GENETIC STUDIES OF PHYSIOLOGICAL AND MORPHOLOGICAL TRAITS ASSOCIATED WITH DROUGHT TOLERANCE IN CASSAVA GENOTYPES

By

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DECLARATION

I hereby declare that except for references to works of other researchers, which have been duly acknowledged, this work is my original research and that neither part nor whole has been presented elsewhere for the award of a degree.

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ABSTRACT

This study was undertaken to identify key traits that are closely related to cassava yield under drought stress and also identify stable high yielding cassava genotypes under varying environments. A survey was conducted using in semi-structured questionnaire in three districts in the Northern Region involving 120 farmers to identify farmers' perception on drought in cassava cultivation, production constraints, mitigation strategies and preferences for improved cassava genotypes. To identify ideal genotypes that meet farmers' preferences, 150 cassava genotypes from local and exotic sources were assembled and assessed for diversity using morphological traits and simple sequence repeat markers. Subsequently 20 genotypes were selected and evaluated under irrigation and no irrigation to assess genetic variability in abscisic acid content, carbon isotope ratio, stomatal conductance, leaf temperature and root yield. Stability of genotypes for physiological and yield traits were also assessed using the additive main effect and multiplicative interaction (AMMI) and GGE biplot analyses. The survey indicated lack of credit as the most important constraint facing cassava cultivation in the region. Drought was the second most important constraint and the intensity was observed to be increasing. Majority of the farmers also preferred early maturing cassava varieties that are high yielding with good plant type and marketability. Factorial analysis of the morphological traits grouped the genotypes based on their origin with few exceptions. Principal component analysis further identified plant height, branching habit, distance between leaf scars, colour of end branches, root yield, harvest index and number of roots per plant as the traits contributing most of the variability in the groups. High level of heterozygosity was revealed by the simple sequence repeat markers which grouped the genotypes into seven distinct clusters irrespective of sources. Genetic variability was established for abscisic acid content which was higher under stress than irrigation. ABA content was negatively correlated with root yield, harvest index and above ground biomass yield meaning it can be used as indirect selection criteria against unproductive genotypes. Narrow genetic variation was observed for carbon isotope ratio which was higher under irrigation than no irrigation. Carbon isotope ratio was positively correlated with above ground biomass yield but not root yield. Stomatal conductance and leaf temperature were significantly different among genotypes and environments but genotype x environment interaction was not significant. Broad sense heritability estimates were high for most of the traits except stomatal conductance, above ground biomass yield, root number and stem diameter. AMMI analysis of plant height, severity of cassava mosaic disease, root yield, root length/girth ratio, above ground biomass yield and harvest index indicated stronger effect of environment than genotypes for all traits except CMD. The study established for the first time relationship between ABA content and cassava root yield on the field. Extension of roots to lower soil depts (L/G ratio) was also found to be detrimental to storage root yield. It was also found from this study that carbon isotope ratio influence above ground biomass and not storage root yield under stress conditions. Based on AMMI selections and the GGE biplot analysis, three genotypes, MM96/1751, UCC2001/449 and 00/0203 were identified as high yielding and stable across environments. These can be used as donor parents in improving local farmer-preferred varieties. Six genotypes (UCC2001/449, 96/1708, MM96/1751, 00/0203, 96/409 and I91934) had significantly higher root yield than the best local farmer preferred variety. These can be tested on-farm for official release to farmers for cultivation.

DEDICATION

To the Almighty God and the people He put in strategic positions to assist in bringing me this far.

To God be all the glory.

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LIST OF ABBREVIATIONS

AGRA	Alliance for a Green Revolution in Africa
AMMI	Additive Main Effect and Multiplicative Interaction
ASV	AMMI Stability Value
CIAT	International Center for Tropical Agriculture
CSIR	Council for Scientific and Industrial Research
DNA	Deoxyribonucleic acid
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organisation
GEI	Genotype x Environment Interaction
GGE	Genotype + Genotype x Environment Interaction
Hr	hour
IFAD	International Fund for Agricultural Development
IFDC	International Fertilizer Development Center
IITA	International Institute of Tropical Agriculture
MOFA	Ministry of Food and Agriculture
PCR	Polymerase Chain Reaction
PIC	Polymorphism Information Content

