bean varieties and 4 levels of imposed leaf defoliation intensities (0, 25, 50 and 75%). The treatments were replicated three times, giving 72 plots. The three common bean varieties were (V1) Lyambai, Lukupa (V2) and Luangeni (V3). Varieties Lukupa and Luangeni have an indeterminate growth habit while Lyambai is determinate. Determinant variety flowered earlier at about 35 days after planting while indeterminant varieties flowered at 42 days after planting. The indeterminant defoliated treatments delayed in flowering and maturity while the determined flowered and matured early. The common bean was sown on the 12th January in 2018 and 17th of January in 2019. The days to maturity of Lyambai, Lukupa and Luangeni were 75, 85 and 100 days respectively. The plot size were 3 m by 6 m with plant spacing of 0.60 m by 0.15 m. Leaf defoliation intensities of 0, 25, 50 and 75% were applied at 28–30 days after planting (452–500 growing degrees days) during the vegetative stage but before flowering in both years. The total numbers of leaflets were counted on 20 plants from the inner four rows and were used to compute defoliation intensities of 25, 50 and 75%. Artificial defoliation was performed by excising the entire leaflet by hand. Defoliation was performed at a single opportunity by removing one, leaflets from each trifoliate leaf (from the bottom branches according to the 25, 50 and 75% defoliation intensity. A compound NPK fertilizer supplying 20 kg N, 40 Kg P_2O_5, 20 kg K_2O per ha was applied to common beans before planting similar to Chekanai et al. (2018). Three common bean seeds were sown at a spacing of 0.15 m × 0.60 m. At two weeks after sowing, the plants were thinned targeting 111,111 plants/ha. At six weeks after sowing, the crop was sprayed with Karate (Lamda-cyhalothrin) 2.5 E.C to control aphids.

3.4.4 Biometric and phenological features

Data collected on phenology included days to 50% flowering which were recorded by counting the total number of days required for 50% of the total population to flower. Days to physiological maturity were recorded when 90% of the pods were dry (Sennhenn et al., 2017). For dry matter partitioning, 10 plants were sampled from two inner rows at six intervals throughout the growing season. The sampled plants were separated into green and dead leaves, petioles, branches, stems, inflorescences or pods and the sample was oven-dried at 60 to 65 °C until constant dry mass. For the grain weight, 10 of the mature and ripened beans pods were harvested from the other two inner rows in which LAI and f were measured. The number of pods/plant, seed/pod, pod length were recorded. To obtain grain yield, pods were dried in the sun and threshed. The grain yield per ha on dry matter basis, was obtained using the plant population per ha when the grain moisture content reached 16%.

In each plot, the leaf area index and intercepted photosynthetically active radiation (f) were measured at 30 days after planting, thereafter it was repeated every 10 days for 6 times until physiological maturity. The LAI and f were measured using the canopy analyser (LAI–2200 Plant Canopy Analyzer, LICOR Inc., Lincoln, NE, USA) and line quantum sensor and LI COR 190R (LICOR Inc., Lincoln, NE, USA). The line quantum sensor was placed parallel to the row direction at the soil surface to measure I and Io was measured at the top of the canopy in each plot. For each plot, the daily fractional intercepted photosynthetically active radiation (f) was calculated on the basis of the ratio daily incident solar radiation (I_o) and solar radiation transmitted (I). Each measurement was the average of six replications at various places in the plot. All sets of measurements were taken under clear-sky conditions between 12:00 and 14:00 hours. The daily incoming solar radiation was multiplied by a factor 0.45 (Monteith 1972) to get incoming incident f. The radiation extinction coefficient (k) being the effectiveness with which canopy intercepts radiation was calculated as the slope of the relationship between the daily fractional intercepted solar radiation and leaf area index (LAI) according to Saeki (1960) and Monteith (1965). Meteorological data including precipitation, air temperature and other relevant parameters were recorded daily at the study site. The RUE was estimated as the regression between the accumulated total above-ground biomass and cumulative intercepted photosynthetically active radiation (Monteith 1977). The RUE of common bean is the effectiveness with which the plants converted the intercepted radiation into dry matter.

3.4.5 Statistical analysis

To assess the treatment effect of common bean varieties, defoliation intensities and fertilizer rates on plant growth characteristics, RUE and selected yield components were analyzed using a linear mixed model with year as a random factor. Fertilizer rates, common beans varieties and defoliation intensities were assigned as main, sub- and sub-sub treatments, respectively. Where treatments differed statistically, the least significant differences (LSD) were used to separate the means at $p \leq 0.05$. For parameters were the "year x treatment" interaction was not significant, data were combined over years, and means were presented. Mean values were separated according to LSD test at $P = 0.05$. Correlation analysis was done using Pearson's simple correlation coefficients to test the strength relationship of variables and their strength of association. Statistical analyses were conducted in R-3.5.2 (R Core Team, 2019).

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1 Cassava management practices effects on soil adequacy levels and tuber yield among smallholder farmers of Luapula Province of Zambia

4.1.1 Crop management practices in cassava systems

The cropping and management practices in cassava farming are presented in Table 1. Cassava is normally planted in October to November depending on the onset of the rains. The main cropping system is cassava intercropping in first year of cassava planting. The main crops in cassava intercropping are cereals and legumes. Improved varieties of cassava were the most commonly grown campared to the local varieties at 95 and 5% respectively. Farmers practice the slash and burn system which supplies the wood ashes which ameliorates soils acidity and provides selected nutrients for cassava production. Therefore, no inorganic fertilizers and pesticides are used in cassava production.

Table 1: Cropping practices for cassava in the study area

Characteristics	Key attribute	Proportion of respondents (%) (n=40)
Cropping practice	Intercropping	100
	Monocropping	0
Most intercropped crop	Maize	45.8
	Beans	25.3
	Cowpea	8.3
Variety	Improved varieties	95
	Local varieties	5
Input use	Fertilizer	0
	Slash and burn	100
	Pesticides and fungicide use	0
Landuse duration (years)	Female (11)	9.2
	Male (29)	8
	Overall mean (40)	8.6

Consistent with this study, several researchers have reported cassava intercropping as the most dominant practice in Africa (Munyahali et al., 2017a; Agwu and Anyaeche, 2007; Fermont et al., 2009). Also Okigbo and Greenland (1976) reported cassava intercropping to produce more than half of the cassava grown in Africa. According to the farmers, practicing intercropping helps reduce risks against crop failure and weed pressure (Agwu and Anyaeche 2007; Fermont et al. 2009; Munyahali et al., 2017a). Further, the farmers indicated that intercropping saves labour for preparing separate lands for other crops. The intercropped species also benefits from the slash and burn practice effects. In the study area, cassava intercropping was not practiced at 24 and 36 MAP to avoid light and nutrients competition. Further, the plant density of more than 20,000 plants/ha was very high for intercropping (Table 4). Cassava was mostly intercropped with maize, common beans and cowpea arranged in order of popularity (Table 1). The common beans and cowpea provides a cheap source of protein apart from fixing nitrogen. These findings are consistent with many studies that have shown cassava intercropping with maize and legumes as the dominant crops (Agwu and Anyaeche, 2007; Munyahali et al., 2017a). For example, Munyahali et al. (2017a) has reported maize and common bean as the most dominant crops in cassava intercropping in DR Congo. Similarly, Fermont (2008) reported maize as the most intercropped crop with cassava in Kenya and Uganda.

All the households depend on agriculture as a source for food and income. Cassava is the staple food in the study area and that all households (Table 1) have cassava at different maturity stages of 12, 24 and 36 MAP (Table 2). The field with cassava at 36 MAP is the main source of tubers, although sometimes cassava at 24 MAP is harvested. During food scarcity times at household level, the tubers are harvested at 12 MAP old for the improved varieties. The majority of farmers use improved varieties in preference to local varieties (Table 1). Also, Munyahali et al. (2017b) has reported improved cassava varieties to be the most cultivated in Uvira, DR Congo since they are resistant to cassava mosaic diseases.

Generally, farmers apply no inorganic fertilizer to cassava fields (Table 1). Some nutrients to support cassava growth are provided by the ash from the slash and burn practices in shifting cultivation (Table 1). According to Biratu et al. (2018), the non-use of fertilizer (Table 1) is due to the higher costs of fertilizers, non-availability at the right time, and poor crop response in dry periods exacerbated by technical and institutional issues hinder the use of inorganic fertilizer. Several researchers have also reported that farmers perceive cassava to be tolerant to low soil fertility status (Salcedo et al., 1997; Hillocks, 2002; Leihner, 2002; Biratu et al., 2018a). Similarly Leihner (2002) reported that farmers believed that cassava could restore the fertility of degraded soils and so does not require fertilization. This practice of not applying fertilizer to cassava system is the reason why many farmers grow cassava on marginal land or land that is about to be abandoned to natural regeneration (Adjei-Nsiah et al., 2007). Studies have shown that local varieties tend to be tolerant to low soil fertility compared to improved varieties when grown without fertilizer (Fening et al., 2009). Ezui et al. (2016) explains the non-use of fertilizer as one of the reasons there is a huge yield gap between actual productivity on farmers' fields and the potential cassava productivity. However, the fact that farmers practice slash and burn as an alternative source to inorganic fertilizer, there is need to recognize fertilizer application to cassava.

The management practices namely weeding frequency, leaf harvesting and field characteristics viz field texture class and field sizes are presented in Table 2. All the respondents indicated that weeding was commonly done using hand hoe (Table 2) and therefore, herbicides were never used in controlling weeds. On average, more than 70% of the farmers weeded once in cassava at first and second year and no weeding was done in cassava at third years. Generally, from planting to harvest, farmers most weeded twice, with the most frequent weeding done in first year fields compared to second year fields. This is due to higher weed pressure in cassava at first years than cassava in second year which has a normally fully developed canopy. The farmers harvest the leaves as vegetables in cassava at 12 and 24 MAP only.

Table 2: Management practices for cassava and field characteristics in the study area

Practice	Attribute	Cassava age (Months) 12	24	36
			%	
Weeding frequency (per year)	1	72.5	72.5	0
	2	27.5	25	0
	3	0	2.5	0
Monthly leaf harvesting frequency	1	15	20	0
	2	40	42.5	0
	3	12.5	12.5	0
	4	32.5	25	0
Texture class	Loamy sand	12.5	12.5	12.5
	Sandy loam (%)	75	62.5	62.5
	Sandy clay loam	12.5	25	25
Field size	Area (ha)	0.58±0.29	0.55±0.43	0.53±0.37

(± s.d=Standard deviation)

Farmers mainly control weeds using the handhoe which is mostly done twice from cassava planting to harvesting (Table 2). This is inconsistent with three weeding operations per cassava growing cycle recommended by IITA (1990) and NACWC (1994). Contrary to our findings, Munyahali et al. (2017a) reported at least three weed operations per cassava growing cycle to be practiced by the majority of farmers in all sites in DR Congo. In this study, weeding was mostly done by family members who took longer which could affect the growth of cassava. These findings are consistent with those reported by Enete et al. (2005), who found family labour not to be often sufficiently available and this leads to weeds adversely affecting crop yields. According to Leihner (2002), the critical period for weed competition in cassava lasts up to 4 months after planting (MAP).

The tender leaves in first year are mostly used for household consumption while the ones obtained in second year are mainly for sell. The leaf harvesting frequency of 2 and 4 times monthly were the most common and were done based on the household demands. The time of the first leaf harvesting was generally at 6 months after planting. Leaf harvesting is more frequent during dry seasons as cassava leaves are present unlike other seasonal traditional vegetables. The leaf harvesting frequency was negatively correlated and non-significantly affecting the yield ($r = -0.10$, $P > 0.05$). The leaf harvesting interval observed in this study (Table 2) is in agreement with those of Munyahali et al. (2017b), who reported 2–or 4–weeks leaf harvesting intervals starting at 3–4 MAP for household consumption. They reported that this harvesting had insignificant effects on tuber yields. However, Lockard et al. (1985) recommended leaf harvesting interval of at least 2–months starting at 4 MAP since monthly intervals significantly reduced tuber size. The non-significant effect of leaf harvesting on tuber yield in the study could be attributed to the larger field size and observation at plant level which requires further research.

The sandy loam textured soils were dominant in the visited fields followed by the sandy clay loam and the loamy sand which was the least. Field sizes were variable and less than 1 ha in the whole study area. The average cassava field size was 0.53 ha with a range of 0.19–0.92 ha (Table 2). There has been a decrease in field sizes compared to those reported by Mansfield et al. (1975) who found field sizes to range between 1.6 and 2.0 ha in the Northern part of Zambia. This pattern of smaller cassava fields has also being reported by Junqueira et al. (2016) in the Amazon Basin under shifting cultivation. The author attributed smaller fields to a strategy to combat the higher weed pressure on fertile land when combined with fast growing species or landraces with shorter cycles. Similarly Munyahali et al. (2017a) reported of smaller field sizes with an average of 0.9 ha in Kivu, DR Congo, although they were slightly larger than those found in this study. Other studies with similar results of average field sizes of 0.3 to 0.9 ha by Fermont et al. (2008) in Kenya and Uganda, 0.1 and 0.98 ha in Kongo Central and between 0.2 and 4.4 ha in Tshopo in DR Congo by Kintché et al. (2017). In this study the fields were located very far from home because of shifting cultivation.

4.1.2 Effects of cassava cropping practices on selected nutrient adequacy levels

Physico-chemical soil properties in farmer's fields of cassava in fields of 12, 24 and 36 MAP are presented in Table 3. The soil pH and total nitrogen were moderately suitable for optimal cassava production. Generally, soil parameters (K, P) were highly suitable for optimal cassava production while Calcium (Ca) and Magnesium (Mg) were low to moderately suitable. Meanwhile, total nitrogen, Cu and Zn were very low compared to the cassava production requirement. Soil organic carbon ranged from low suitability levels for cassava at 12 and 24 MAP to moderately suitable for matured cassava at 36 MAP.

Table 3: Chemical and physical analyses of soil samples collected in cassava fields of varying maturity at 12, 24 and 36 MAP and their suitability for cassava production

Parameter		Cassava age (Months)						Significant level	Suitable levels
		12	Rating[ǂ]	24	Rating[ǂ]	36	Rating[ǂ]		
pH_{H2O}		5.54±0.29	M	5.62±0.68	M	5.66 ±0.48	Medium	ns	4.5 - 7.0
K	$cmol_{(+)}$/kg	0.60±0.12b	H	0.45±0.11a	H	0.48±0.11b	h	*	>0.25
Ca	$cmol_{(+)}$/kg	0.79±0.85a	L	0.96±0.81a	L	1.77±2.03b	m	**	1.0-5.0
Mg	$cmol_{(+)}$/kg	0.76±0.25	M	0.82±0.26	M	0.74±0.29	m	ns	0.4-1.0
P	Mg/kg	37.81±15.24	H	32.65±12.56	H	36.32±17.78	h	ns	10 - 14
SOC	%	0.78±0.36a	L	0.81±0.37a	L	1.34±0.25b	m	***	2.0-4.0
N	%	0.18±0.03	L	0.19±0. 02	l	0.19±0.05	l	ns	0.2-0.5
Cu	Mg/kg	0.154±0.1	L	0.15±0.06	L	0.16±0.05	l	ns	0.3-0.8
Fe	Mg/kg	33.86±2.11	M	35.625±18.95	M	30.02±13.91	m	ns	10-100
Zn	Mg/kg	0.368±0.05	L	0.2475±0.19	L	0.35±0.28	l	ns	1.0-3.0
Mn	Mg/kg	17.54±2.07	M	15.48±3.87	M	17.41±12.71	m	ns	10-100

Means followed by the same letters in a column are not significantly different from each other according to Tukey's HSD. TN=Total soil nitrogen, SOC=Soil organic carbon, **Signif. codes: 0 '***' 0.001 '**' 0.01 '*' P≤0.05;** vl, l, m, h and vh stand for very low, low, medium, high and very high; Numbers are average (± standard deviation)

The soil pH varied from very strongly acidic to strongly acidic and is classified as moderately suitable for optimal cassava production (Howler, 2002) (Table 3). In this study, the soil pH was higher in cassava at 36, 24 MAP maturity stages than 12 MAP. These findings are in agreement with those reported by Giardina et al. (2000) who found that soils under shifting cultivation to be generally less acidic than those under forest because of the combustion of vegetation and subsequent addition of ash that may increase the soil pH.

The results show that exchangeable cations; potassium and other nutrients such as phosphorus were above the critical levels (Table 3) (Fermont et al., 2009). This result contradicts several findings in literature which have reported of low soil exchangeable potassium which limits cassava tuber yield (Howler, 1991; Carsky and Toukourou, 2005). Generally, there were higher amounts of soil exchangeable potassium at 12 MAP than cassava at 24 and 36 MAP. This trend of higher exchangeable K could be explained by the immediate effects of the slash and burn practices in recently opened fields with cassava at 12 MAP. Meanwhile, the low values of exchangeable K at 24 and 36 MAP could be attributed to the high uptake of exchangeable K during the growing periods. These findings are in agreement with those by many other authors who have reported cassava to take-up more of exchangeable potassium than any other nutrient during the growing season (Howler, 1991; Carsky and Toukourou, 2005; Howler, 2002; Putthacharoen et al., 1998). Similarly, Pellet and EL-Sharkawy (1997) found plant-available soil K concentration to decrease from the first to the second growing season, irrespective of the fertilization treatment. This observation supports high K uptake by cassava. The low to moderate levels of exchangeable Ca and Mg for optimal cassava production (Table 3), indicates nutrient imbalance and could limit cassava growth and the need for liming.

Total nitrogen was less than 1% and was very low (Table 3) for optimal cassava production (CIAT, 2011). These findings are consistent with those conducted by several studies which have observed nitrogen as the most limiting macronutrient in the tropical regions of sub-Sahara Africa (Sanchez, 1976). For example, in a soil suitability assessment for cassava production in Nigeria, total nitrogen contents for surface and subsurface soils were found to be lower than the critical limits of 0.08 and 0.05% respectively (Abua, 2015). Results from this study are consistent with those reported by Imakumbili et al. (2019) who found that low levels of organic matter to be associated with very low levels of total nitrogen under cassava systems in Tanzania. The lower nitrogen levels in shifting cultivation systems could be because of the oxidation of organic carbon and subsequent volatization during the slash and burn which limits organic matter available for nitrogen mineralization (Giardina et al., 2000). However, at 36 MAP, the moderate levels of SOC is due to organic matter build up after the slash and burn activities. The low levels of nitrogen could limit growth of cassava despite other nutrients such as exchangeable K being above the critical limit.

4.1.3 Effects of cropping practices on cassava characteristics

4.1.3.1 Cassava leaf area index, light interception and tuber yield

Cassava leaf area index, light interception and tuber yield in farmers' fields at 12, 24 and 36 MAP are presented in Table 4. There was a non-significant difference ($p > 0.05$) in plant densities, intercepted radiations and light extinction coefficients across all the 3 cassava maturity stages. However, there was a significant different ($p < 0.05$) in cassava LAI at 24 MAP only. The LAI ranged from 0.87–1.75, 0.97–2.07 and 1.46–2.68 respectively. The average light extinction coefficients (k) in cassava at 12, 24 and 36 MAP were 0.56, 0.59 and 0.64 respectively (Figure 4). The cassava light extinction coefficients increased from 12 to 36 MAP and varied from 0.53–0.58, 0.61–0.69, 0.62–0.66 at 12, 24 and 36 MAP respectively.