CHAPTER ONE

1.0 GENERAL INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is the third most important source of calories in the tropics after rice and maize with millions of people depending on it in Africa, Asia and Latin America (FAO, 2014). It can be cultivated under marginal ecologies characterised by poor, erratic rainfall and extended periods of drought where most crops will fail (Hillocks, 2002; El-Sharkawy, 2004). The production areas are mostly confined to developing tropical and sub-tropical countries with over 40% of world production occurring in Sub-Saharan Africa (El-Sharkawy, 2006). It is grown by resource-poor farmers, mainly women, often on marginal lands for food security and income generation (Okogbenin *et al.*, 2003). It also has the potential to produce starch for industrial purposes as well as feed for livestock production at a relatively cheaper cost than maize (Nweke *et al.*, 1994). Cassava is grown in four out of the five major agroecological zones of Ghana covering nine out of the ten regions of Ghana (SRID, 2009). Apart from serving as the main source of carbohydrates to meet the dietary requirements of most rural dwellers, it contributes immensely to Ghana’s Agricultural Gross Domestic Product (AGDP) (Ofori, 2005). According to FAO (2014), the crop earned the country over US$ 1.51 million, which was second to only yam (US$ 1.69 million) in foreign exchange. The crop is mainly consumed as *ampesi* (boiled storage roots) or in the form of *fufu* (pounded boiled cassava) with the remainder being processed into *gari or kokonte*, dried products for storage. In the northern parts of Ghana, it is mainly processed into dried chips for storage by resource poor farmers who use the flour prepared from it for preparing *tuo zaafi*, a local staple.

Cassava cultivation is severely affected by several biotic and abiotic stresses that impact negatively on production, consumption and marketability (Bull *et al.*, 2011). Low yields in cassava have been attributed to the use of late bulking varieties, disease and pest susceptibility and low yielding potential of many varieties (Nweke, 1996). Yields are far below par in developing countries, particularly in the tropical regions (El-Sharkawy, 2007). Crop yields per unit area have remained low (<12 t/ha) (MoFA, 2012). Whereas progress has been made in developing disease-resistant varieties leading to the release of several varieties in Ghana (Manu-Aduening *et al.*, 2005), little progress has been made in developing varieties for drought prone areas. Most of the released cassava varieties in Ghana targeted high yield potential in the forest and transition zones of Ghana which have bimodal rainfall pattern, totally different from the monomodal rainfall pattern of the Guinea Savannah ecologies. The presence of genotype by environment interaction in yield and yield components in cassava (Egesi *et al.*, 2007a; Aina *et al.*, 2009) means that the performance of these varieties cannot be predicted in the savannah zones. Additionally, these released varieties are often rejected due to their inability to adapt into the farmers' cultivation systems and food (Manu-Aduening *et al.*, 2005; Acheampong *et al.*, 2013). Involving farmers in the development of crop varieties has resulted in faster rates of adoption and dissemination of improved varieties (Kapinga *et al.*, 1997; Odendo *et al.*, 2002; Manu-Aduening *et al.*, 2014).

The cultivation of cassava has been under rain fed conditions making its performance climate dependent. However, the advent of climate has made the rainfall pattern more unpredictable thereby affecting crop productivity in the decades to come in drought-prone areas (Saxena and John, 2002; Turyagyenda *et al.*, 2013). Increased temperatures are associated with increased rates of evapotranspiration resulting in decline in the yield potential of crops (FAO, 2011). Yield losses due to water deficits however, vary depending on timing, intensity and duration of the deficit, coupled with other location-specific environmental stress factors such as high irradiance and temperature (Serraj *et al.*, 2005; Farre and Faci, 2009). About 82 to 96% yield decline has been reported in cassava under severe moisture stress (Aina *et al.*, 2007a). Drought affects crops through chlorophyll degradation and inhibition of photosynthetic capacity, leading to low yields (Epron and Dreyer, 1993; van der Mescht *et al.*, 1999; This *et al.*, 2000; Jiang and Huang, 2001; Li *et al.*, 2004). A genotype that has the ability to maintain its chlorophyll content under water deficit conditions is believed to be drought resistant or tolerant. The adaptation of plants under drought conditions is a complex phenomenon that depends on plants' attributes and their interactions with environmental factors (Parry *et al*, 2005; Tardieu, 2005).

Past research activities have focused on evaluating introduced cassava genotypes for high yields, low HCN content and excellent cooking qualities and, subsequently, breeding for improved pest and disease resistance (Nweke *et al.*, 1994) in humid ecologies, without much emphasis on resistance to abiotic stresses such as drought. Ability to identify drought-tolerant and resistant varieties is of paramount importance for the maximization of productivity potential in these areas of low rainfall and unpredictable conditions (Okogbenin *et al.*, 2003). It has been suggested that the main way to ensure food security in the presence of drought is to increase the development and deployment of drought-tolerant crop varieties (EPA, 2003). Therefore, zone-specific research is necessary to identify cassava varieties that can meet the expectations and needs of farmers and consumers in the Guinea Savannah Zones of Ghana.