Table 4. Cassava characteristics in farmer's field at 12, 24 and 36 MAP (± standard deviation)

Property	Cassava age 12	 24 Months after planting	 36
Plant density/ha	23794±14764	21760±11168	26294±20073
LAI	1.31±0.44	1.52±0.55	2.07±0.61
Intercepted radiation (%)	49.07±14.66	55.95±10.01	70.43±12.14
Light extinction coefficient	0.56±0.17	0.58±0.25	0.64±0.13
Fresh root tuber yield (t/ha)	6.01±2.50	19.68±6.16	23.95±7.03

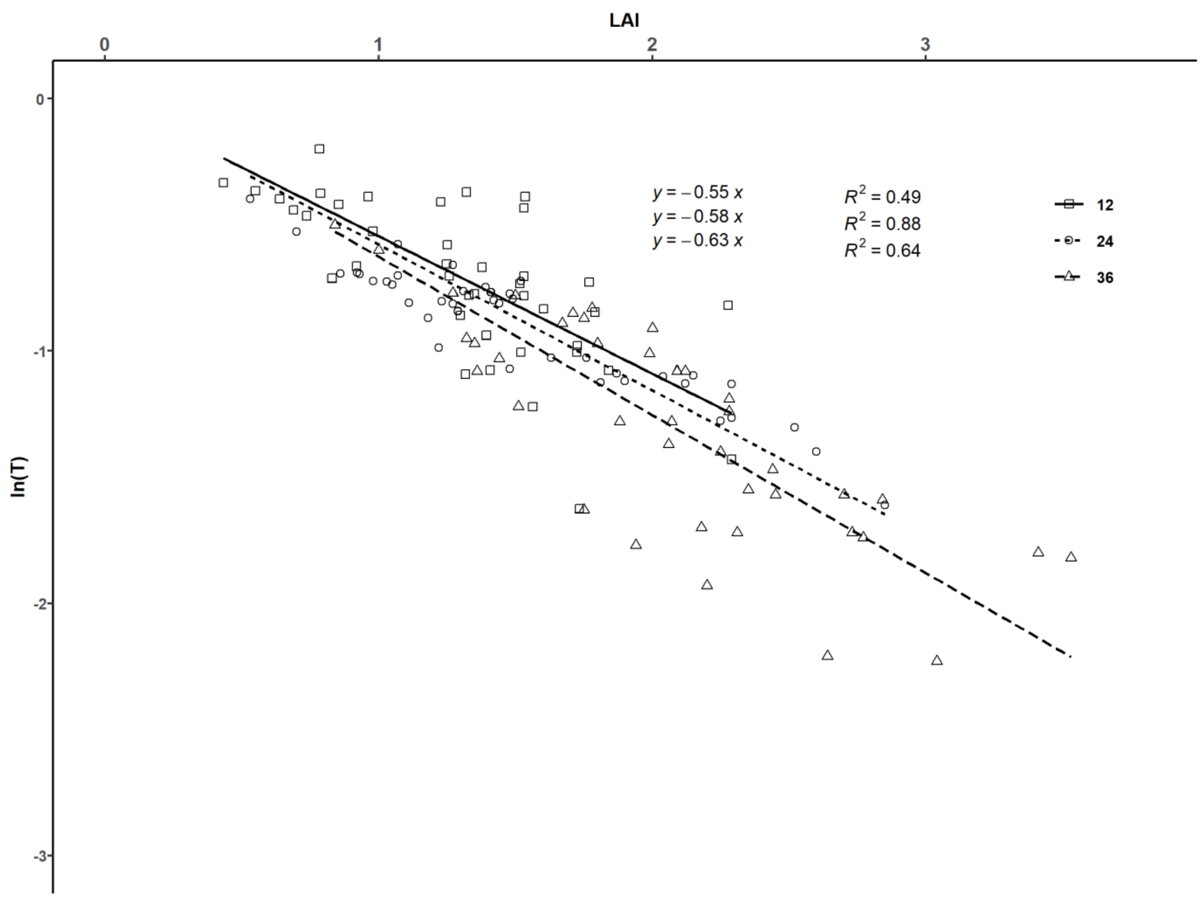

Figure 4: Relationship between natural logarithm of light transmission and leaf area index (LAI) called the light extinction coefficient in cassava maturity stages at 12, 24 and 36 MAP

The light extinction coefficient (k) is a function of leaf size and orientation and values obtained in this study are within the recommended range of 0.3 to 1.3 (Saeki 1960). Values of k less 1 indicate clumped leaf distributions and greater light penetration while those with values above 1 show more of horizontal leaves and greater light interception (Jones 1992). The average light extinction coefficients (k) were higher in cassava at 36, 24 MAP maturity stages than 12 MAP (Table 4 and Figure 4. This indicates more light interception for the cassava at 36 MAP old than at 24 and 12 MAP. This could be attributed to a higher density and better leaf positioning, possibly as a result of differences in leaf curving and leaf angles among the different years. This pattern corresponds to that of Pellet and EL-Sharkawy (1997) who obtained higher k values in fertilizer treatments than in unfertilized treatments. The k values obtained in this study are within the range of 0.50–0.78 also reported by Pellet and EL-Sharkawy (1997) in Cauca, Colombia for different varieties under fertilizer and unfertilized conditions.

The cassava LAI and yields were lower at 12 MAP than at 36 MAP. The tuber yield was characterized by higher variability. The average fresh yields of cassava at 12, 24 and 36 MAP were 6.01, 19.68 and 23.95 t/ha (Table 4). The LAI for cassava regardless of the maturity age was below the critical level of 2.5–3.5 considered ideal for tuber production (Cock et al., 1979; Lebot 2009). Howler (1987) observed a LAI greater than 4 to indicate higher nitrogen fertilization which enhances more of vegetative growth by partitioning less assimilates for growth of storage roots. Similarly, Lahai (2013) observed excessively larger canopies to reduce yield due to shaded leaves which respire more carbon than partitioning it to the tubers. Biratu et al. (2018a) found a LAI of 2.7 which is within the ideal range considered for tuber production in Zambia after a combined application of 1.4 t/ha manure plus 150N:33P:124.5K kg/ha. The LAI was significantly positively ($r = 0.39$, $p < 0.001$) related to soil organic carbon, indicating that available nitrogen is important in leaf area index growth. The low LAI obtained in this study could be attributed to the low soil fertility levels, similar to observations by Pellet and EL-Sharkawy (1997) in Columbia for a cassava varietal response to fertilization trials. Contrary, Cock et al. (1979) observed low LAI regardless of whether the cassava was fertilized or unfertilized. The LAI was significantly correlated ($r = 0.56$, $p < 0.001$) to intercepted radiation and tuber yield ($r = 0.58$, $p < 0.001$). These findings are in line with many authors as this relationship is key to the amount of dry matter produced (Tesfaye et al., 2006).

Generally, cassava tuber yields varied widely between the different fields within the same maturity age group and across the different age groups (Table 4). This variability in tuber yields has been observed by several authors when cassava is grown without fertilizer and is attributed to heterogeneity in soil fertility (Kintché et al., 2017; Munyahali et al., 2017a). In this study, the average farmer fresh cassava tuber yield at maturity groups of 12, 24 and 36 MAP obtained were 6.01, 19.68 and 23.95 t/ha. Yields at 24 and 36 MAP are within range with those obtained in Uganda and Kenya of 15–40 t/ha by Ntawuruhunga et al. (2006) and Fermont et al. (2009) from on-farm breeding trials. The tuber yields at 12 MAP were skewed towards the lower bounds of 6–17 t/ ha reported by Fermont et al. (2010) in farmer fields in Kenya and Uganda without fertilizer. Several other on-farm studies showed higher yields at

12 MAP than in this study which includes 6–10 t/ha (FAOStat, 2018), 10.6 t/ha in Kenya and 12.0 t/ha in Uganda (FAO, 2008), 8.6 t/ha (Fermont et al., 2009), 13–14 t/ha in DR Congo (Kintché et al., 2017) and 7–17 t/ha in DR Congo (Munyahali et al., 2017a). Munyahali et al. (2017b) obtained 20–25 t/ha of tuber yield under field trials which is higher than those in this study at 12 and 24 MAP but consistent with the yield obtained at 36 MAP. According to Cock et al. (1979), potential fresh root yields of 75–90 t/ha are attainable for late branching genotype that possesses large leaves with a long leaf life. Similarly, El-Sharkawy (2004) observed that yields of between 25–30 t/ha of dry matter are attainable under experimental conditions in Colombia and India. The cassava yields reported in literature were obtained at 12 MAP which is higher or comparable to the yields obtained at 24 or 36 MAP in the study. The lower nitrogen levels in this study partly affected by lower levels of soil organic carbon could limit the exchangeable K uptake and ultimately affects cassava growth and yield. Thus, there is great potential to obtain yields of even more than 20 t/ha at 12 MAP in the study area if fertilizer regimes can be adopted. Further, this could be attributed to the unimodal rainfall pattern experienced in Zambia in which cassava undergoes a physiological rest mainly in the dry seasons and cold seasons associated with stagnant growth (Figure 2). This could imply water management in form of irrigation could increase cassava productivity.

Cassava yield variation against number of years of field cultivation is presented in Figure 5. For every year of cultivation without fertilizer application, the cassava yield decreased by 620, 210 at 36, 12 MAP and increased by 34 kg/ha at 24 MAP. The yield loss of 622 kg/ha at 36 MAP is higher than the 209 kg/ha of cassava at 12 MAP because of the many number of years of cassava cultivation without applying fertilizer (Figure 5). This is supported by the overall average land cropping period before abandonment of a field which is 8.6 years based on results from semi structured interviews (Table 1). The farmers resort to opening up of new field to meet the escalating cassava demand (Greenland et al., 1997; Bruun et al., 2006; Mertz et al., 2009; Biratu et al., 2018a). This landuse duration contradicts earlier findings by Mansfield et al. (1975) who reported 4–6 years in the northern part of Zambia. The observed increase in the landuse duration in this study could be attributed to increased population and may result in high rates of deforestation and degradation of the environment (Chase and Singh, 2014).

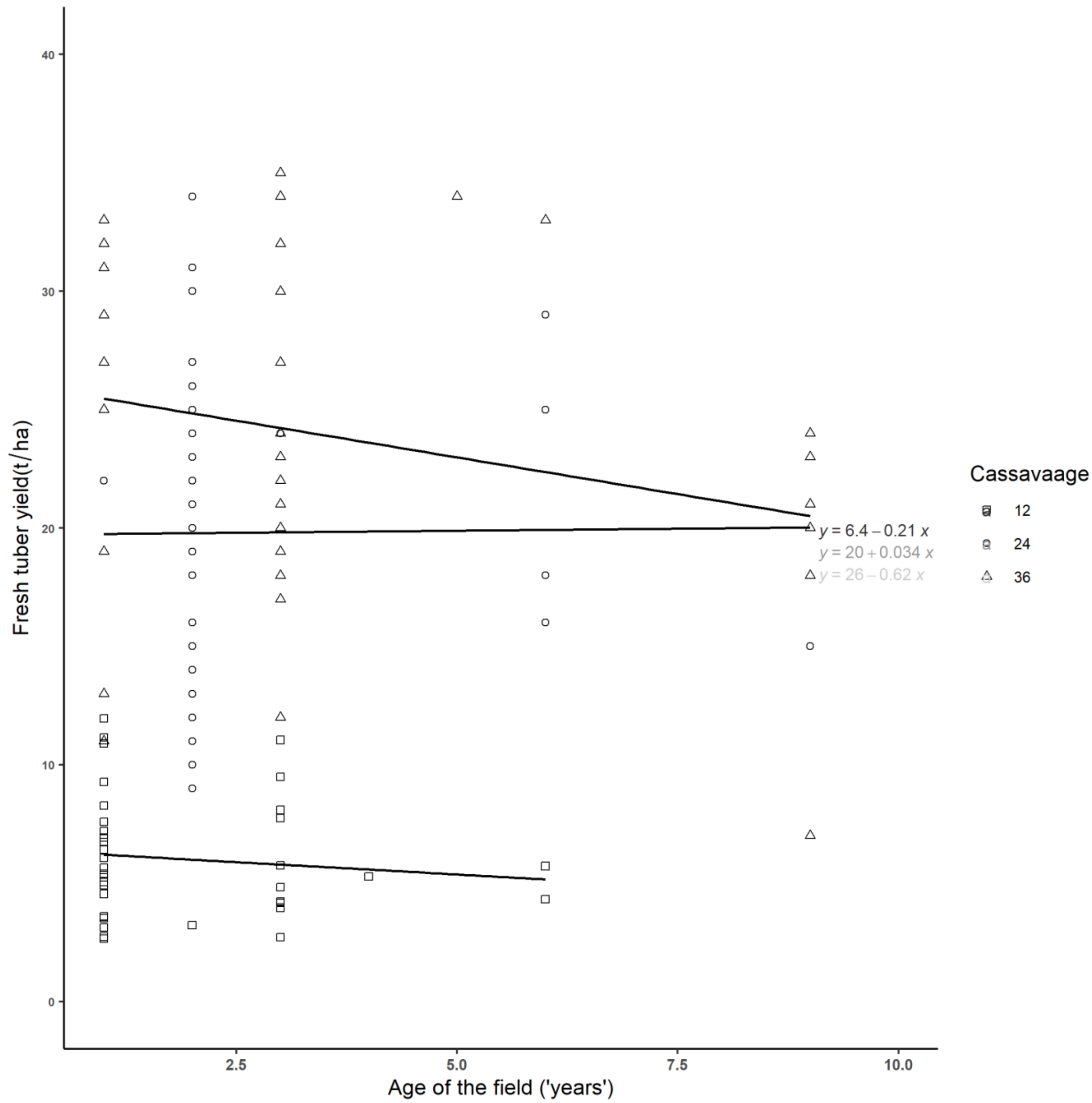

Figure 5: Effects of continuous years of field cultivation on cassava yield without fertilizer

4.1.4 Factors affecting tuber yield within each cassava maturity group

Table 5 presents soil, plant and management practices which explained differences between low and high yields based on the median within each maturity group. At 12 MAP, weeding frequency ($p < 0.05$) explained yield differences between high and low yielding farmers. Meanwhile, at 24 and 36 MAP, exchangeable K ($p < 0.03$), LAI ($p < 0.01$) and SOC ($p < 0.01$) significantly distinguished yield differences between high and low yielding farms.

This could be attributed to the higher intercepted radiation enhanced by the quick establishment of LAI due to the higher exchangeable K levels (Silva and Trevizam, 2015; Umeh et al., 2015; Fernandes et al., 2017). The higher uptake of exchangeable K has been observed to have synergist effects in cassava which brings about increased uptake of other nutrients such as exchangeable Mg and Ca (Silva and Trevizam, 2015; Fernandes et al., 2017) which optimizes growth and increases yields.

Table 5. Cassava yield determining factors within each maturity group

Variable	12			24			36		
	Months after planting (MAP)								
	5.7-12	**2.7-5.6**	**p-value**	**20-34**	**9 - 20**	**p-value**	**24 -35**	**9 - 20**	**p-value**
	t/ha			t/ha			t/ha		
K (cmol/kg)	0.52	0.48	ns	0.52	0.38	*	0.52	0.46	*
SOC (%)	0.94	1.02	ns	1.23	0.92	*	1.32	1.44	*
LAI	1.29	1.33	ns	2.13	1.37	*	2.21	2.0	*
WF	1.45	1.10	*	2.76	2.58	ns	2.83	2.48	ns

Signif. codes: 0 '*' 0.001 '**' 0.01 '*' ns=0.05 ', WF=Weeding frequency, SOC=Soil organic carbon (asterisk denote significant within the age group at p=0.05) and ns denote no without difference within the age group.**

4.1.5 Determinants of tuber yield at each cassava maturity group

A stepwise regression for the all data set revealed that weeding frequency (r= 0.34, p < 0.000), LAI (r= 0.33, p < 0.000), soil organic carbon (SOC) (r= 0.17, p < 0.000) and exchangeable magnesium (r= 0.08, p < 0.000) arranged in order of importance as the main factors explaining the variability observed in cassava yields (Table 6). For every unit increment in exchangeable K, the cassava yield increased by 435 kg/ha at 12 MAP. At 12 MAP, exchangeable K was the main factor explaining 19 % of the tuber yield variability (p < 0.049) (Table 6). At 24 MAP, for every unit increment in K, Mg and LAI, cassava yield increased by 268, 525 and 262 kg/ha respectively. The main factors explaining yield variability at 24 MAP, arranged in order of importance were exchangeable Mg (r= 0.20, p <0.00), exchangeable K (r= 0.37, p < 0.05) and LAI (r = 0.19, p < 0.05) (Table 6). At 36 MAP, for every unit increment in SOC, exchangeable K and Mg, cassava yield increased by 255, 406 and 326 kg/ha respectively. Therefore, exchangeable Mg (r= 0.38, p < 0.00), K (r= 0.28, p < 0.01), and SOC (p < 0.01) at 36 MAP arranged in order of importance were the main factors explaining variability in cassava yields (Table 6).

Table 6: Cassava yield determining factors and their correlation at various maturity stages

Variable	Cassava age (Months) 12 (n=40)			24 (n=40)			36 (n=40)			All dataset (n=120)		
	t/ha	rs	p-value	t/ha	Rs	p-value	t/ha	rs	p-value	t/ha	rs	p-value
K	0.435	0.19	0.000	0.268	0.37	0.023	0.406	0.28	0.003			
Mg				0.525	0.2	0.000	0.326	0.38	0.016	0.188	0.08	0.018
LAI				0.262	0.19	0.017				0.313	0.33	0.000
SOC							0.255	0.11	0.028	0.245	0.17	0.004
WF										0.425	0.34	0.000

Variables scaled beforehand to enable comparison, significant differences indicated as $p \leq$ **0.05;** rs =correlation coefficient; WF=Weeding frequency, SOC=Soil organic carbon

The various variables accounted for 18.9, 62.8 and 64.5% of the variation in observed tuber yields for cassava maturity stages of 12, 24 and 36 MAP of respectively. For the all dataset, the variables exchangeable Mg, LAI, SOC and weeding frequency explained 57.4% of the variation in the observed cassava tuber yields. Exchangeable potassium was the common determinant of tuber yield in cassava at 12, 24 and 36 MAP (Table 6). Exchangeable K has several functions in plant growth among them is the quick reestablishment of the leaf area of crop, which consequently improves yield (Silva and Trevizam, 2015; Umeh et al., 2015; Fernandes et al., 2017). Also, exchangeable Mg, LAI and SOC were limiting factors to tuber yield in cassava at maturity stages of 24, 36 MAP and across the whole area.

Exchangeable Mg being limiting in tuber yield could indicate the need to include it in fertilization regimes. Several authors have observed exchangeable K to influence the mineral nutrition of Ca and Mg (Silva and Trevizam, 2015; Umeh et al., 2015; Fernandes et al., 2017). Kintché et al. (2017) found imbalanced K versus exchangeable Ca and Mg to be the limiting factor in most cases in the DR Congo. This nutrient imbalance is supported by many authors who have found cassava to take up more potassium from the soil than Ca and Mg (Howler, 1991; Putthacharoen et al., 1998). In a cassava soil suitability assessment in Nigeria, total nitrogen, exchangeable cations and phosphorus were found to be deficient and limited tuber formation (Abua, 2015). Apart from exchangeable K and Mg, Munyahali (2017a) further found soil reaction (pH) to be one of the factors explaining the variability observed in cassava yields in DR Congo. This finding corresponds to the results in this study in which exchangeable Mg was one of the factors explaining variability in cassava tuber yield at 24 and 36 MAP and across the whole area. In this study, SOC was lower and limited cassava yield at 36 MAP and for the entire area (Table 6). Soil organic carbon being the major source of available nitrogen could explain why nitrogen is moderately suitable for cassava production in the study area. The low to moderate suitability of nitrogen (Table 3) for optimum cassava production seems to further limit LAI and intercepted radiation with consequent low tuber yields.

Weeding frequency was the most significant ($p<0.001$) contributing factor in explaining 34% of the observed variability in tuber yield across the area (Table 6). Also, weeding frequency was the significant ($p < 0.05$) main variable explaining differences between high and low yielding farmers in cassava at 12 MAP (Table 5). As in this present study, several other studies have recognized poor weed management as an important constraint to cassava production (Munyahali et al., 2017a; Fermont et al., 2009; Leihner, 2002; Melifonwu, 1994). Majority of farmers in this study, weeded twice during the entire cassava cycle which is recommended to increase cassava productivity when done at the right time (Kintché et al., 2017).

Despite the slash and burn method being productive for three cassava growth cycles of up to 9 years (Table 1), this practice is not sustainable in the long run due to soil nutrient depletion and causes farmers shift to other places (Chase and Singh, 2014). Similarly Howeler (2002) found exchangeable K to decrease to 0.07 cmol (+)/kg below the critical level of 0.15 cmol

(+)/kg in the seventh year of continuous cassava cultivation without K fertilizer application at CIAT-Quilichao in Colombia. In India, Kabeerathumma et al. (1990) observed a yield decrease from 22 t/ha in the first year to about 6 t/ha in the tenth year without K fertilizer application. These results from this study are consistent with those from den Doop (1937) who reported a decrease in cassava yields after three consecutive plantings without applied K (15 t/ha in the first year to 4 t/ha in the third year). The intercropping of legumes in cassava systems help to suppress weed pressure and complement the little fertilizer applied in cassava production systems. Also the use of balanced K fertilizers in cassava systems can impede nutrient mining whilst sustaining cassava production without land degradation.

Cassava is intercropped with maize, beans and cowpea in order to suppress weed and reduce labour ultimately achieving food security. Shifting cultivation only support cassava production for up to 8–9 years at which the field is abandoned due to substantial cassava yield decline for every year of cultivation. Soil nutrients of K, P were adequate for cassava production. The low yields in this study could be partly explained by the low to moderate levels of SOC which concede with moderate suitability of N for optimal cassava production. Under slash and burn, there is limited SOC thus lower N which limits LAI expansion resulting in reduced intercepted radiations and yields. Despite exchangeable K being above the soil critical limit, it was the common limiting factor affecting all cassava maturity groups. This could be due to the moderately availability of exchangeable Mg and low N which limit protein synthesis thus causing low yields. This results suggest that legume species, fertilizer, pesticide and fungicide integration in cassava production systems should be promoted with the immediate benefits of improved food security and increased income and in the long run improves soil fertility. Thus, the effects of cowpea, common beans and soybean intercropping effects on cassava yield under different liming and fertilizer levels on exhausted soils was evaluated.