Cassava has been perceived to be a hardy crop with ability to withstand moderate moisture stress making research to improve its water use efficiency limited (Turyagyenda *et al.*, 2010). Breeding crops for drought prone areas requires the identification and the establishment of the genetic basis of key traits as well as their interactions with the environment to assess their stability (Rebetzke *et al.*, 2002; Tardieu, 2005). Such traits should be positively and closely associated with yield to bring about the desired genetic improvement. Parry *et al.* (2005) proposed that directed breeding strategies must focus on key traits that are important to performance under drought stress. For instance, traits such as carbon isotope discrimination, which measures the extent to which photosynthesis is maintained under limited moisture, and stable chlorophyll content have been used in wheat and groundnut improvement under drought conditions (Condon *et al.*, 2004; Arunyanark *et al.*, 2008). Though an association has been found between carbon isotope discrimination and yield in cereals (Monneveux *et al.*, 2005), the mechanism of carbon isotope discrimination and its potential in determining transpiration efficiency has been poorly exploited in root and tuber crops (Monneveux *et al.*, 2013). Most crops have specific phases in their phenology that can be targeted for improvement against drought, it has not been easy to do so for cassava due to differential partitioning of dry matter into the above ground biomass and roots (Alves, 2002; El-Sharkawy, 2004). It has been difficult to separate productive traits from survival traits which in most cases are negatively correlated yield under drought but only useful for perennial crops (Mitra, 2001; Clary *et al.*, 2004). The cassava plant is naturally a perennial shrub and can grow indefinitely alternating periods of vegetative growth and root bulking (Alves, 2002). It undergoes various physiological, morphological and adaptive mechanisms such as abscisic acid accumulation to induce leaf senescence, partial closure of stomata as well as root elongation to deeper soil depths (El-Sharkawy *et al.*, 1992; Santisopasri *et al.*, 2001; El-Sharkawy, 2007) to combat periods of moisture deficit. Identification of relevant traits closely associated with root yield, their genetic basis as well as stability across environments will provide opportunity for selection for high-yielding drought tolerant cassava varieties.

1.1 Objective of research

The main objective of this work was to determine the genetic basis of the physiological traits associated with cassava productivity under drought stress conditions for adaptation in the guinea savannah ecology of Ghana. The specific objectives were to:

1. Identify farmers perception of drought, coping strategies, cropping systems and varietal preferences in cassava cultivation,
2. Determine genetic variability among cassava genotypes in physiological traits associated with drought tolerance in cassava,
3. Estimate broad sense heritability and stability of morpho-physiological traits associated with yield in different growing environments, and
4. Determine the efficiency of abscisic acid and carbon isotope discrimination in identifying drought tolerant genotypes as well as the effect of drought stress on root bulking in cassava.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Cassava production and utilization

Cassava is the third most important source of dietary energy after rice and maize for developing countries of the world (Fauquet and Tohme, 2008). It serves as a food security and income generation crop. In Africa, it is the second most important source of energy, an inexpensive food, and emerging cash crop (El-Sharkawy, 2004). Besides being a major staple crop, it serves as an important source of raw material for the starch, feed, and bioethanol industries (Ceballos *et al.*, 2012). Cassava is the most widely utilized root and tuber crop grown for its starchy storage roots and its leaves, which are rich in protein (El-Sharkawy, 2007). Though described as a subsistence crop in Africa, the crop is gradually becoming a cash crop and plays four vital roles according to Nweke *et al.* (2002). These include its role as: famine-reserve crop, rural staple food, cash crop for both rural and urban households and raw materials for industrial purposes.

In Ghana, the crop has long been estimated to contribute up to 22% of the agricultural gross domestic product (AGDP) (Ofori, 2005) which is higher than any other crop including cocoa (16% of AGDP). The crop is cultivated in nine out of the ten regions of Ghana (MoFA, 2012) and constitutes an important dietary carbohydrate source for several people particularly rural dwellers and occupied 840,000 hectares of farmland in 2013 (FAO, 2014).