4.2 Understanding the performance of cassava under lime, fertilizer, and grain legume intercropping on exhausted soils of Luapula Province of Zambia

4.2.1 Selected Soil physicochemical properties of exhausted soil at the experimental site

The soil analyses for selected soil chemical and physical properties for the study site are presented in Table 7. The soil texture at the experimental site was Sandyloam. The soil reaction was slightly acidic and moderately suitable for optimum cassava production. The soil organic carbon and total nitrogen were very low and below the critical levels suitable for cassava production. The P levels were moderately suitable for cassava production. Exchangeable K level was below the optimum range of 0.15–2.5 cmol/kg required for cassava production. The soils are classified as Ferric Acrisol in the FAO legend. These are characterized by highly weathered soils with low base cations and experiences strong phosphorus fixation due to higher acidity.

Table 7: Selected physicochemical properties of topsoil at the experimental sites

Soil parameter	0–30 cm	Suitable level for cassava production
pH (H_2O)	4.47	4.5–7.0
Total Nitrogen (%)	0.015	0.20–.50
OC (%)	0.39	2.0–4.0
C/N	26	
P (mg/kg)	11	10 – 14
Exchangeable acidity (cmol/kg)	0.54	
Exchangeable bases (cmol/kg)		
K	0.07	0.15–2.5
Ca	0.865	1.0–5.0
Mg	0.165	0.4–1.0
Na	0.004	
Micronutrients (mg/kg)		
Zn	0.64	0.5–1.0
Cu	5.18	0.1–0.3
Mn	51	10 – 100
Fe	71	10 – 100
Particle size (%)		
Sand	75	
Clay	4.8	
Silt	20.2	Sandyloam

(Cassava suitability production levels. Source: CIAT, 2011)

4.2.2 Effects of fertilizer, lime and legume intercropping on Leaf area index and Fraction of intercepted photosynthetic active radiation (f)

The effects of lime, fertilizer and sole cassava and cassava soybean, common bean, cowpea intercropping (cropping system) on cassava leaf area index and f are presented in Figure 6a–b. The LAI ranged from 1.01–3.5 with a mean of 1.96 in the first season. In the second season, the LAI ranged from 1.51–3.48 with a mean of 2.05. The fastest increase in LAI was recorded in the cassava common bean intercropping and sole cassava compared to cassava cowpea and cassava soybean intercropping in both seasons. The canopy growth pattern reached a higher value after a few months of growth conciding with the rain season. The development of cassava LAI was slow during crop establishment phase upto the third month. The two sharp decreases at 170 and 272 days after planting corresponded to the cold and hot seasons of the year. This pattern is consistent with several authors who have reported that during drought and cold stress, there is a reduction in LAI, f and dry matter partitioning to stems and leaves since the photo-assimilates are mostly channelled to the growth of storage roots and only increase with the onset of the rainfall (Ezui et al., 2017; Howeler, 1991). Generally, the final regrowth was high in fertilized treatments than in unfertilized treatments. These patterns are consistent with findings reported by several authors who have observed enhanced LAI for high soil fertility (Pellet and El-Sharkawy, 1997). The reduced LAI during the cold and dry season corresponds to a mechanism which allows the crop to consume limited amount of available water slowly during the dry season, resulting in greater dry matter gain during stress periods and larger water use efficiency (El-Sharkawy, 2004). This trend of reduced LAI associated with the dry seasons and cold seasons causes stagnant growth since cassava undergoes physiological rest (Fernandes et al., 2017). Cassava leaves may also drop or fold, to decrease interception of sunlight, in turn decreasing, leaf temperature and water loss (Liao et al., 2016).

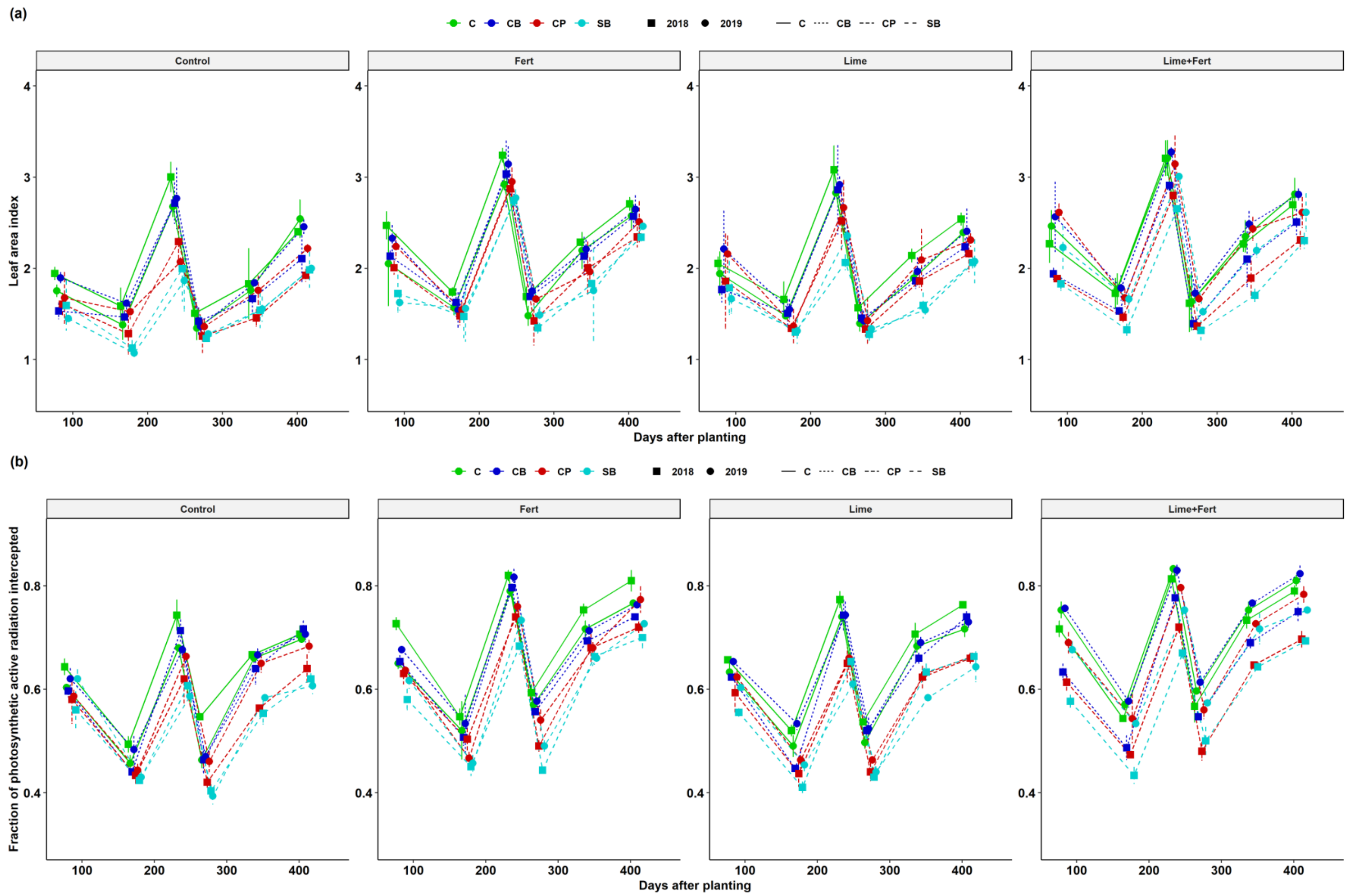

Figure 6 (a-b) : Effects of lime, fertilizer and intercropping soybean (SB), beans (CB) and cowpea (CP) on the cassava leaf area index (LAI) and fraction of intercepted PAR during the 2017–2018 and 2018–2019 seasons

The lower LAI of cassava in soybean intercropping is consistent with the findings reported by Tsay et al. (1988a) in a cassava soybean intercropping experiment. Contrary to our findings, Cenpukdee and Fukai (1992) reported the cassava LAI planted at 6.7 plants/m^2 not to be affected in soybean intercropping. The unfertilized cassava regardless of the intercropped species developed a smaller LAI compared to the fertilized treatments in both years, thus intercepted lower f (Figure 6b). The higher LAI in the mixed N: P: K fertilized treatments is attributed to significant increases in leaf expansion via cell division and enlargement (Kar and Kumar, 2015; Pradhan et al., 2018; Mwamba et al., 2021). There was a significant ($p = 0.02$) cropping system by year interaction on the LAI (Figure 6a). Soybean intercropping reduced the pooled cassava LAI by 21 and 16% in the 2017–2018 and 2018–2019 season respectively. The pooled cassava LAI reduction in cassava-cowpea intercropping was 16 and 6% in the 2017–2018 and 2018–2019 season respectively. The pooled cassava LAI reduction in cassava-common bean intercropping was 9.4 and 4.5% in the 2017–2018 and 2018–2019 respectively. The positive effect of the cropping system by year interaction on the LAI indicates the need for routinely applying liming fertilizer and legume intercropping in cassava smallholder farming systems.

The cropping system by year interaction effect was significant ($p = 0.047$) on f (Figure 6b). The f ranged from 38–84% across all the treatments for two seasons. Similar to the LAI, the cassava intercepted the lowest f at 170 and 272 DAP which are the cold and hot seasons of the year. The highest intercepted f was achieved at 240 and 410 DAP for 2017–18 and 2018–2019 seasons respectively which coincide with the spring season and the peak of the rain season. The cassava in the cassava-soybean intercropping reduced the pooled f by 16 and 11% in the 2017–2018 and 2018–2019 season respectively. The reduction in pooled f of cassava in cowpea intercropping was 13 and 6% in the 2017–2018 and 2018–2019 season respectively. The reduction in pooled f of cassava in common bean intercropping was 6 and 1.8% in the 2017–2018 and 2018–2019 respectively. Fertilizer resulted in a 5 and 16% significant ($p = 0.000$) increase in f in the 2017–2018 and 2018–2019 season respectively.

The low LAI and f in cassava soybean and cowpea intercropping compared to the sole cassava and cassava common bean intercropping in this study results from crowding and competition for light. The soybean and cowpea grew vigorusly and intercepted more f than the cassava and that the LAI and f only increased after the two legumes were harvested at

170 DAP. The f of cassava in common bean intercropping was not significantly different from sole cassava. This indicates that common beans did not strongly compete for light with cassava. The low f of cassava in legume species intercropping agrees with the results of Cenpukdee and Fukai (1992) who have reported lower intercepted f in cassava in soybean intercropping at 6.7 plants/m^2 which only rose after harvesting soybean at 101 DAP and became similar to sole cassava.

4.2.3 Effects of fertilizer, lime and legume intercropping on canopy extinction coefficient

There was a significant ($p = 0.025$) fertilizer by year interaction on k (Figure 7). Fertilizer application significantly increased the k values compared to unfertilized treatments. The canopy extinction coefficient ranged from 0.47–0.55 over the two growing seasons respectively (Figure 7). The k values obtained in this study are lower compared to the lower bound of 0.50–0.78 of cassava reported by Pellet and EL-Sharkawy (1997). Similarly, the k values in the study are lower than those estimated by Ezui et al. (2017) which ranged from 0.66–0.77 of cassava under different treatments with an overall value of 0.66. The author attributed the variation in k and RUE to variety. In the current study, the k values were higher for fertilized treatments than unfertilized treatments. This is attributed to enhanced better leaf positioning, due to differences in leaf curving and leaf angles of the fertilized treatments. This result indicates that severe stress conditions such as no fertilizer application can modify the leaf angle and orientation thus resulting in a lower k. These findings are consistent with those reported by other authors who have reported low k values and attributed them to the modification of leaf angle and orientation in response to water deficits (Tesfaye et al., 2006).

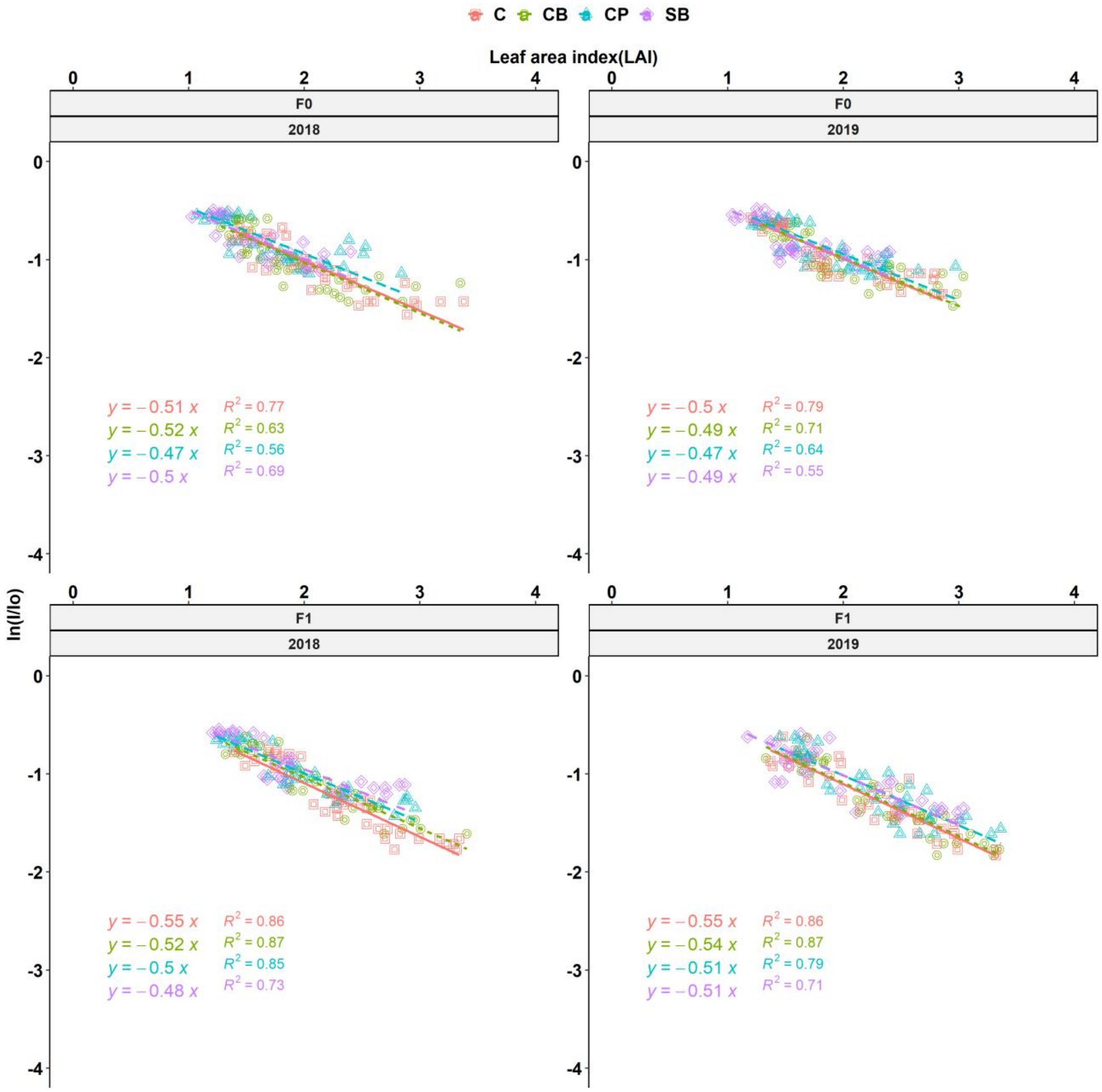

Figure 7 : Effects of fertilizer and year on the cassava canopy extinction coefficient (k) under soybean (SB), common beans (CB) and cowpea (CP) intercropping

Similarly, Pellet and EL-Sharkawy (1997) and Mwamba et al. (2021) reported fertilizer to significantly increase the k values of cassava varieties in Colombia and Zambia respectively. Similarly Pradhan et al. (2018) reported significantly lower k values of wheat at lower fertilizer rate of 40 Kg N/ha compared to higher rate of 160 kg N/ha in Indian. Our results showed no significant differences in k between the unfertilized and fertilized treatments in the 2017–2018 season which indicates a similar distribution of radiation within the canopies of the different treatments since the soils were of low soil fertility (Table 7), a result consistent with Bassu et al. (2011).

4.2.4 Effects of fertilizer, lime and legume intercropping on the radiation use efficiency

The lime by fertilizer x cropping system x year interaction was highly significant ($p < 0.001$) on RUE (Figure 8 and Table 8). The positive response of RUE to lime by fertilizer x cropping system x year is due to the liming effect which neutralizes the soil acidity hence increasing the available nutrients for crop growth. The legumes in cassava intercropping further fixed the nitrogen and improved the organic carbon which improves the soil fertility which is poor at the study site (Table 7). The strongest responses of RUE to lime x fertilizer x cropping system was in the second year, indicating the need for such practices to be incorporated in land management for sustainable land management for cassava production without resorting to deforestation (Table 8). The pooled RUE of 0.60–1.80g DM/MJ PAR obtained in our study are lower than the lower bound of 1.34–1.40 g DM/MJ but higher on the upper bound reported by Veltkamp (1985) during the first 6 month after planting (MAP) for four different cassava cultivars.

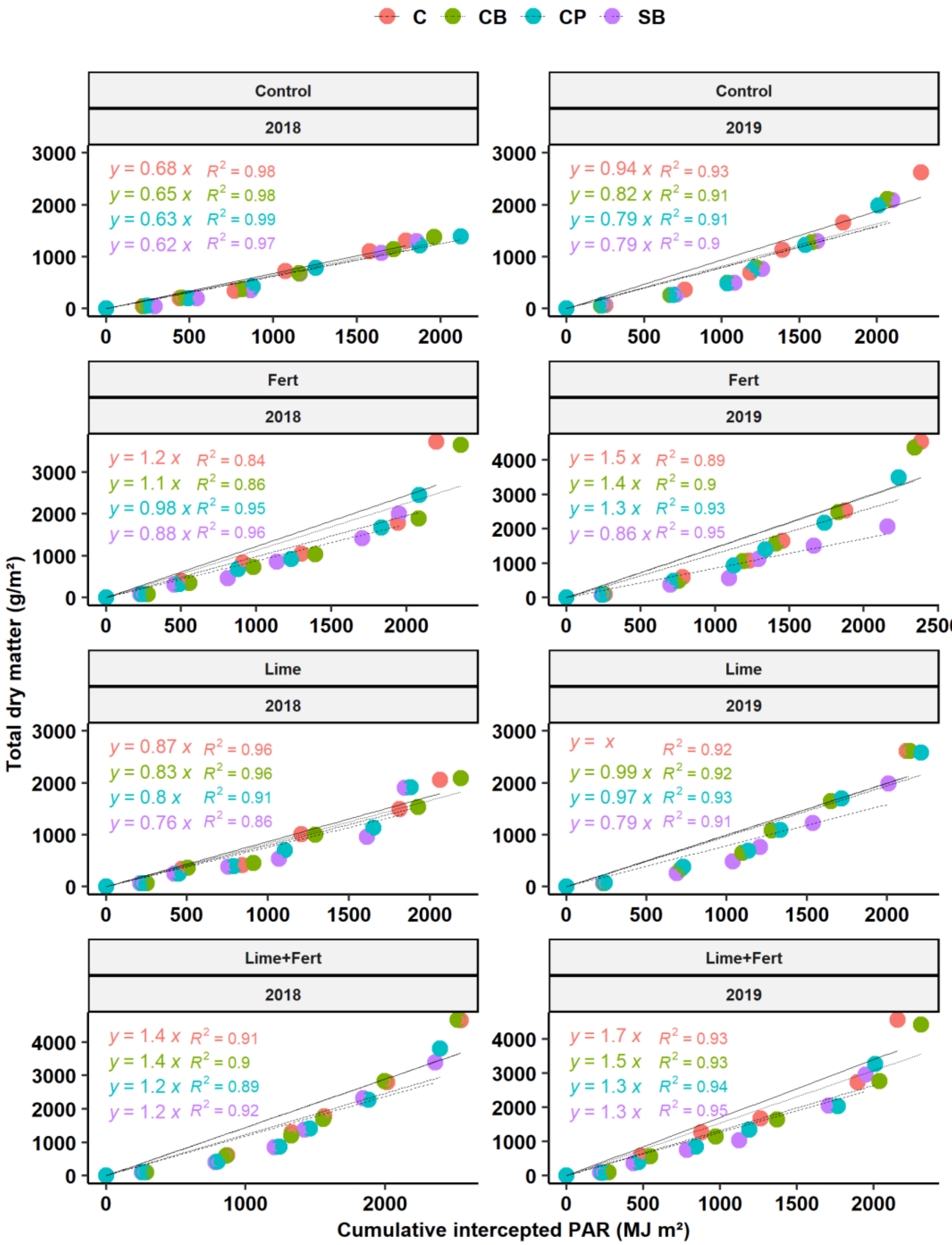

Figure 8: Interaction effects of fertilizer, lime, legume species intercropping and year on the radiation use efficiency

However, Veltkamp (1985) further reported a decrease in RUE at more than 6 MAP. The RUE values in our study were lowest in unfertilized treatments compared to the lower bound of Pellet and El-Sharkawy (1997) of between 1.15–2.30 g DM/MJ PAR but within the range of the upper bound. The higher RUE values reported by Pellet and El-Sharkawy (1997) could be ascribed to the higher soil fertility and good rainfall distribution of 1800 mm per year than the poor soils and unimodal distribution of the 1200 mm in the study area. The RUE values for individual treatments were variable and within range of 0.55–2.30 g DM/MJ found by Ezui et al. (2017) in West Africa. The higher RUE values on the upper bound found by Ezui et al. (2017) compared to this study is attributed to the bi-modal rainfall distribution with annual rainfall of 574–36 mm. The RUE values obtained in this study are comparable with those of Tsay et al. (1988a) who found 0.88 and 1.01 g/MJ PAR for cassava soybean intercropping and sole cassava respectively.

The significant increase in RUE is ascribed to the fertilizer which enhances LAI growth thus intercepting more f which results in higher biomass per unit of radiation absorbed than in the unfertilized treatments. These findings are consistent with Pellet and El-Sharkawy (1997) and Mwamba et al. (2021) who observed different cassava genotypes to show a significant increase in RUE in response to fertilizer application and ascribed it to increased LAI. Similarly, the Ezui et al. (2017) observed the smallest values of RUE in treatments without fertilizer with RUE of 0.92 g DM/ MJ PAR without K application, and 1.26 and 1.29 g DM/ MJ PAR with the application of 50 and 100 kg K/ha, respectively. Ezui et al. (2017) explained the poor RUEs with low K concentration in cassava due to highly deficient soil K which consequently lowers cytosol K concentration. Also, Uhart and Andrade (1995) reported of decreased RUE values due to nutrient deficiency. The RUE values of unfertilized treatments obtained in this study were very low suggesting that cassava dry matter accumulation is slow in stressed environmental such as poor soil fertility status explaining why the cassava takes about 24–36 MAP to reach maturity compared to 12 MAP in this study.

The RUE values obtained within individual fertilized and individual unfertilized treatments were comparable within each group regardless of the lime and intercropping species. This indicates that the effects of lime take time and should be incorporated in cassava production systems. The legume species intercropping effects on the comparable RUE is attributed to the fact that nitrogen fixation cannot substitute inorganic fertilizer and that soil organic matters build up from the legumes takes a long time. The beneficial effects of the legumes on nitrogen fixation and soil organic matter build up and ultimately on cassava RUE may require that legume species intercropping is done periodically. The exchangeable soil K in this study was 0.07 cmol (+)/kg which was below the critical limit of 0.15–0.25 cmol (+)/kg suitable for cassava production. This could indicate that NPK fertilizer application on K deficient soils may increase the RUE in the short run. Pooled over the seasons, the RUE was more strongly and significantly correlated (0.85***) to fertilizer than TIPAR (0.53*). This result agrees with those of Ezui et al. (2017) who reported that K fertilizers mainly affect efficiency of converting light into photosynthates than the amount of light intercepted.

4.2.5 Effects of fertilizer, lime and legume species intercropping on total dry matter production (TDM) and total intercepted PAR (TIPAR)

The pooled effects of lime, fertilizer and legume intercropping on cassava total dry biomass (g/m^2) are presented in Figure 9. Generally, the fertilized and lime plus fertilized treatments had a higher TDM than unfertilized and limed only treatments regardless of the legume species intercropping. There was a highly significant ($p < 0.001$) interaction effect of lime by fertilizer by cropping system on total dry biomass (Figure 9 and Table 8). This is attributed to the combined effects of liming which neutralized the soil acidity, resulting in more nutrients available for plant growth and further the legumes intercropping fixed the nitrogen which is limited in the study site soil (Table 7) and organic carbon.

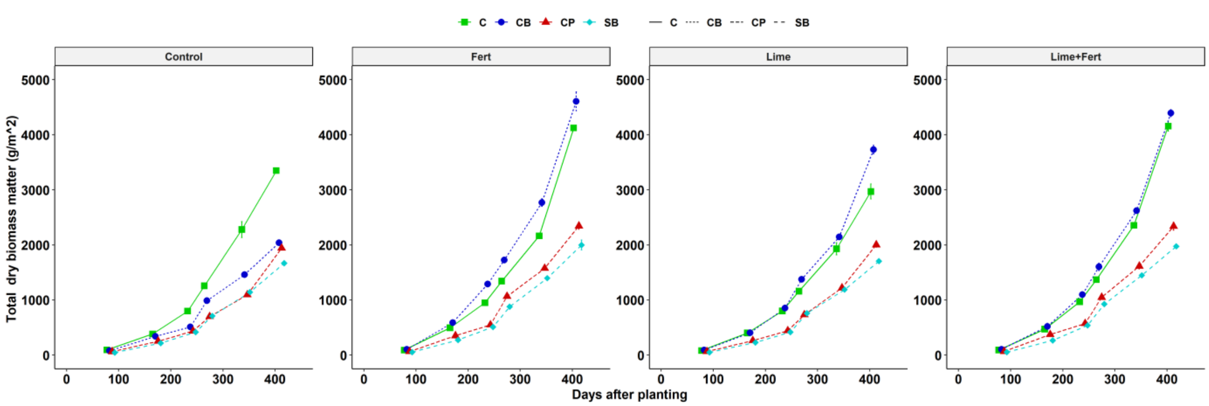

Figure 9: Effects of fertilizer on cassava total dry biomass (gm^{-2}) in monocropping (C), soybean (SB), beans (CB) and cowpea (CP) intercropping pooled over two seasons. (Fert- fertilized and Control-unfertilized+unlimed treatments)

There was low dry matter cassava production in cassava soybean and cassava-cowpea intercropping is mainly attributed to the vigorous growth of cowpea and soybean which outgrew cassava thus intercepting less f (Tesfaye et al., 2006; Cenpukdee and Fukai, 1992). The common beans had slightly affected the cassava TDM compared to soybean due to their shortest growing period of about 80 days. Since soybean took 120 days to harvest, this coincides with the sensitive period for cassava growing into a full canopy. Thus the soybean severely competed for f (Figure 6b) more than the cassava resulting in low TDM (Figure 9). This result agrees with those found by Willey (1979) who reported longer duration to maturing of grain legumes to cause more severe competition for light. Also consistent with Tsay et al. (1987, 1988a, 1988b) who have reported soybean growth dominating cassava in intercropping and cassava only recovers after the soybean is harvested (Tsay et al., 1987, 1988a, 1988b).

Cassava TDM and tuber yield under intercropping was less than those under sole-cropping at any harvest (Cenpukdee and Fukai 1992) (Figure 9). Tsay et al. (1988 a, b) reported a cassava N yield reduction due to soybean intercropping and attributed it to N competition as the major factor which reduced growth of intercropped cassava before soybean was harvest. However, several authors have reported the wider maturity gap between the grain legumes of about 90 and 360 days for cassava combined by its slow initial growth to enhances their compatibility in intercropping systems (Udealor and Asiegbu, 2005; Njoku and Muoneke, 2008).

The TIPAR was highly significant ($p < 0.001$) and positively correlated ($r = 0.87$) with the cassava TDM yield. The linear relationship between TIPAR and TDM depicted that 87% variation in TDM yield of cassava yield was explained by TIPAR. Pooled over the seasons, tuber yield was significantly related to RUE ($r2 = 0.78$, $p = 0.000$) and TIPAR ($r2 = 0.69$, $p < 0.0001$). This indicates that 78 and 87% of the variability in the tuber yield can be explained by RUE and TIPAR respectively. In the current study, the strong significant correlation between TDM and RUE and TIPAR visibly indicate that RUE and TIPAR are key factors for TDM and tuber yield formation as reported by Adeboye et al. (2016). Therefore, maximizing TIPAR and RUE via breeding large canopy cassava varieties, appropriate fertilizer, liming and legume intercropping is vital for increased and stable cassava productivity on exhausted soils.

4.2.6 Effect of lime, fertilizer and legume species intercropping on yield, yield components and source traits of cassava across the growing seasons

Significant differences for lime x fertilizer x legume species intercropping x year were observed for chlorophyll index ($p < 0.011$) and plant height ($p = 0.005$) (Table 8). There was a significant interaction effect of legume species x year on seasonal LAI ($p = 0.048$) and number of branches ($p = 0.007$). There was a significant interaction effect of fertilizer x legume species intercropping on number of tubers and tuber diameter. Lime x fertilizer x legume species intercropping had a significant effect on tuber yield ($p < 0.001$), total dry matter (TBM) and HI ($p < 0.001$) (Table 8, Figure 9–10). This is attributed to the combined effects of liming which neutralized the soil acidity and made more nutrients available and stimulated the uptake of other nutrients by the crops. Further the legumes intercropping fixed the nitrogen and provided organic carbon which is limited in the study site soils (Table 7). The higher response of cassava tuber yield in fertilized and fertilizer + lime treatment (Figure 10 and Table 8–9) is consistent with the findings reported by Howeler (1991) of a significant yield increase of upto 162 to172% in the first year to fertilizer application on exhausted soils.

Similar to this study, Carsky and Toukourou (2005) also observed fertilizers application in cassava to increase the uptake of nutrients, such as N, P, and K. Agbaje and Akinlosotu (2004) reported that only sufficient K levels are required to stimulate cassava response to other nutrients such as N. In this study, the lime application neutralized the soil acidity and made more nutrients available for plant growth. Cassava tuber yield has been reported to respond positively to K when cassava is grown continuously in the same field (Howeler and Cadavid, 1990). The application of NPK fertilizer in this study ensured that the nitrogen increased the storage roots DM, biomass DM and intercepted PAR while the K increased the RUE, storage roots and biomass as reported by Ezui et al. (2017).

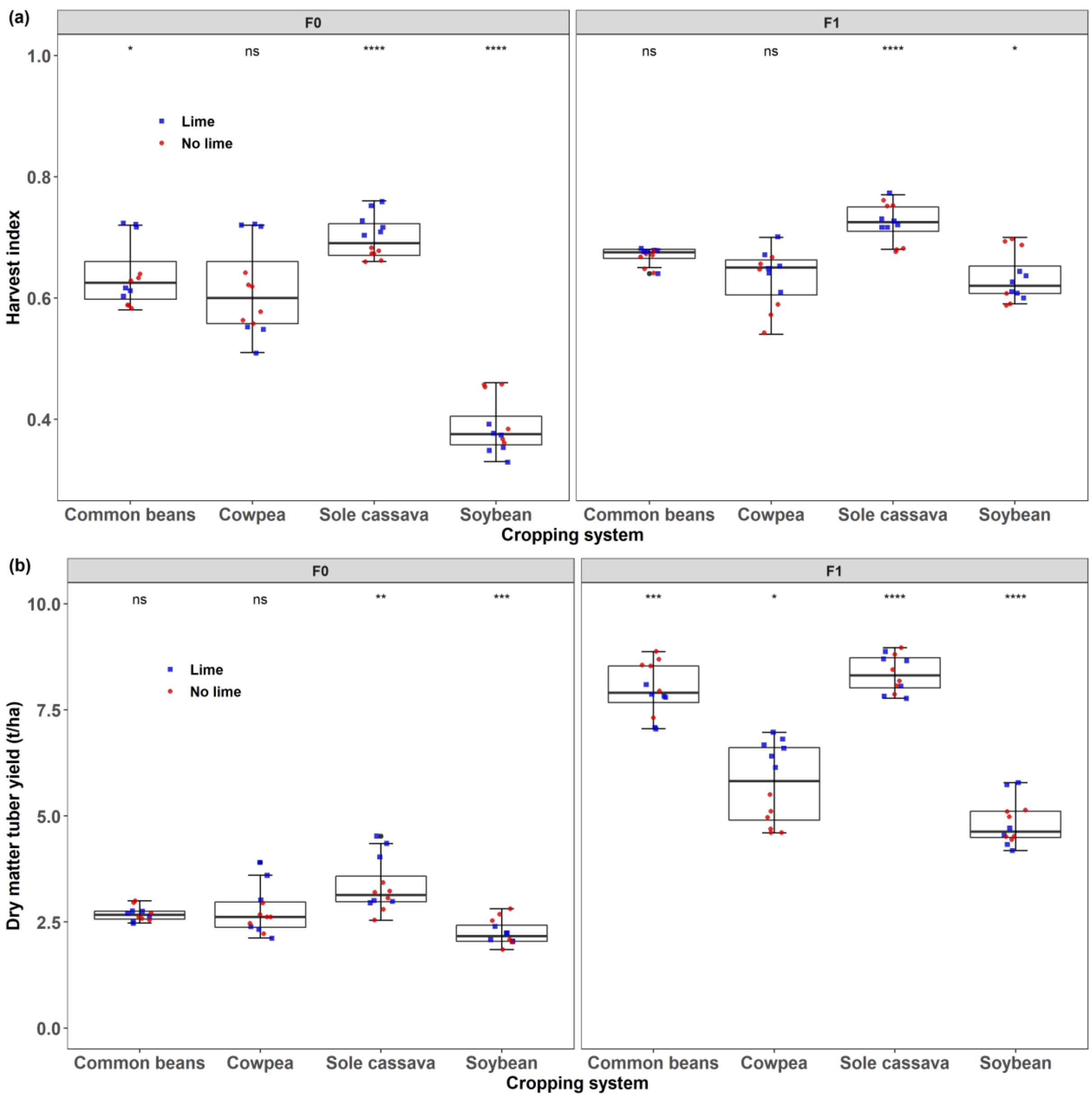

Figure 10: Interaction effects of lime, fertilizer and cropping system on cassava tuber yield and harvest index pooled over two seasons (F1-fertilized and F0-unfertilized treatments)

The poor response in cassava tuber yield to fertilizer and lime application could be attributed to the poor soil fertility levels (Figure 10 and Table 7). Similarly Pypers et al. (2011) reported of the non-significant increase in cassava yield to fertilizer application on soils with low fertility with consequent inefficient use of the fertilizer nutrients applied. Sanchez (1976) suggests the use lime is applied to ameliorate soil acidity to have a short residual effect. The liming effects on degraded soils are significant starting from the second year of experiments (Sanchez, 1976). Liming neutralized the soil acidity and made available nutrients such as phosphorus for plant growth. Phosphorus is an important plant nutrient for plant growth and plays a role in plant metabolism, structure and reproduction and 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 (Table 7). Therefore, rather than wait for the land to degrade, the use of fertilizer and lime in tandem with legume intercropping could increase fertilizer use efficient and increase both grain and cassava yield.

In this study, the highest cassava storage root yields were under common beans intercropping relative to other legume intercrops (cowpea and soybean) (Figure 10 and Table 9). The lower tuber yield and HI of cassava in cowpea and soybean intercropping is due to the severe competition which slows the grow rate of cassava. This result agrees with those of Thung and Cock (1978) who found common beans population not to affect cassava tuber yield. This result is similar to that of Eke-Okoro et al. (1999) who observed the lowest cassava storage root yields when intercropped with soybean, cowpea and bambara relative to groundnut. The plant height was highest for the cassava in soybean, followed by cassava in cowpea, and common beans intercropping and sole cassava was the lowest (Table 8 and 9). This is evidence that the cassava under intercropping responded by partitioning more assimulates to enhance height rather than to the root tubers in order to compete for light. The intercropping of legumes may build up organic matter and fix N which can enhance K uptake, and therefore contribute to increase RUE on N and K deficient soils. The liming reduces soil acidity making more nutrients available and ensures quick increase in tuber yield increase without nutrient depletion with application of NPK fertilizers.

Table 8: Analysis of the variance for lime, fertilization, cropping systems and year effects and their on interaction effects on yield, physiological and morphological plant traits (F stat)

Source of variation	Seasonal LAI	Chlorophyll Index	Number of branches	Plant height (cm)	Number of Tubers	Tuber diameter (mm)	Tuber yield (T/ha)	TDM (g/m2)	HI
Lime	20.68***	484.10***	4613.60***	49.74***	17.17***	0.03ns	7.80*	1.99ns	31.44***
Fert	4613.60***	6687.86***	20.68***	3514.78***	342.06***	131.16***	2873.52***	1885.43***	717.71***
Cropping system	133.71***	150.19***	133.71***	19.56***	7.96***	17.47***	196.95***	42.14***	788.44***
Year	24.49***	262.26***	24.49***	1.97ns	7.45*	0.03ns	12.78***	3.47ns	97.99***
Lime*Fert	18.70***	274.57***	18.70***	45.28***	2.95ns	0.74ns	0.37ns	0.07ns	4.61*
Lime*Cropping system	1.06ns	10.38***	2.93*	15.74***	2.22ns	0.46ns	15.85***	11.33***	36.36***
Fert*Cropping system	2.93*	6.29***	1.06ns	4.32*	**12.84*** **	**3.31***	85.78***	114.93***	335.30***
Lime*Year	0.04ns	2.52ns	0.80ns	0.01ns	3.69ns	0.55ns	3.31ns	0.77ns	17.83***
Fert*Year	0.80ns	2.71ns	0.04ns	25.16***	1.24ns	0.07ns	10.66*	0.16ns	178.50***
Cropping system*Year	**2.79***	3.15*	**2.79***	1.47ns	0.77ns	0.08ns	3.07*	9.75***	49.52***
Lime*Fert*Cropping system	1.09ns	5.22*	1.09ns	21.23***	0.53ns	0.13ns	10.50***	6.39***	9.45***
Lime*Fert*Year	0.08ns	6.00*	0.08ns	1.47ns	0.50ns	1.22ns	0.12ns	0.06ns	8.86***
Lime*Cropping system*Year	2.05ns	6.54***	0.50ns	0.66ns	0.45ns	0.11ns	2.51ns	3.67*	2.33ns
Fert*Cropping system*Year	0.5ns	4.81*	2.05ns	1.81ns	0.99ns	0.18ns	**3.78***	**5.28***	**5.08***
Lime*Fert*Cropping system*Year	1.32ns	**4.06***	1.32ns	**4.66***	0.31ns	0.14ns	2.00ns	2.31ns	40.41ns

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

Table 9: Liming, fertilizer, cropping system and year effects on cassava yield components across two growing seasons

Treatments	Seasonal LAI	Chlorophyll Index	Number of branches	Plant height (cm)	Number of Tubers	Tuber diameter (mm)	Tuber yield (T/ha)	TDM (T/ha)	HI	RUE (g/MJ PAR)
Lime (300 kg/ha)										
0	1.90	33.50b	3.04a	131.0a	9.06a	60.17a	4.64a	7.35b	0.62b	0.95b
300	1.82	38.16a	2.81a	125.2b	8.21b	59.95a	4.84b	7.54a	0.63a	1.12a
LSD(0.05)	0.037	0.992	0.2429	1.623	0.412	2.357	0.1481	0.242	0.006	0.026
Fertilizer (10:20:10 N:P:K kg/ha)										
0	1.23b	27.17b	2.74b	104.0b	6.73b	53.3b	2.754b	4.82b	0.58b	0.83b
200	2.50a	44.49a	3.10a	152.2a	10.54a	66.81a	6.725a	10.06a	0.66a	1.24a
LSD(0.05)	0.037	1.986	0.2429	1.623	0.412	2.357	0.1481	0.242	0.006	0.026
Cropping system										
Common beans	2.01a	36.99ab	2.91b	127.1c	8.71a	62.09b	5.325b	8.08ab	0.65a	1.04b
Cowpea	1.83ab	34.46bc	2.75bc	129.5b	8.67b	55.64c	4.248c	6.78c	0.62b	1.02b
Sole cassava	2.04a	38.85a	3.38a	123.6d	9.29a	66.07a	5.845a	8.15a	0.71a	1.17a
Soybeans	1.57b	33.02c	2.67bc	132.1a	7.88c	56.42c	3.541d	6.75c	0.51c	0.90c
LSD(0.05)	0.053	0.599	0.3435	2.296	0.583	3.334	0.2094	0.342	0.009	0.037
Year										
2018	1.81a	34.11b	2.5b	128.7a	8.92a	59.96a	4.607b	7.33a	0.61a	0.94b
2019	1.91a	37.55a	3.35a	127.5a	8.35b	60.15a	4.872a	7.55a	0.64a	1.12a
LSD(0.05)	0.037	0.992	0.2429	1.623	0.412	2.357	0.1481	0.242	0.006	0.026

Means with the same letter are not significantly different

4.2.8 Effects of legume intercropping on cassava tuber yield

Tuber yield of cassava tradeoff in common bean, soybean and cowpea intercropping's for the 2018 (a) and 2019 (b) season are presented in Figure 11. There was a reduction in cassava tuber yield intercropped with the three legume species. On average every kg of cassava yield loss was compensated by 0.49 kg soybean, 0.19 kg common beans and 0.23 kg of cowpea in the 2017–2018 season (Figure 11a). In the 2018–2019 seasons, for every kg of cassava yield loss was compensated by 0.42 kg soybean, 0.21 kg common beans and 0.28 kg of cowpea (Figure 11b). The large reduction in cassava tuber yield was compensated by highest grain yields of soybean.

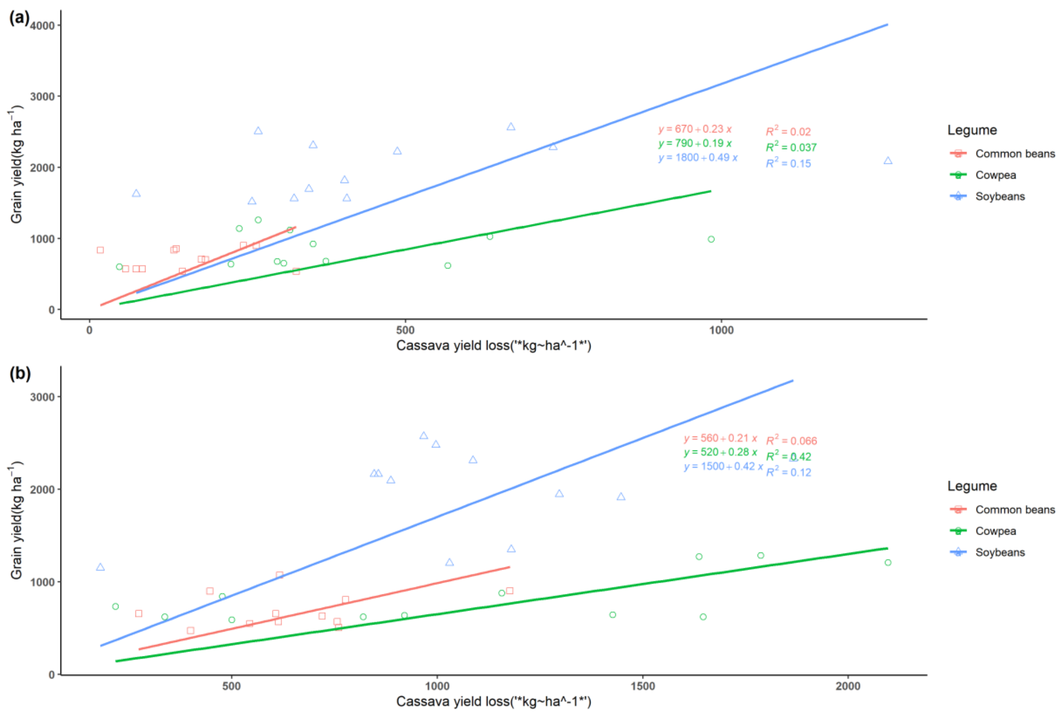

Figure 11 (a-b): Cassava tuber yield tradeoff in common bean, soybean and cowpea intercropping's

The obtained reductions in cassava yield as affected by legume intercropping's in this study are much lower than those reported by several other studies. This is attributed to the low legume density population and poor soil fertility status in the study area. For example, reductions of 40–50% in soybean (Tsay et al. 1988a), 20–40% common beans (Thung and Cock 1979), 30% by cowpea in South America (CIAT, 1993), 9–13% due to common bean or soybean (Kawano and Thung, 1982), 22–36% and 44–48% due to soybean, maize and cowpea (Dapaah et al., 2003) have been reported. Similarly Pypers et al. (2011) has reported a significant tuber yield loss of 6–8 t/ha when soybean was grown as the first legume intercrop in a 1m x 1 m or 2 m x 0.5m arrangement relative to common bean or groundnut. Similarly to this study, Pypers et al. (2011) has also reported of poor tuber yields of 2–5 t/ha in common beans and groundnuts intercropping than in the current study. Contrary to this study Makinde et al. (2007) observed a 10–23% increase in cassava yield in after incorporation soybean residues in after 2 years of cassava soybean intercropping. Contrary to this study, Cenpukdee and Fukai (1992) found higher mean tuber yield of 10.21 t/ha when intercropped with soybean than sole-crop yield at 9.46 t/ha, though the difference was not significant.

The higher soybean yield in this study (Figure 11a) are consistent with those reported by Tsay et al. (1988a) who have reported soybean cultivars to dominate intercropped cassava, without affecting their dry-matter growth and seed via competition. Contrary to this study, Cenpukdee and Fukai (1992) found soybean yield was affected more severely by tall cassava with high TDM production during the early stages, thus reducing intercepted f by soybean. Severe shading was likely to account for its adverse effects on cowpea yield. Podding and seed formation of cowpea were severely affected because of shading (Dapaah et al., 2003). The low yield of common beans could be attributed to the competition for nitrogen and severe shading from cassava.

4.2.9 Effects of lime, fertilizer and cassava legume intercropping on grain yield and HI of common beans, cowpea and soybeans

There was a significant lime x fertilizer x year interaction effect on the grain yield ($p = 0.001$) and HI ($p = 0.007$) of the three legume species (Figure 12a-b). Grain yield and HI were significantly increased in the fertilized and lime+fertilizer treatments than in the control and significantly increased in the fertilized and lime+fertilizer treatments than in the control and lime only treatments (Figure 13a–b). In all treatments, soybean had the highest grain yield and HI followed by cowpea and common beans (Figure 12a–b). In both seasons, there was a relative increase in grain yield due to fertilizer application of 51–76, 44–52 and 67% for soybean, common beans and cowpea, respectively. The common bean and cowpea yields were severely affected by light competition in cassava intercropping than soybean yield (Willey, 1979) and poor soil fertility status (Table 7). The low seed yield and HI of common beans agrees with the findings of Tsay et al. (1988a) who reported soybean to produce low seed yield and attributed it largely to low the harvest indices.

Legume intercropping with short maturing period (common beans, cowpea and soybean) can enhance the effects of lime and fertilizer on exhausted soils and allow smallholder farmers obtain reasonable cassava and legume yields. In this study, soybean and cowpea intercropping produced the highest grain yield than common beans. This is due the competitive effects of the two legumes and thus produced the lowest tuber yield (Figure 10 and 11). Similar to this study, Leihner (1983) reported common beans and cowpea to be more suitable legume intercrops than soybean because of their shorter maturity period. Soybean reduced the cassava LAI, TIPAR, RUE and tuber yield in this study. These findings agrees with those reported by Makinde et al. (2007) that intercropping late maturing soybean varieties have severe negative effects on cassava growth and production. However, Ennin and Dapaah (2008) suggested delaying soybean planting or reducing the soybean crop density to reduce cassava yield penalties. Tsay et al. (1988b) has shown that cassava intercropped with early maturing soybean varieties recovers quickly, producing storage root yields similar to sole cassava.

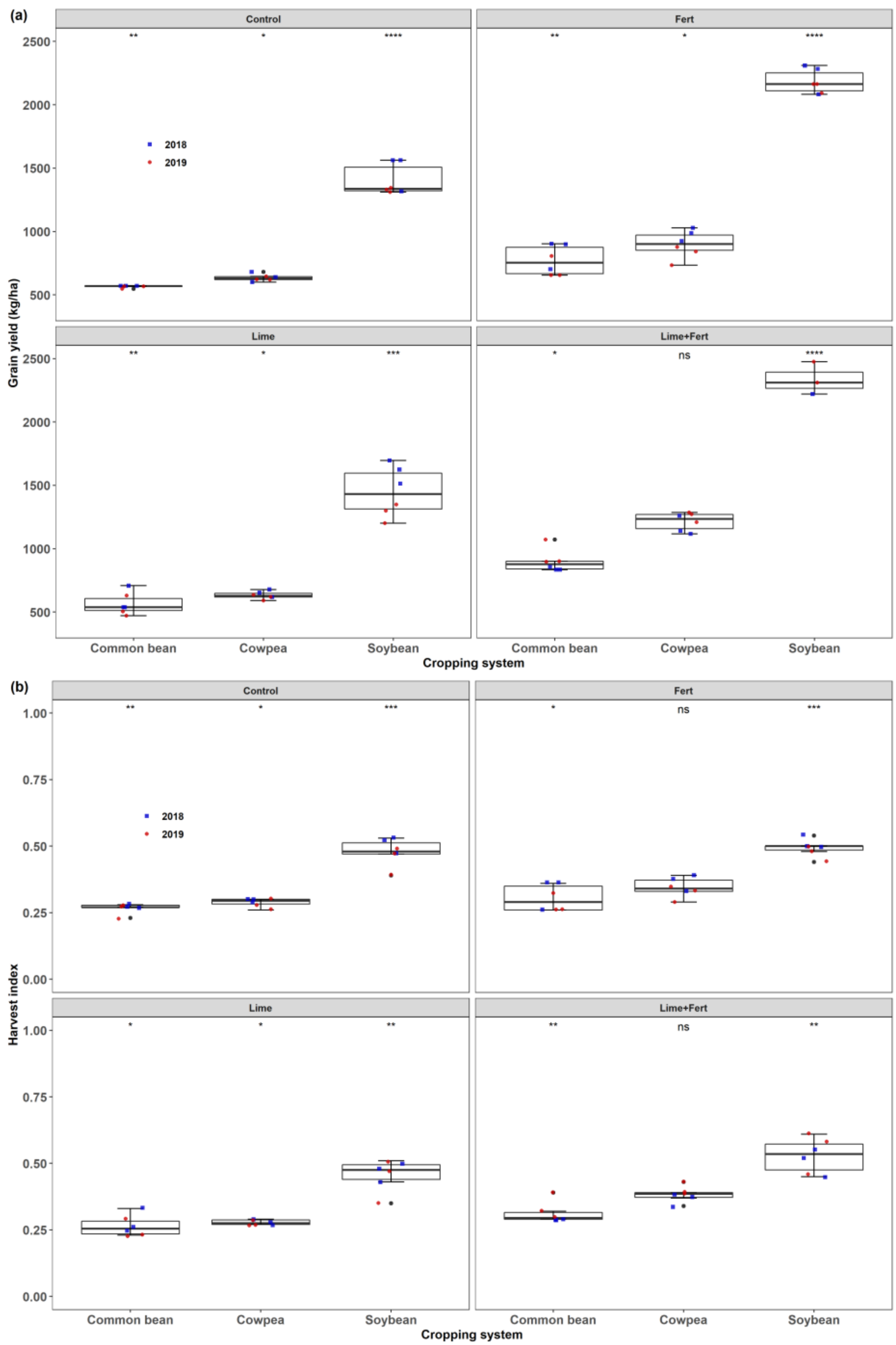

Figure 12(a-b): Interaction effects of lime, fertilizer and year on the grain yield and harvest index of the three legume species

Total nitrogen was very low (0.015%) and below the critical levels suitable for cassava production. Thus, cassava could benefit from the nitrogen fixed by the soybean, common beans and cowpea as well as from the organic matter via residues after harvest (Njoku et al., 2010). Assessment of RUE is vital in informing cassava growth models in simulating potential yields under rapid declining soil fertility characterizing shifting cultivation by smallholder farmers and provides sustainable management of abandoned fields ultimately increasing food security without deforestation.

Generally the LAI, f, RUE, tuber yield under fertilization and fertilization + lime were highest in the sole cassava and cassava common bean intercropping than cassava cowpea and cassava soybean intercropping. The cassava in sole cropping and common bean intercropping had the highest LAI thus intercepted the highest f compared to cassava cowpea and cassava soybean intercropping and partitioned more assimulates to the tubers thus obtained the highest tuber yield. Common beans was the suitable option for cassava intercropping since it resulted in a negligible loss in tuber yield and RUE compared to cowpea and soybean intercropping. The reduction in cassava tuber yield was compensated for by legume grain yield which provides a cheaper protein source and biomass contribution to organic carbon in cassava production systems. Fertilization and fertilization + lime treatments in sole cassava and cassava common bean intercropping significantly increased the radiation use efficiency (RUE) and light extinction coefficient (k) compared to non-fertilized and only lime treatments. Tuber yield and total dry matter were strongly significant correlated to RUE and TIPAR, indicating that RUE and TIPAR are key factors for TDM and tuber yield formation. Therefore, maximizing TIPAR and RUE via breeding large canopy cassava varieties, appropriate fertilizer, liming and short maturing grain legume intercropping is vital for increased and stable cassava productivity on degraded land. The integration of amendment options of liming and fertilizing in tandem with grain legumes achieved cassava yields obtained between 24–36 MAP on exhausted under shifting cultivation at 12 MAP. This approach can increase and stabilize cassava yields to meet the increasing demand due to population increase and agro-industries. Furthermore, the legumes provides a cheaper source of protein and biomass which contribute to build up of the organic carbon in cassava production systems ensuring food security without deforestation and abandonment of land. The common bean is the most prevalent legume in cassava intercropping and that its leaves are harvested as leaf vegetable during the growing season. This practice affects the photosynthetic capacity of the crop reducing both grain and biomass yield, therefore, an evaluation of the effects of defoliation and fertilizer on compensatory growth and yield of common beans varieties was imperative.

4.3 Effects of fertilizer and defoliation intensity on compensatory growth and radiation use efficiency of common bean

4.3.1 Selected soil physicochemical properties and seasonal conditions during the duration of the experiment

The results of analysed soil physicochemical properties of the topsoil (0–20 cm) depths at the experimental site are presented in Table 10. These soils were highly weathered and strongly acidic with low base cations (ZEMA, 2013).

Table 10: Selected physicochemical properties of topsoil (0–20 cm depth) at the Mansa site

pH (water)	Organic Carbon	Total nitrogen	P (mg /kg)	Exchangeable acidity (cmol /kg)	K	Ca	Mg	Na	Textural class
	%	%				(cmol/ kg)			
5.2	0.98	0.054	15	0.28	0.28	0.61	0.61	0.05	Sandy clay

There was a slight difference in seasonal minimum and maximum temperatures of 16.5 and 29.7 °C in 2018 and 17.0 and 29.6 °C in 2019 respectively. There was a significant difference ($p = 0.000$) in rainfall during the two growing season of 956 and 732 mm for 2018 and 2019 season respectively (Figure 13).

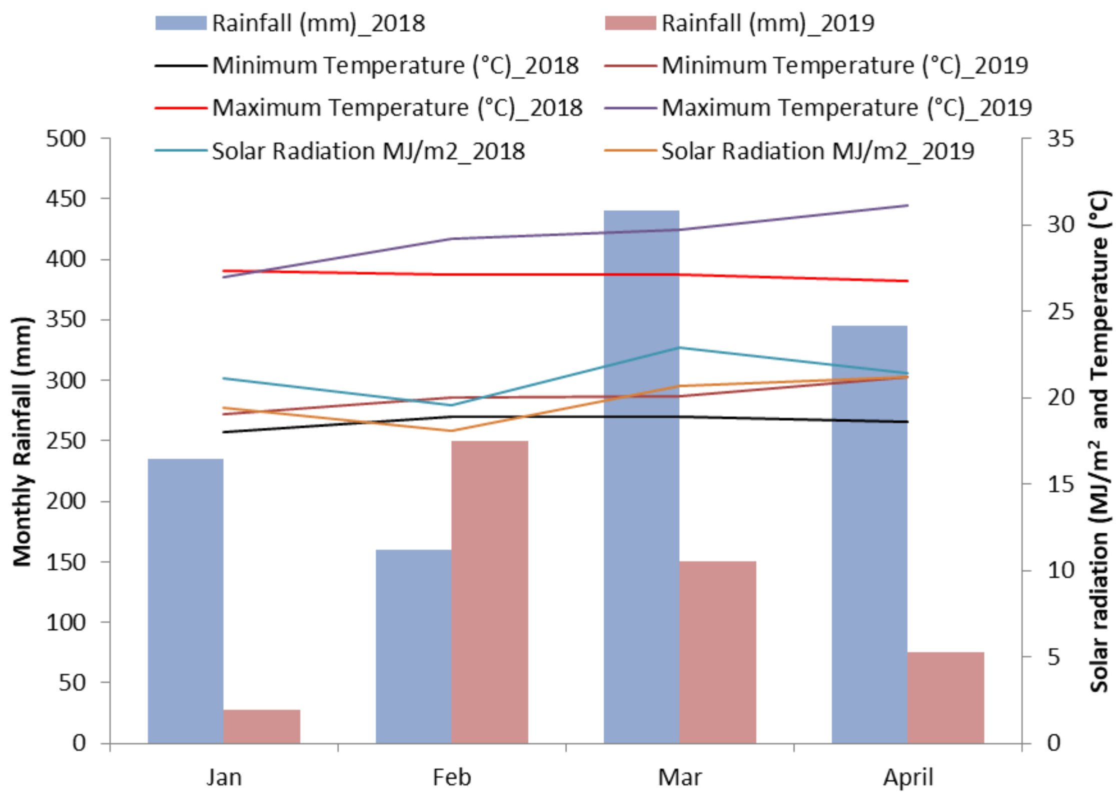

Figure 13: Mean monthly maximum and minimum temperature with total monthly rainfall for the 2018 and 2019 seasons. Bar graphs show the total monthly rainfall and the line graphs show the mean maximum, minimum temperature and solar radiation.

4.3.2 Interaction effects of fertilizer and defoliation intensity on days to 50% flowering and days to maturity

The fertilizer x defoliation intensity interaction significantly (p = 0.004) increased the days to 50% flowering (Table 11). The increases in days to 50% flowering were 3.92, 11.39 and 12.97 at 25, 50 and 75% DI relative to the 0% DI in unfertilized treatments. The increases in days to 50% flowering were 1.08, 7.48 and 11.30% relative to the 0% DI under fertilized treatments. The days to 50% flowering were significantly increased at high defoliation intensity of 50 and 75% DI compared to the 0 and 25% DI (Table 11 and 12) both in unfertilized and fertilized treatments.

The variety x defoliation intensity interaction significantly increased the days to 50% flowering (Table 11 and 12). The days to 50% flowering increased by 1.02, 12.45 and 15.14% at 25, 50 and 75% DI for Lukupa and by 5.56, 6.35 and 9.13% at 25, 50 and 75 % DI for Luangeni relative to the 0% DI. For Lyambai, the increase in days to 50% flowering relative to the 0% DI were 0.84, 9.77 and 12.32% at 25, 50 and 75 % DI. The fertilizer, defoliation interaction and the variety, defoliation intensity interactions both increased the days to 50% flowering. The increase in days to 50% flowering is attributed to defoliation which reduced the rate of leaf photosynthesis and altered the ability of the photosynthetic source leaves to export assimilate. For example, Selter et al. (1980) reported defoliation to alter the hormone balance, starch, sugar, protein and chlorophyll concentration of source leaves as well as stomata resistance and senescence rate. Our results are consistent with those of Bubehein et al. (2010) who found that the days to 50% flowering was increased by two days when cowpea were defoliated at the early stage (Ibrahim et al., 2010).

The fertilizer x Defoliation intensity x variety interaction was significant ($p = 0.000$) on the days to maturity (Table 11 and Figure 14). There was no significant difference on the days to maturity among the unfertilized and fertilized treatments, except at 50% DI in unfertilized treatments. Generally, the varieties Lukupa (V2) and Luangeni (V3) had longer days to maturity than Lyambai (V1). The higher DI of 50 and 75%, increased the days to maturity (Figure 14).

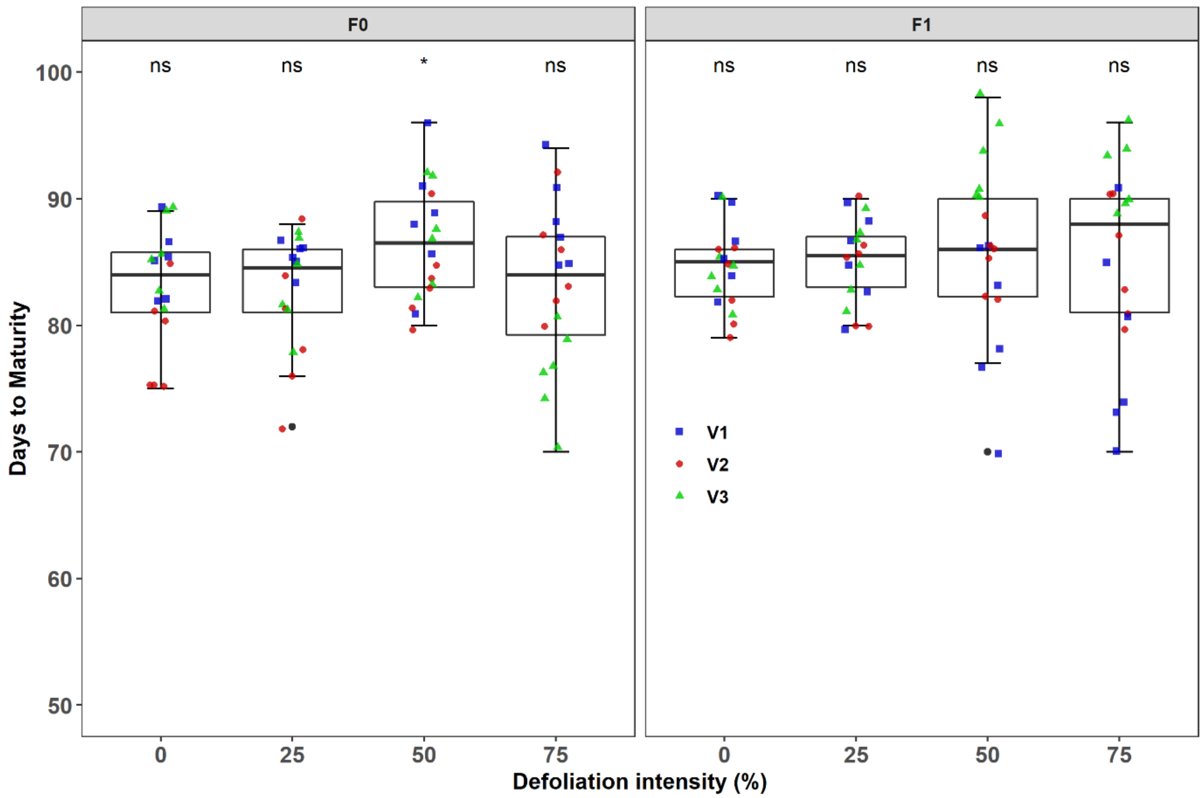

Figure 14: Effects of fertilizer and defoliation intensity on the days to maturity of three common bean varieties

Generally, the varieties Lukupa (V2) and Luangeni(V3) had longer days to 50% flowering and days to maturity than Lyambai (V1). These results are consistent with the varieties growth habit of indeterminant for Lukupa and Luangeni and determinant growth habit for Lyambai. Further, the increase in days to maturity observed at 50 and 75% DI (Figure 14) could result from the slow growth after severe defoliation. The higher number of pods per plant at 25% DI than 0% DI could be due to compensatory growth of the LAI after defoliation which further produces more assimulates as pods.

4.3.3 LAI and fractional photosynthetic active radiation interception (f)

The two growing seasons were characterized by similar pattern of LAI development (Figures 15a–b). Generally, the maximum LAI was reached between 50 to 60 days after planting (DAP) in 2018 and 55 to 65 DAP in the 2019 seasons. The maximum LAI occurred after flowering for all the varieties following a shift in the partitioning of dry matter from leaves into reproductive structures. Thereafter, the LAI decreased at same rates due to senescence in both seasons for the non-defoliated treatments and 25% DI. The 50 and 75% DI treatments were affected not only by the moment for maximum LAI for the defoliated treatments but also timing of senescence initiation.

The significant interaction (p = 0.006) effects of fertilizer with defoliation intensities with year as random factor on seasonal LAI and f of common bean varieties are presented in Table 11 and 12. This could be that the fertilized enhanced nutrient uptake by the plant and led to a higher LAI which intercepted more radiation (f). The LAI development was quick and extensive at lower defoliation intensity (DI) of 25%, regardless of fertilizer level in all the varieties. The two varieties, Lukupa (V2) and Luangeni (V3) delayed in reaching the maximum LAI compared to Lyambai (V1). This could imply that the Lyambai which is determinant in growth habit allocated the assimulates to the pods thus, had the earliest days to maturity. The LAI development was slow in defoliated treatments of 50 and 75% DI compared to the 0 and 25% DI.

According to Ibrahim et al. (2010) the effect of defoliation depends on the growth stage of cowpea at which defoliation occurs. In this study, the 25% DI effects on LAI was not significantly different from the 0% DI. Similarly, Gregorutti et al. (2012) reported a 33 and 66% DI performed at pod initiation stage in soybean to intermediately affect seed yield compared to the control. The effect of stage and intensity of defoliation during the vegetative stage, showed that the removal of young expanding leaves prior to podding suppressed the vegetative growth and altered partitioning (Ibrahim et al., 2010). Dube and Fanadzo (2013) recommended a judicious defoliation of cowpea plants during vegetative development to have a lesser effect on reduction of grain yield than defoliation during the reproductive stage. Periodic or partial defoliation can stimulate leaf production (Figure 15a), prolonging the duration of the leaf harvesting period and therefore making food available for longer to resource poor farmers.

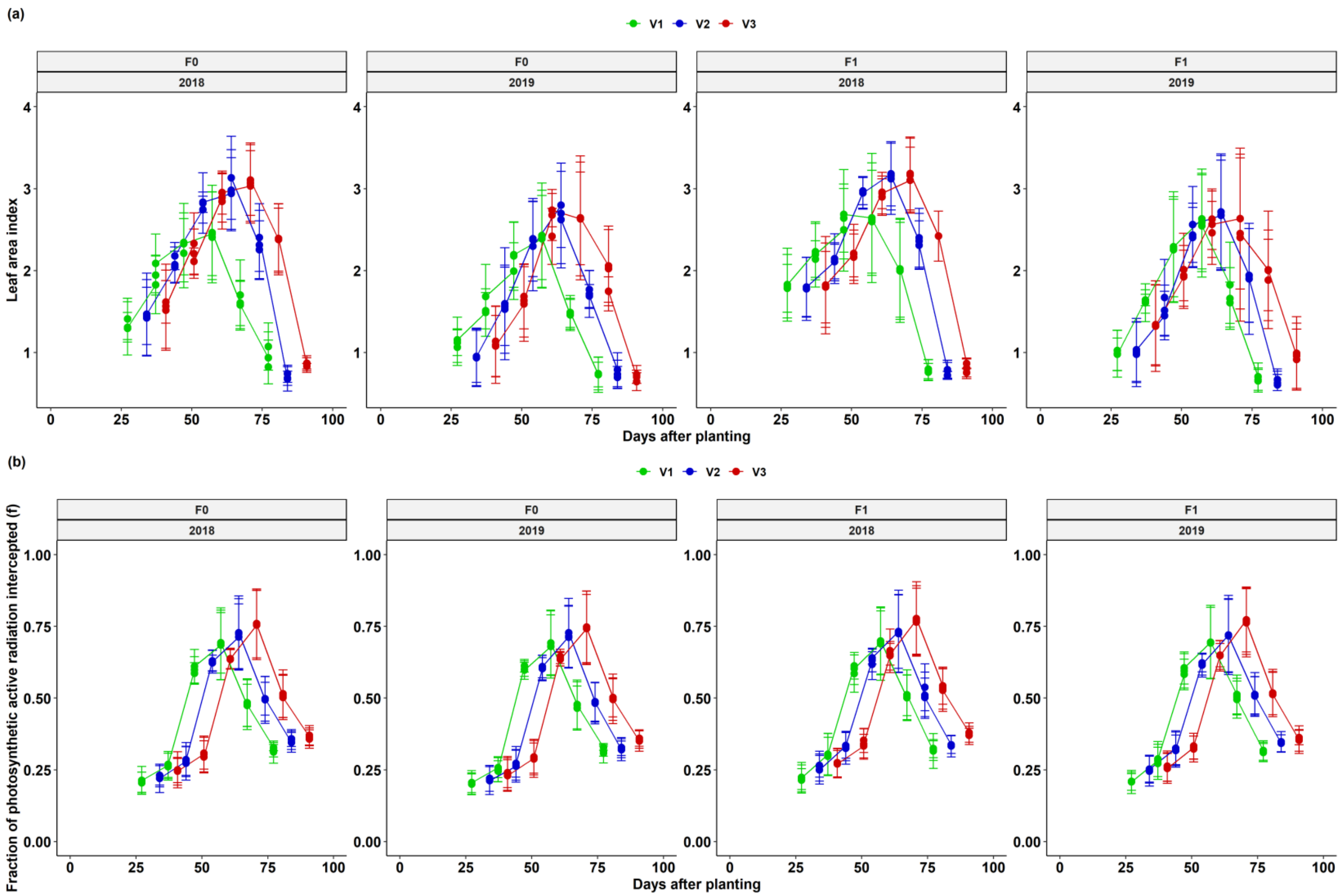

Figure 15 (a–b): Fertilizer and defoliation intensities effects on LAI and f of common bean cultivars (V1=Lyambai, V2= Lukupa, V3= Luangeni, F0=No fertilizer, F1=Fertilizer applied) pooled over two growing season. Standard error is shown for all the treatments

The amount of solar radiation available to a plant is key to determining the potential AGB production imposed by prevailing limiting factors such as water supply and nutrient availability at any given location. The quantity of f intercepted by a crop can be increased by rapid attainment of complete ground cover and by increasing the amount of canopy cover at any time, up to a definable threshold (Ayaz et al., 2004). These mechanisms accounted for higher LAI, f and AGB production with fertilizer application at lower defoliation intensities of 0 and 25%. This is ascribed to the higher LAI resulting in a fast canopy closure and good leaf coverage of soil in the 0 and 25% DI than the 50 and 75% DI (Pradham et al., 2018). The 50 and 75% defoliation intensities showed lower LAI evolution in both seasons due to slow recovery from the severe defoliation. These observations are consistent with those reported by several researchers showing that more water and nitrogen stressed treatments exhibited similar results to the 50 and 75% defoliation intensities (Tesfaye et al., 2006; Sennhenn et al., 2017; Pradham et al., 2018).

Seasonal fractional photosynthetic active radiation (f) interception followed similar trends as observed for the LAI developments and was comparable over the two seasons (Figure 15b). All the varieties subjected to 0, 25 and 50 DI reached maximum levels of f earlier than for the 75% DI. The DI mostly affected the early stages of seasonal f interception and that at later stages, f levelled off. The seasonal f continuously increased until the end of flowering (> 60 DAP) in the 3 varieties. The 50 and 75% DI adversely reduced the light interception in Lyambai compared to Lukupa and Luangeni. The variety V1 intercepted the lowest f compared to Lukupa and Luangeni. Light interception was positively correlated with LAI (r= 0.78* to 0.98**) in all varieties and treatments. When pooled over two seasons, the LAIs accounted for 67% of the variability in the fractional photosynthetic active radiations.

The severe defoliation intensities limited the LAI regrowth, resulting in lower f and reduced photosynthetic source leaves to export assimilate which significantly affected AGB. The higher LAI in fertilized treatments in the current research is consistent with Pradham et al. (2018) who have reported a higher LAI in response to increasing N levels in wheat. This is attributed to the significant increase in leaf expansion (length and breadth) arising from cell division and cell enlargement at higher N rates (Pradham et al., 2018).

4.3.4 Canopy extinction coefficient (k) of three (3) common bean varieties

The k value was estimated as a the slope of linear regression of the natural logarithm of fractional transmitted light Ln(1-f) on LAI (Figure 17) in Table 11. The interaction effects of fertilizer, DI and variety were significant (p = 0.005) on the k (Table 11 and Figure 16). The k values were higher for fertilized treatments than for unfertilized treatments. The k values decreased with increasing defoliation intensities. Luangeni and Lukupa had higher k values both in fertilized and unfertilized treatments. There was no significant difference in k values at 25 and 50% DI both in fertilized and unfertilized treatments. There was a significant difference in k values at 0 and 75% DI.

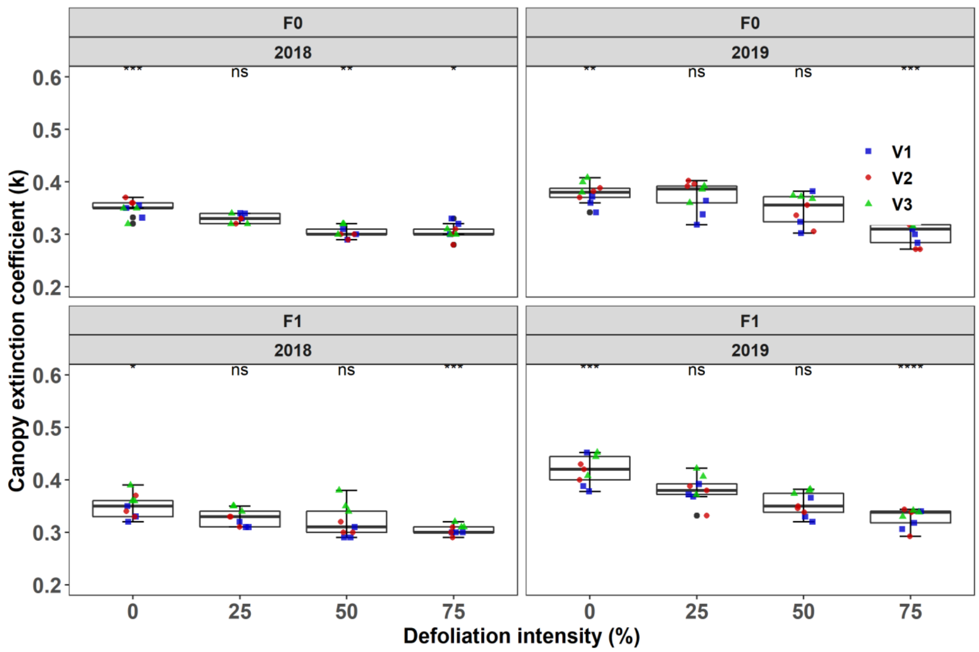

Figure 16: Effects of fertilizer and defoliation intensity on the light extinction coefficient of three common bean varieties

The k value is a function of the size and orientation of leaves (Saeki, 1960; Adeboye et al., 2016) which are the major organs for radiation interception. The lack of significant differences in k among varieties at 25 and 50% DI (Figure 16) indicates a similar distribution of radiation within the canopies of the different varieties, consistent with Bassu et al. (2011). The k values decreased with increasing DI regardless of fertilizer rate and varieties (Figure 16 and Table 13). This result indicates that severe DI, modified the leaf angle and orientation. These findings are consistent with those reported by other authors who have reported low k values and attributed them to the modification of leaf angle and orientation in response to water deficits (Jeuffroy and Ney 1997; Tesfaye et al., 2006). Contrary to observations in this current work, Adeboye et al. (2016) reported water stress to not significantly affect the k values under varying irrigation intervals in soybeans.

The high k values under fertilization of Luangeni followed by Lukupa and Lyambai indicate a more uniform canopy distribution resulting in higher light interception for the same LAI which had better leaf positioning, attributed to the differences in leaf curving and leaf angles among genotypes (Pellet and El Sharkawy, 1997). Higher k values of fertilized treatment than the unfertilized treatment is in agreement with several authors who have reported more erect leaves and better light distribution into the canopy with consequent higher light interception and higher RUE under nitrogen fertilization (Zhi-qiang et al., 2018). However, very higher k values may lead to the lower leaves not capturing light and not photosynthesizing hence relying on young leaves for the assimulates to maintain respiration.

The k values obtained in this study were less than 1 and fell within the recommended range of between 0.3–1.3 (Szeicz, 1974; Jones, 1992). The k values found in this study were slightly within range of *P. sativum* (0.34-0.41 –Bassu, 2011); *L. culinaris* (0.26 –McKenzie and Hill, 1991); common beans (0.4 by Gardiner et al., 1979). These differences may reflect differences in varieties between studies, but may also reflect differences in environment. The k values differed among cultivars within a season, and for the same cultivar between seasons (Siddique et al., 1989; Muchow et al., 1993). The k values in the present study are lower compared to several grain legumes: 0.45–0.84 for common beans, 0.63–1.02 for chickpea, 0.53–0.86 for cowpea (Tesfaye et al., 2006).

4.3.5 Radiation use efficiency of three (3) common bean varieties

The interaction effects of fertilizers, varieties and defoliation intensity was significant ($p = 0.015$) on RUE (Table 11 and Figure 17). The highest RUE was observed in fertilized treatments of Luangeni and Lukupa at defoliation intensity of 0 and 25% respectively (Figure 17). The variety Luangeni had the highest RUE values of the three varieties under both fertilized and unfertilized treatments regardless of the defoliation intensity (Figure 17). The varieties Luangeni and Lukupa accumulated biomass at a faster rate than Lyambai regardless of the fertilizer rate. Therefore, varieties with the greatest cumulative intercepted

PAR from emergence to maximum biomass developed the largest maximum biomass yield (r = 0.99 and 0.70 in the 2018 and 2019 seasons).

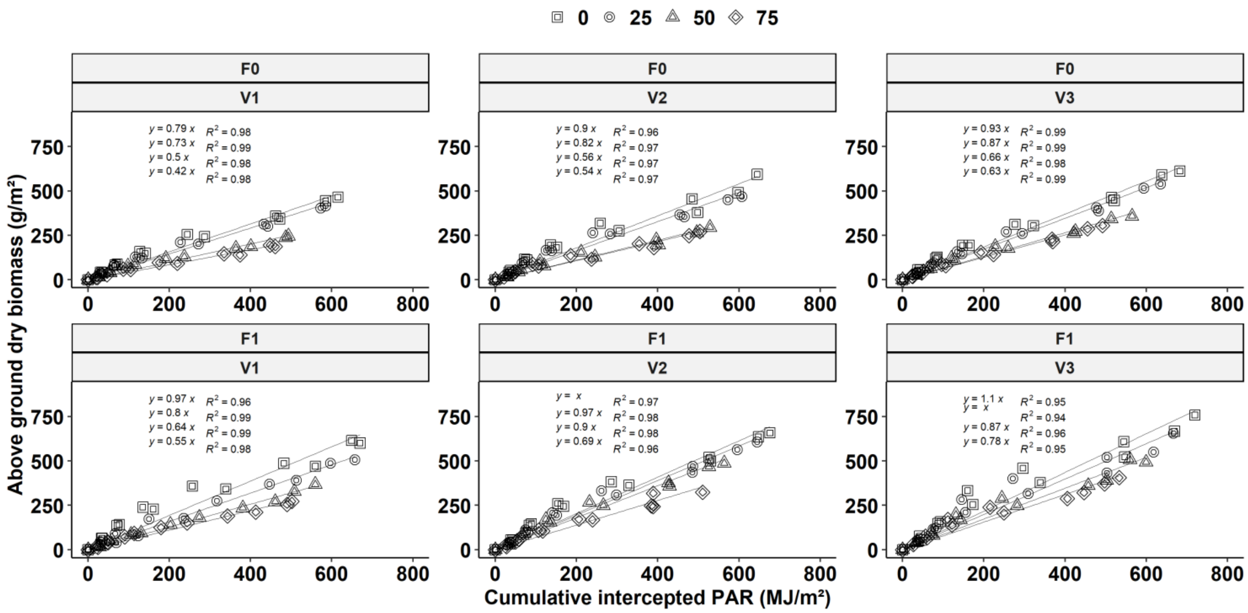

Figure 17: Radiation use efficiency (RUE, g /MJ PAR) of common bean varieties as influenced by fertilizer application and defoliation intensities for pooled data over two seasons

All varieties in the current study showed significant increase in RUE in response to fertilization. This indicates that fertilized treatments accumulated dry matter biomass at a faster rate than the unfertilized, thus easily recovered in response to defoliation. The RUE decreased with increasing defoliation intensity in both fertilized and unfertilized treatments (Table 12 and Figure 17). According to Pradham et al. (2018), the N fertilizer application led to significant increase in leaf expansion. The effects of defoliation on RUE were severe when no fertilizer was applied compared to fertilized treatments in all varieties (Table 12 and Figure 17). This could be that defoliation only slightly affected the rate of leaf photosynthesis and did not significantly alter the ability of the photosynthetic source leaves to export assimilate (Ibrahim et al., 2010). Defoliation is one of the stressful conditions which cause low photosynthetic rates and ultimately low RUE (Sinclair and Horie, 1989). The current research results agree with those of Shibles and Weber (1966) who found lower values of 0.72 g/MJ PAR and attributed it to the low specific leaf nitrogen. Similarly to this study, several authors have reported a significant increase in RUE values for all cassava genotypes in response to fertilization which significantly increased the LAI (Pellet and El Sharkawy, 1997; Mwamba et al., 2021). At all defoliation intensities, the indeterminant varieties, Luangeni and Lukupa had higher RUE than the determinant variety Lyambai. This is attributed to the higher compensatory growth for Lukupa and Luangeni. The indeterminant varieties, responded to 25% DI by continuing producing more leaves, hence captured more f and had higher RUE (Figure 17). At higher DI of 50 and 75% DI, the recovery capacity was slow and thus affected the RUE regardless of the variety. The RUE values obtained in this study were higher than the 0.49 g/MJ PAR obtained by Sennhenn et al. (2017) for common beans under rainfed conditions in Kenya but lower under partially and fully irrigated conditions of 1.42 and 1.40 g/MJ PAR respectively. Tesfaye et al. (2006) reported higher RUE values of 1.5, 1.59 and 2.44 g/MJ PAR for common bean in Ethiopia under mid-season stress (MS), late season stress and non-stress water conditions respectively. The author attributed the much higher estimated AGB accumulation to the varieties used.

The RUE values found in this current paper are within range with those found for several grain legumes (in g/MJ PAR) in different environments, including 0.30–0.93 for chickpea (Hughes et al., 1987); 0.15–0.78 for common beans (Tsubo et al., 2003); 1.09 for cowpea (Muchow et al., 1993), 0.88–1.05 for various grain legumes (Muchow et al., 1991) under well-watered conditions in tropical and subtropical environments. The lower RUE values obtained at 50 and 75% defoliation intensities are explained by severe defoliation and that the plant fails to recover through compensatory growth. The yield differences in the current paper corresponded to differences in RUE values.

4.3.6 Effects of fertilizer application and leaf defoliation intensity on yield components and yields of three (3) common bean varieties

4.3.6.1 Number pods per plant and number seeds per pod

The significant interaction effects of fertilizer, defoliation intensities with year as random factor on number of pods per plant (p = 0.013) and number of seeds per pod (p = 0.041) of common bean varieties are presented in Table 11 and Figure 18(a–b). Regardless of the fertilizer rate and variety used, the number of seeds per pod decreased with increasing defoliation intensity, though the reduction was more severe in unfertilized treatments. The fertilized treatments had a higher number of seeds than the unfertilized treatments. The varieties Luangeni and Lukupa had a higher number of seeds per pod than Lyambai. In both fertilized and unfertilized treatments, the number of pods per plant was higher at 25% DI than at 0% DI though there was no significant difference.

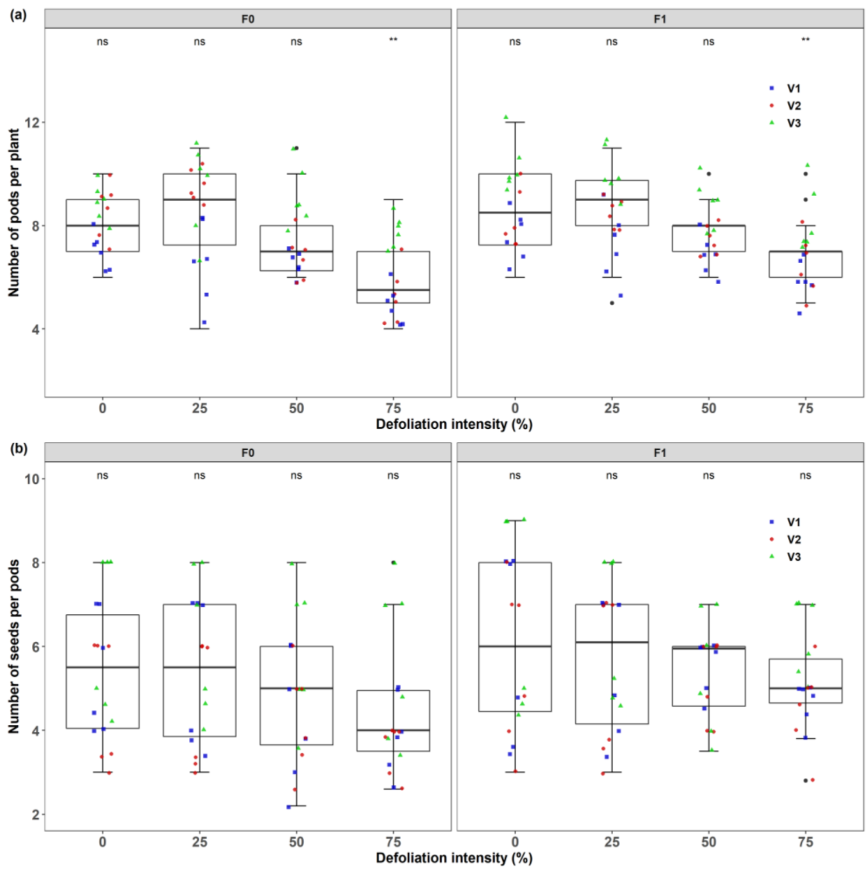

Figure 18: Effects of fertilizer and defoliation intensity on the number of pods per plant and number of seeds per pod of three common bean varieties

The number of pods per plant, number of seeds per pod and grain yield were higher in fertilized treatments than in unfertilized treatments regardless of the variety and defoliation intensity. This could be attributed to the fertilizer which increased LAI and crop duration with greenness (Figure 18 a–b and Table 12), which resulted increased interception of radiation similar to the results of Prahdan et al. (2018) in wheat.

In the current study, the 0 and 25% DI resulted in significantly higher number of seeds per pod, number of pods per plant, grain yield and above ground biomass (AGB) production yield than the 50 and 75% DI. The reduction in yield components at 50 and 75% DI are supported by several authors who have reported reduced soybean yield due to defoliation and attributed it to decreased light interception, canopy photosynthesis, loss of leaf storage material and shortened effective grain filling period (Haile et al., 1998; Li et al., 2009; Ali et al., 2013). Several authors who have demonstrated that seed number and pod number are limited by the source photoassimilate supply during the critical period (Jiang and Egli, 1995; Gregorutti et al., 2012). Thus, the use of fertilizer in tandem with a suitable defoliation intensity in indeterminant common bean variety can improving light interception during the growing period in order to maximize the pod and seed number.

Table 11: Analysis of the variance of effects of fertilizer, defoliation intensities and year effects on yield components, yield and RUE of common bean varieties (F stat)

Source of Variation	Days to 50% flowering	Days to maturity	Seasonal LAI	Seasonal f	Seasonal k	Number of pod/plant	Pod length (cm)	No. Seed/pod	Grain yield (kg/ha)	Harvest index	RUE (g/MJ PAR)	AGB (g/m2)
Rep	0.89ns	2.03ns	2.66	87.62	1.270	0.24	0.34	0.6	0.51	38.39	12.990ns	310.510
Fertility	3.46ns	2.63ns	39.570***	58.770***	17.120***	9.320*	29.720***	50.660***	422.450***	152.030*	76.600*	641.160*
Defoliation Intensity	39.62***	3.69*	215.250***	299.450***	93.080***	42.200***	6.250***	30.690***	267.780***	49.640***	264.460***	399.580***
Year	1.35ns	4.53ns	3.540ns	12.690***	164.890***	50.740ns	757.110ns	965.150ns	2.560ns	0.010ns	15.560*	1.800ns
Variety	7.88*	6.63*	34.600***	99.520***	24.910***	96.390***	15.140***	102.740***	584.290***	2.840ns	12.680*	47.860***
Fertilizer x Defoliation Intensity	0.86ns	1.18ns	6.480***	4.310*	1.520ns	1.560ns	0.440ns	1.110ns	50.730***	11.280***	6.890*	18.430***
Fertilizer x Year	0.07ns	3.09	6.390*	4.370*	8.670*	0.080ns	0.000ns	0.140ns	0.020ns	0.120ns	0.520ns	7.09*
Defoliation Intensity x Year	2.63ns	0.12ns	1.180ns	7.570***	9.510***	0.080ns	3.780*	27.270***	0.030ns	0.320ns	1.860ns	3.690*
Fertilizer x Variety	12.04*	20.53**	0.600ns	1.950ns	3.390*	1.460ns	1.200ns	5.480*	**15.010******	0.390ns	0.290ns	5.040*
Variety x Defoliation Intensity	**2.74***	4.33**	0.600ns	1.080ns	2.470*	2.790*	0.960ns	2.860*	**8.990*****	2.150ns	1.770ns	2.770*
Variety x Year	1.61ns	4.12*	5.270*	9.800***	2.420ns	0.110ns	10.850***	8.330***	0.100ns	0.860ns	15.240***	4.260*
Fertilizer x Defoliation Intensity x Year	0.45ns	1.15ns	**5.580*****	2.630ns	3.450*	0.080ns	1.020ns	**6.520*****	0.010ns	0.280ns	**2.830***	2.370ns
Fertilizer x Variety x Defoliation Intensity	0.93ns	**9.79*****	0.610ns	0.890ns	1.430ns	**2.780***	0.860ns	**2.420***	1.540ns	**3.320***	**2.650***	**4.130***
Fertilizer x Variety x Year	0.89ns	2.56ns	**7.240*****	**5.160***	**6.170***	0.180ns	**4.110***	2.270ns	0.250ns	0.560ns	2.700ns	0.270ns
Variety x Defoliation Intensity x Year	1.88ns	2.05ns	1.050ns	0.920ns	0.560ns	0.080ns	1.030ns	1.330ns	0.130ns	0.180ns	0.200ns	1.110ns
Fertilizer x Variety x Defoliation Intensity x Year	0.39ns	1.94ns	1.740ns	1.840ns	1.230ns	0.080ns	1.400ns	2.020ns	0.030ns	0.170ns	0.980ns	1.870ns

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

Table 12: Main effects of fertilizer, defoliation intensities and year effects on yield components, yield and RUE of common bean varieties

Source of variation	Days to 50% flowering	Days to maturity	Seasonal LAI	Seasonal f	Seasonal k	Number of pods/plants	Number of seeds/pod	Aboveground biomass (g/m2)	Harvest Index	Grain yield (kg/ha)	RUE (g/MJ PAR)
Year											
2018	43.19a	83.96b	1.89a	0.45a	0.32a	8.3a	4.0b	101.5a	0.36a	1228a	0.80a
2019	43.62a	85.24a	1.85a	0.44a	0.36a	7.2b	6.6a	99.5a	0.32a	1206a	0.75b
LSD (0.05)	0.744	1.213	0.047	0.007	0.006	0.298	0.164	3.037	0.085	28.030	0.024
Fertilizer (kg N:P: K /ha)											
0	44.01a	83.89b	1.80a	0.43a	0.34a	7.5b	5.0b	92.4b	0.37a	1070b	0.69b
20: 40 :20	42.81b	85.31a	1.95a	0.46a	0.35a	8.0a	5.6a	108.6a	0.31b	1364a	0.87a
LSD(0.05)	0.744	1.213	0.047	0.007	0.006	0.298	0.164	3.037	0.085	42.210	0.024
Variety											
Lyambai	42.90b	84.75ab	1.74c	0.41c	0.33b	6.5c	5.1b	87.2b	0.31b	927c	0.70b
Lukupa	43.04b	83.10b	1.89b	0.44b	0.34b	7.6b	4.7b	102.1a	0.38a	1197b	0.80a
Luangeni	44.29a	85.94a	1.98a	0.48a	0.36a	9.1a	6.1a	112.1a	0.33b	1526a	0.83a
LSD(0.05)	0.912	1.485	0.058	0.009	0.007	0.365	0.200	3.719	0.104	31.070	0.030
Defoliation intensity (%)											
0	40.94c	83.83b	2.24a	0.51a	0.37a	8.4a	58a	130.5a	0.35a	1434a	0.97a
25	41.97c	83.97b	2.05b	0.47b	0.35b	8.6a	5.5a	118.2b	0.34a	1363a	0.88b
50	44.81ab	86.31a	1.76c	0.42c	0.33c	7.6b	5.1ab	87.8c	0.31b	1159b	0.67c
75	45.92a	84.28b	1.44d	0.36d	0.31d	6.4c	4.8b	65.6d	0.27c	912c	0.59d
LSD(0.05)	1.053	1.715	0.067	0.010	0.008	0.422	0.231	4.295	0.120	44.840	0.035

Means with the same letter are not significantly different

4.3.6.2 Grain weight and harvest index (HI)

The interaction effects of fertilizers, varieties and defoliation intensity was significant (p=0.002) on the grain yield (Table 11 and Figure 19).

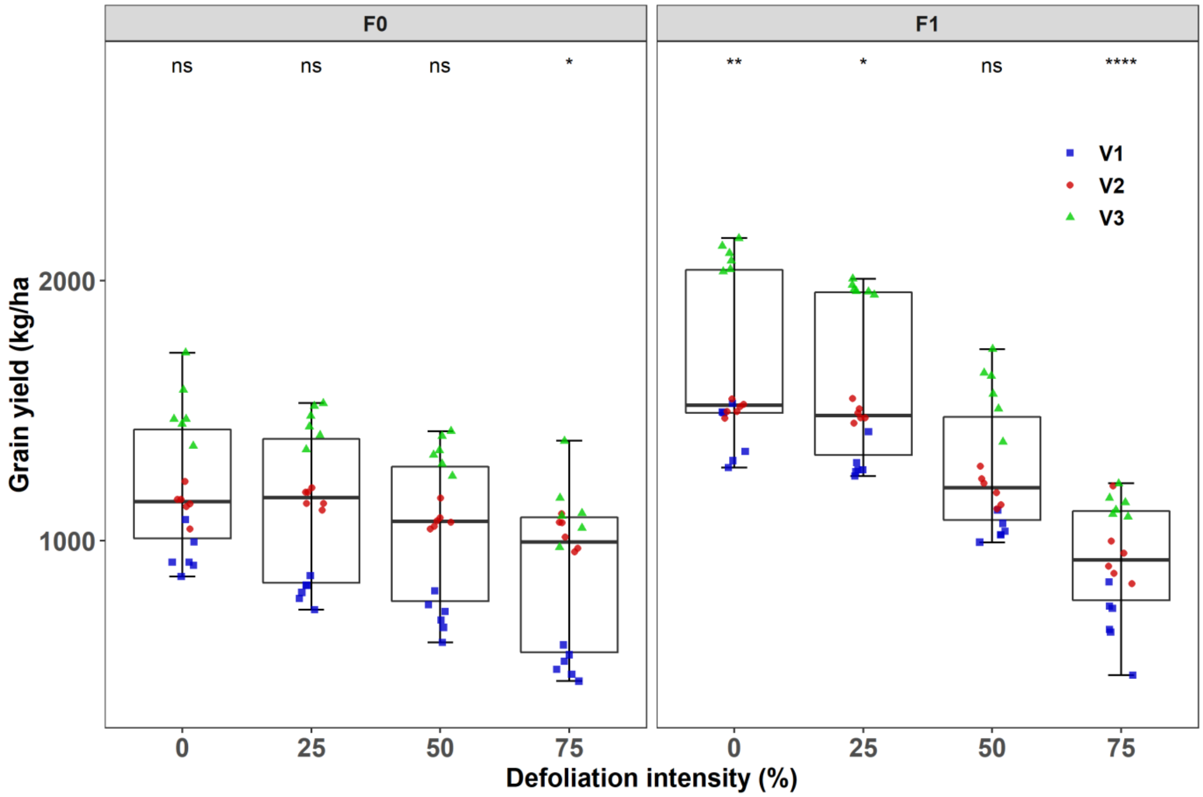

Figure 19: Effects of fertilizer and defoliation intensity on the grain yield of three common bean varieties

Regardless of the treatments, the varieties Lukupa (V2) and Luangeni (V3) had higher grain yield than Lyambai (V1). Generally, the highest seed yield reduction was at 50 and 75% DI for all varieties. The interaction effects of fertilizers, varieties and defoliation intensity was significant ($p = 0.006$) on the harvest index (HI) (Figure 20 and Table 11). The HI of the 0 and 25% DI were not significantly different ($p > 0.05$) but were significantly different for the 50 and 75% DI. Generally, the HI was observed to be higher in unfertilized treatments than fertilized treatments (Figure 20).

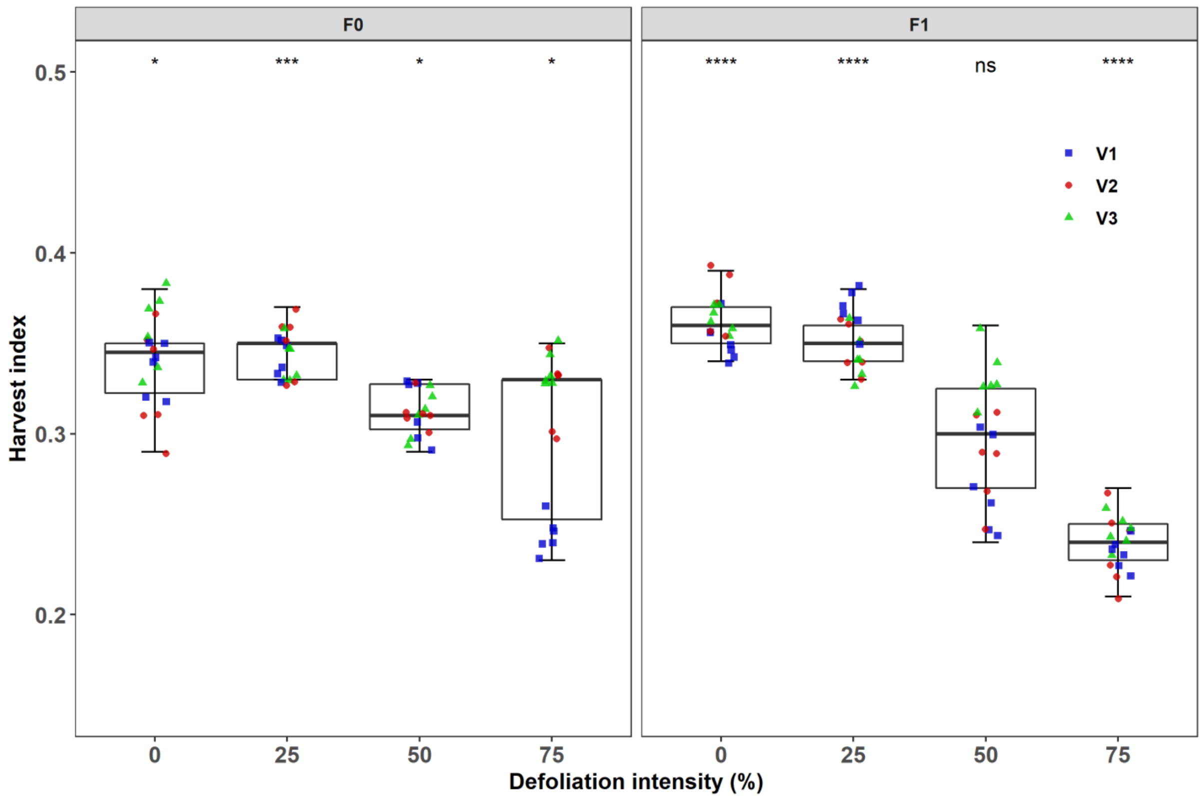

Figure 20: Effects of fertilizer and defoliation intensity on the harvest index of three common bean varieties

Generally, there were no significant results in LAI, f, AGB, grain yield production and HI between the 0 and 25 % DI. The non-significant difference in LAI, intercepted PAR, AGB, HI between the 0 and 25% defoliation intensities indicate good compensatory growth by remobilisation of dry matter of the 25% DI (Tesfaye et al., 2006; Sennhenn et al., 2017). Since the defoliation was performed during the vegetative period, the higher capacity for compensatory growth (Gregorutti et al., 2012) at 25% DI is due to the crop ability to generate new branches and buds. Our results agree with those of Ali et al. (2013) who reported a 25% basal defoliation to result in high seed yield because of higher TDM and greater number of pods compared to higher defoliation intensities. According to Ali et al. (2013), the basal leaves were aged, photosynthetically weaker and might act as a burden and compete for assimilate with growing pods (sink), while most of the assimilates transported to the pods absence of lower leaves (basal defoliation) which resulted in greater partitioning and thereby resulted in higher yield.

4.3.6.3 Effects of fertilizer application and leaf defoliation intensity on dry matter (DM) production of 3 common bean varieties

The interaction effects of fertilizers, varieties and defoliation intensity was significant ($p = 0.002$) on the above ground biomass (AGB) (Table 11 and Figures 21). The highest AGB was observed in fertilized treatments of Luangeni and Lukupa at defoliation intensity of 0 and 25% respectively. The 25% DI was not significantly ($p > 0.05$) different from the 0% DI in AGB yield. The 50 and 75% DI resulted in a significant ($p < 0.001$) reduction in AGB yield (Figure 21).

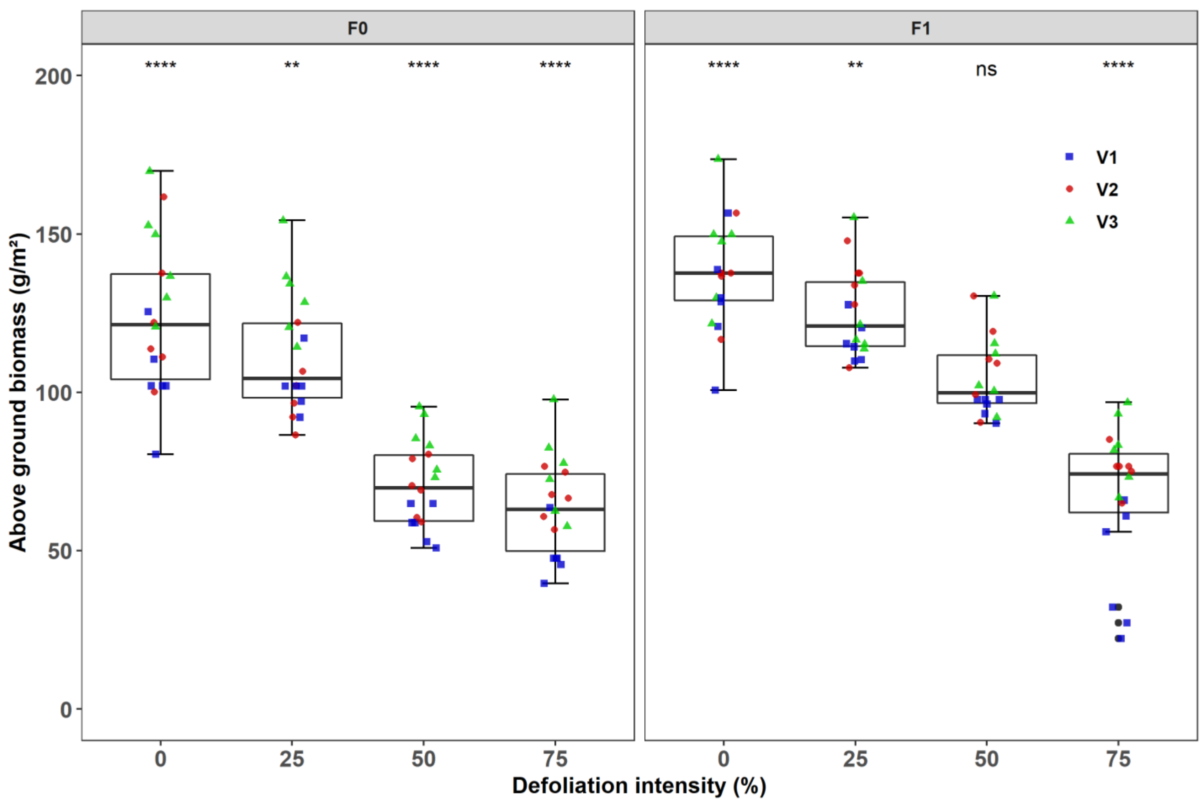

Figure 21: Effects of fertilizer and defoliation intensity on aboveground biomass of three common bean varieties

Defoliation may enhance growth through two mechanisms namely compensatory regrowth (Haile et al., 1998) and delayed leaf senescence, including delayed leaf abscission (Li et al., 2005) which ultimately increase leaf photosynthetic rates (Haile et al., 1998; Li et al., 2005). These mechanisms may aid defoliated plants to recover their leaf area and capacity for dry mass production. Rao and Ghildiyal (1985) has reported that the remaining leaves of defoliated plant of having a higher net photosynthetic rate than intact plant and in this way remaining leaves might compensate for the loss caused by defoliation. Several studies have reported leaf defoliation to increase the sink-source ratio thus increasing the photosynthetic rates in the remaining leaves. For instance, photosynthetic rate increased by 33–39% in mungbean (Pandey and Singh, 1984), 20–40% in soybean (Chen and Lia, 1991) and 30–40% in groundnut (Ghosh and Sengupta, 1986). This indicates involvement of an effective compensatory mechanism, which helps in production of more assimilate in the remaining leaves (Ali et al., 2013). Similar to this study, Hossain et al. (2006) and Mondal et al. (2011) reported increased cowpea and mungbean seed yield and attributed it to greater light penetration in the canopy.

The higher number of pods per plant, number of seeds per pod, grain yield and AGB of Luangeni and Lukupa despite defoliation could be attributed to the indeterminate growth habit compared to Lyambai which has a determinate growth habit (Egli and Leggett, 1973; Fehr et al., 1977). Several authors have reported the seed yield of leafy indeterminate cowpea and soybeans types to be more tolerant to defoliation than determinate types (Li et al., 2005; Dube and Fanadzo, 2013; Madamba, 2000). Similar to this study, Egli and Leggett (1973) observed indeterminate cultivars to flower when plants have reached less than half their mature height, but determinate cultivars flower at nearly full height. Since reproductive and vegetative development occur simultaneously over a longer time for indeterminate than determinate cultivars, their response to leaf and stem injury may not be the same (Fehr et al., 1977). Upon defoliation, Lyambai being a determinate cultivars allocated a greater proportion of assimilates to the reproductive organs resulting in less leaf regrowth and early senescence of remaining leaves (Li et al., 2005). However, indeterminate cultivars resort to increased biomass partitioning to leaves therefore delaying reproductive development, which allowed defoliated plants to produce more new leaves (Li et al., 2005).

Harvest index (HI) varies with the ability of a genotype to partition current assimilate to the seed (Turner et al., 2001; Tesfaye et al., 2006). The HI in the current study, was higher in unfertilized treatment than in fertilized treatments. These findings are consistent with Araújo et al. (2000) and Argaw et al. (2015) who reported higher vegetative growth with P fertilizer application than grain yield improvement, thus reducing the harvesting index of common bean. Fertilized treatments had significantly increased AGB than unfertilized treatments.

This result is similar to those reported by Pacheco et al. (2012) who found higher biomass production of common bean is achievable on fertile soils than in our study. This could also be related with an improvement in N derived from symbiotic N2 fixation of the NPK compound fertilized treatments which lead to a quick growth and expansion of leaves which intercepted more f and then increased the TDM and grain yield (Giller, 2001; Argaw et al., 2015).

Luangeni had the highest LAI and intercepted the highest f which in turn produced the highest above ground biomass (AGB) and seed yield followed by Lukupa and Lyambai in response to defoliation intensities and fertilizer rates. The high yield of Luangeni and Lukupa despite defoliation is due to the indeterminant growth habit which had a greater capacity for compensatory growth compared to Lyambai which exhibited a determinant growth habit. The effects of defoliation were minimised by fertilizer application except at 50 and 75% DI which had adverse effects on the LAI and thus low AGB and seed yield. The 25% DI allowed greater compensatory growth and resulted in no significant decrease in LAI, AGB and seed yield relative to the 0% DI with or without fertilizer application. The 25% DI would allow the dual purpose use of indeterminant common bean varieties in cassava intercropping systems without causing significant grain yield and biomass loss. This could provide a cheaper source of protein during and after the growing seasons thus ensuring food security among smallholder and provides biomass which can contribute to the low organic carbon in cassava production systems over time. The different baseline RUE values could be used in crop growth simulation models to assess common bean growth limitation.

CHAPTER FIVE

5 CONCLUSIONS AND RECOMMENDATIONS

The study found soil nutrients namely K and P to be highly suitable for optimum cassava production under shifting cultivation in Luapula Province of Zambia. It was found that cassava yield declines for every year of cultivation with minimal or no fertilizer application up to 8–9 years after which the field is abandoned. The low to moderate levels of soil organic carbon (SOC) content for optimal cassava production in the study area is because of the slash and burn practices. The low SOC amounts in tandem with the very low nitrogen levels and moderate exchangeable cations (Ca and Mg) levels for optimal cassava production limited growth resulting in reduced intercepted radiations and tuber yields. SOC, LAI, Exchangeable K and Mg explained cassava yield differences at 24 and 36 MAP while weeding was important at 12 MAP. Despite being above the soil critical limit, exchangeable K was the common limiting factor affecting all cassava maturity groups. This could be due to the moderately availability of exchangeable Mg and low N which limit efficient use of K in plant functions thus causing low yields. The cassava in sole cropping and common bean intercropping had the highest LAI thus intercepted the highest f compared to cassava cowpea and cassava soybean intercropping and partitioned more assimulates to the tubers thus obtained the highest tuber yield. The reduction in cassava tuber yield was compensated for by legume grain yield which provides a cheaper protein source and biomass contribution to organic carbon in cassava production systems. Tuber yield and total dry matter were strongly significant correlated to RUE and TIPAR, indicating that RUE and TIPAR are key factors for TDM and tuber yield formation. Therefore, maximizing TIPAR and RUE via breeding large canopy cassava varieties, appropriate fertilizer, liming and short maturing grain legume intercropping is vital for increased and stable cassava productivity on degraded land. The integration of amendment options of liming and fertilizing in tandem with grain legumes achieved cassava yields obtained between 24-36 MAP on exhausted under shifting cultivation at 12 MAP. This approach can increase and stabilize cassava yields to meet the increasing demand due to population increase and agro-industries. The varieties Luangeni and Lukupa had the highest LAI and intercepted the highest photosynthetic active radiation (f) which in turn produced the highest above ground biomass (AGB) and seed yield compared to Lyambai in response to defoliation intensities and fertilizer levels. The high yield of Luangeni and Lukupa despite defoliation is due to the indeterminant growth habit which continues to grow despite defoliation taking a longer period to maturity compared to the determinant variety Lyambai. The high yield of Luangeni compared to Lukupa is due to the longer period to maturity. The effects of defoliation were minimised by fertilizer application except at 75% defoliation intensity due to severe effects on LAI growth which resulted in low AGB and seed yield. The 25% defoliation level allowed compensatory growth after defoliation. This resulted in non-significant LAI, AGB and seed yield decrease relative to the 0% DI. The dual purpose of common beans for leafy vegetable and grain yield during the growing season is optimal at 25% defoliation intensity with application of compound NPK fertilizer supplying 20 kg N, 40 Kg P_2O_5, 20 kg K_2O per ha. This will enhance LAI growth which compensates for the harvested leaves as vegetables and still produce optimal common bean grain yield at the end of the growing season.

The cassava in common bean, soybean and cowpea intercropping positively responded to liming and fertilizer application. Therefore, applying lime, fertilizer and intercropping are recommended practices which should be included in cassava cultivation for sustainable cassava production. This will ensure sustainable land management with increased cassava and legume yields. The study found exchangeable Ca and Mg to be moderately suitable for optimal cassava production, thus the need for a study that includes dolomitic lime to assess the effects on cassava growth and yield on exhausted would be imperative since the functions are synergist in relation to other nutrients. The defoliation of common bean leaves as vegetables was performed in a sole experiment setup, thus the need for a similar study in cassava intercropping in farmer's field to account for resource use (Biological nitrogen fixation and water dynamics).

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5.2 Appendices

Appendix 1: Results of best model selection using analysis of variances for 12 MAP data

```
Analysis of Variance Table

 anova(c2,c6)
Model 1: yield ~ K + Mg
Model 2: yield ~ Mg
  Res.Df    RSS Df Sum of Sq      F
Pr(>F)
1     37 19.969
2     38 22.814 -1   -2.8442 5.2698
0.02746 *
Signif. codes:  0 '***' 0.001 '**'
0.01 '*' 0.05 '.' 0.1 ' ' 1
> summary(c2)
Call:
lm(formula = yield ~ K + Mg, data =
ms1)
Residuals:
    Min      1Q  Median      3Q
Max
-1.2248 -0.5880 -0.1427  0.4242
1.7821
Coefficients:
            Estimate Std. Error t
value Pr(>|t|)
(Intercept)   0.1526     0.5400
0.283   0.7791
K             2.3612     1.0286
2.296   0.0275 *
Mg            0.8556     0.5046
1.696   0.0984 .
---
Signif. codes:  0 '***' 0.001 '**'
0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 0.7347 on 37
degrees of freedom
Multiple R-squared:  0.2477,
Adjusted R-squared:  0.207
```

Appendix 2: Results of best model selection using analysis of variances for 24 MAP data

```
n<-lm(yield~K+ Mg+LAI,data=24 MAP data)
> summary(n)
Call:
lm(formula = yield ~ K + Mg + LAI, data = ms2)

Residuals:
   Min      1Q  Median      3Q     Max
-2.4576 -1.2002  0.2568  1.0257  2.4930
Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  -0.2300     1.1298  -0.204  0.83981
K             7.0511     2.2640   3.114  0.00361 **
Mg            2.5629     0.9288   2.759  0.00905 **
LAI           1.2473     0.4418   2.824  0.00769 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.48 on 36 degrees of freedom
Multiple R-squared:  0.5086,    Adjusted R-squared:  0.4676
F-statistic: 12.42 on 3 and 36 DF,  p-value: 9.981e-06
```

Appendix 3: Results of best model selection using analysis of variances for 36 MAP data

```
c<-lm(yield~K+Mg,data= 36 MAP data)
> summary(c4)

Call:
lm(formula = yield ~ K + Mg, data = ms3)

Residuals:
   Min     1Q Median     3Q    Max 
-3.265 -1.371  0.146  1.258  2.854 

Coefficients:
            Estimate Std. Error t value
Pr(>|t|)   
(Intercept)   1.1013     1.2050   0.914
0.36665   
K             8.7332     2.6166   3.338
0.00193 **
Mg            3.3989     0.9866   3.445
0.00144 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*'
0.05 '.' 0.1 ' ' 1

Residual standard error: 1.671 on 37 degrees of
freedom
Multiple R-squared:  0.5124,    Adjusted R-
squared:  0.486 
F-statistic: 19.44 on 2 and 37 DF,  p-value:
1.696e-06
```

Appendix 4: stepwise regression outputs of key determinants of cassava yield in the study area

Cassava age	Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
12	(Constant)	0.511	0.509		1.005	0.321
	K	2.952	0.991	0.435	2.978	0.005
24	(Constant)	-0.23	1.13		-0.204	0.84
	K	7.051	2.264	0.385	3.114	0.004
	LAI	1.247	0.442	0.338	2.824	0.008
	Mg2	2.563	0.929	0.333	2.759	0.009
36	(Constant)	1.101	1.205		0.914	0.367
	Mg	3.399	0.987	0.433	3.445	0.001
	K	8.733	2.617	0.42	3.338	0.002
Whole data	(Constant)	-11.325	2.614		-4.333	0.000
	Weedinffre	3.749	.593	.418	6.321	0.000
	LAI	4.626	1.050	.303	4.405	0.000
	OC	6.236	1.605	.250	3.886	0.000
	Mg2	6.817	2.195	.193	3.106	0.002

Appendix 5: Correlation coefficients (n=96) for cassava in legume species intercropping under different fertilizer and lime rates over the two growing seasons

Traits	TDM (t/ha)	Leaf yield (t/ha)	Stem diameter (mm)	Number of tubers	Number of branches	Tuber diameter (mm)	Plant height (cm)	LAI	TIPAR	Chlorophyll index	RUE	Tuber yield (t/ha)
TDM (t/ha)	1.000											
Leaf yield (t/ha)	0.859***	1.000										
Stem yield (t/ha)	0.697***	0.334***										
Stem diameter(mm)	0.015ns	0.051ns	1.000									
Number of tubers	0.845***	0.813***	0.171*	1.000								
Number of branches	0.713***	0.760***	0.002ns	0.670***	1.000							
Tuber diameter (mm)	0.754***	0.772***	0.054ns	0.666***	0.594***	1.000						
Plant height (cm)	0.773***	0.847***	0.043ns	0.755***	0.640***	0.585***	1.000					
LAI	0.877***	0.969***	-0.018ns	0.825***	0.745***	0.765***	0.873***	1.000				
TIPAR	0.547***	0.648***	-0.032ns	0.551***	0.531***	0.672***	0.374***	0.646***	1.000			
Chlorophyll index	0.822***	0.914***	-0.111ns	0.805***	0.742***	0.745***	0.830***	0.925***	0.648***	1.000		
RUE	0.714***	0.794***	-0.266*	0.678***	0.620***	0.668***	0.657***	0.812***	0.627***	0.829***	1.000	
Tuber yield (t/ha)	0.960***	0.919***	0.004ns	0.836***	0.758***	0.803***	0.750***	0.926***	0.691***	0.863***	0.781***	1.000

Appendix 6: Correlation coefficients (n=144) for common bean varieties yield components, yield and RUE over the two growing seasons

Traits	Days to 50% flowering	Days to maturity	Grain yield (t/ha)	Number of pod/plant	Pod length (cm)	Number of seed/pod	HI	LAI	f	RUE	AGB
Days to 50% flowering	1										
Days to maturity	0.017ns	1									
Grain yield (t/ha)	-0.274**	0.044ns	1								
Number of pod/plant	-0.261	-0.013ns	0.702***	1							
Pod length (cm)	-0.151ns	-0.178*	0.135ns	0.335	1						
Number of seed/pod	-0.054ns	0.084ns	0.333***	0.050	-0.626***	1					
HI	-0.329***	-0.0262ns	0.500***	0.360	0.040ns	0.160ns	1				
LAI	-0.4335***	-0.086ns	0.613***	0.444	0.137ns	0.202*	0.499***	1			
F	-0.389***	0.035ns	0.731***	0.622	0.198*	0.250*	0.597***	0.671***	1		
K	-0.385***	0.099ns	0.543***	0.359	-0.3086***	0.671***	0.407***	0.436***	0.620***		
TIPAR	-0.576***	0.004ns	0.716***	0.605	0.312***	0.167*	0.604***	0.689***	0.808***		
RUE	-0.4592***	0.071ns	0.681***	0.568	0.254*	0.197*	0.427***	0.570***	0.789***	1	
AGB	-0.452***	0.083ns	0.719***	0.582	0.173*	0.264**	0.542***	0.683***	0.841***	0.860***	1

Appendix 7: Journal publications

Kaluba, P., Mwamba, S., Moualeu-ngangue, D.P., Chiona, M., Munyinda, K., Winter, E., Stutzel, H., Chishala, B.H., 2021. Cropping Practices and Effects on Soil Nutrient Adequacy Levels and Cassava Yield of Smallholder Farmers in Northern Zambia 2021. https://doi.org/10.1155/2021/1325964

Abstract

Cassava is a staple food and a major source of income for many smallholder farmers. However, its yields are less than 6 t/ ha compared to a potential yield of 20–25 t/ ha in Zambia. Understanding cropping practices and constraints in cassava production systems is imperative for sustainable intensification. Therefore, a survey of 40 households each with three fields of cassava at 12, 24, and 36 months after planting (MAP) was conducted. Analyzed soil data, leaf area index (LAI), intercepted photosynthetically active radiation, and management practices from 120 fields were collected and subjected to descriptive statistics. To explain yield differences within the same cassava growth stage group, the data were grouped into low- and high-yield categories using the median, before applying a nonparametric test for one independent sample. Stepwise regressions were performed on each growth stage and the whole dataset to determine factors affecting tuber yield. Cassava intercropping and monocropping systems were the main cropping systems for the 12 and 24–36 MAP, respectively. Cassava yields declined by 209 and 633 kg/ ha at 12 and 36 MAP due to soil nutrient depletion for each year of cultivation until field abandonment at 8–9 years. Fresh cassava yields ranged from 3.51–8.51, 13.52–25.84, and 16.92–30.98 t/ ha at 12, 24, and 36 MAP, respectively. For every one unit increment in exchangeable K (cmol (+)/kg soil), cassava yield increased by 435, 268, and 406 kg/ha at 12, 24, and 36 MAP, respectively. One unit increment of magnesium (cmol (+)/kg soil) gave the highest yield increase of 525 kg ha^{-1} at 24 MAP. (e low levels of soil organic carbon explained the deficient nitrogen in cassava fields, which limits the LAI growth and consequently reduced intercepted radiation and low yields. (e effect of exchangeable K on growth was limited by the moderate availability of Mg and low N, thus the need for balanced fertilizer regimes.

Kaluba, P., Mwamba, S., Moualeu-ngangue, D.P., Chiona, M., Munyinda, K., Winter, E., Stutzel, H., Chishala, B.H., 2022. Performance of cassava under lime, fertilizer and grain legume intercropping on exhausted land in Northern Zambia. https://doi.org/10.1155/2022/3649355

Abstract

Cassava yields of 6 t/ ha are lower than the potential yield of 20–25 t/ ha obtained in Northern Zambia. It is grown in legume intercropping with little or no fertilizer, causing nutrient depletion with consequent land abandonment. Therefore, the study objective was to investigate the performance of cassava under lime, fertilizer, and grain legume intercropping on exhausted land in Northern Zambia. A split-split plot design experiment was conducted over two seasons, comprising two lime rates (0 and 300 kg/ ha), two fertilizer rates (0 and 100N : 23P:80 K kg/ ha), and three grain legumes (common beans, cowpea, and soybean) intercropped in cassava and sole cassava arranged in RCBD with three replications. Periodic measurements of leaf area index (LAI), light interception, weather data, and yield components were recorded. A linear mixed model with year as a random factor was performed to assess the treatment effect of lime, fertilizer, and legume species intercropping on cassava growth characteristics, radiation-use efficiency (RUE), and selected yield components. Lime, fertilizer rates, and legume species intercropping were assigned as main, sub-, and sub-sub-treatments, respectively. Fertilization and fertilization + lime treatments in sole cassava and cassava-common bean intercropping significantly increased the RUE and light extinction coefficient (k) compared to non-fertilized and only lime treatments. Lime x fertilizer x cropping system interaction was significant on chlorophyll index and plant height, RUE, tuber yield, HI, and total dry matter (TDM) yield. Cropping system x year interactions were significant on season LAI. On average, every kg of cassava yield loss in intercropping was compensated by 0.46 kg soybean, 0.20 kg common beans, and 0.26 kg of cowpea. NPK fertilizer + lime, NPK fertilizer, and grain legume intercropping may be adopted to increase cassava tuber yields and legume grain yield response on nutrient-depleted soils in high rainfall areas of Zambia.