2.2 Cassava production constraints

Cassava cultivation is affected by several biotic and abiotic stresses that impact negatively on its production, consumption and marketability (Bull *et al.,* 2011). Its heterozygous nature and long growing cycle have made breeding new varieties more difficult than other crops (Ceballos *et al.,* 2004). This has resulted in slow development and release of new improved varieties for cultivation by farmers. Low yields in cassava have been attributed to the use of late bulking varieties, disease and pest susceptibility and low yielding potential of many varieties (Nweke, 1996). Pests such as mealy bugs, cassava green mites, white flies, grasshoppers and rodents impact negatively on the growth and yield of the crop (Akinbo, 2008). Whiteflies are considered one of the major pests of cassava due to their dual role as direct pest and as vector for viruses that cause major diseases in cassava (Bellotti and Arias, 2001). The species *Bemisia tabaci* (Bellotti *et al.*, 1999) is the vector of cassava mosaic disease (CMD) caused by geminiviruses (Thresh *et al.,* 1994; Akano *et al.*, 2002; Egesi *et al.*, 2007a) with reported yield losses of 20% - 100%. Cassava anthracnose disease, which attacks mainly the stem, also reduces the yield and the availability of planting materials for subsequent seasons (Akinbo *et al.*, 2007). Besides biotic factors, several abiotic constraints such as drought impact negatively on cassava growth and yield (Aina *et al.,* 2007a; El-Sharkawy, 2007; Turyagyenda *et al.*, 2013).

2.3 Drought

Drought is a weather condition that is characterized by the absence of rainfall for a long period leading to crop losses as a result of depletion of soil moisture (Mishra and Singh, 2010). For agriculture purposes, it may be defined as the inadequate availability of water and soil-moisture storage capacity and distribution during the life cycle of a crop plant, which restricts the expression of full potential of the plant (Sinha, 1986; De Boeck and Verbeeck, 2011). It is one of the major abiotic constraints to crop production in the Guinea Savannah Zones of West and Central Africa particularly in areas of unpredictable rainfall (Subbarao *et al.*, 2005). Drought is one of the factors that limit cassava production and identification of morphological traits that may be used in selecting drought tolerant cultivars is needed (Nassar, 2002; Nasser, 2007; Nassar *et al.*, 2008).

2.4.1 Effect of drought on yield of crops

Drought reduces crop productivity by inhibiting photosynthesis and growth (Taiz and Zeiger, 2002). Under drought stress conditions the source capacity, which represents the ability of the photosynthetic apparatus to produce carbohydrates, is reduced as a result of stress effects on leaf area, gaseous exchange and storage of carbon available for assimilation (Anjum *et al.*, 2011). Drought stress can decrease yield of crops by affecting the sink or the source. Reduction in source capacity stems from hastened leaf senescence that occurs as a result programmed cell death which results in reduced canopy size, loss of photosynthesis and low yields (Rivero *et al.*, 2007). The reduction in sink capacity under drought stress is caused by arrested organ differentiation as well as by the dysfunction of the differentiated reproductive organs (Blum, 2011). In crop plants, the morphological and physiological processes that account for yield are impacted negatively by drought stress. For instance, high transpiration rate and photosynthesis are positively correlated with improved yield of crops (Parry *et al.*, 2005; Blum, 2009). However, the occurrence of drought disrupts this association due to certain adaptive responses which inhibit dry matter production and partitioning into the sinks (Anjum *et al.*, 2011). Drought that occurs at any stage during the growing season may reduce root yield in cassava (Alves, 2002; El-Sharkawy, 2004). However, the most critical stages are emergence, storage root initiation and development. Yield reduction may be due to a reduced number of storage set and poor storage root size distribution (Aina *et al.*, 2007a; Aina *et al.*, 2007b).

2.4.2 Mechanisms of drought tolerance

Crop plants use more than one mechanism at a time to resist drought (Mittler, 2006). These mechanisms are discussed below.

2.4.2.1 Drought escape

Drought escape is defined as the ability of a plant to complete its life cycle before serious soil and plant water deficits occur (Turner, 1979). It involves rapid phenological development (early maturity), developmental plasticity (variation in duration of growth period depending on the extent of water-deficit) and remobilization of assimilates to grain in the case of cereals. Under low soil water conditions, plants enhance their ability for improved water uptake through extending the rooting system and increasing root length density (RLD, cm root per cm soil) (Ahmadi *et al.*, 2011). Soil water distribution, soil texture, and soil structure have major effects on root growth and distribution (Wang *et al.*, 2006).

2.4.2.2 Drought avoidance

Drought avoidance is the ability of plants to maintain relatively high tissue water potential despite a shortage of soil-moisture (Beebe *et al.*, 2013). Drought avoidance is achieved by maintenance of turgor through increased rooting depth, efficient root systems and increased hydraulic conductance and by reduction of water loss through reduced epidermal (stomatal and lenticular) conductance, reduced absorption of radiation by leaf rolling or folding (Ahmadi *et al.*, 2011) and reduced evaporation surface (leaf area) (Turner, 1986). Plants under drought condition survive by doing a balancing act between maintenance of turgor and reduction of water loss (Shashidhar *et al.*, 2000).

2.4.2.3 Drought tolerance

Drought tolerance is the ability to withstand water-deficit with low tissue water potential (Beebe *et al.*, 2013). The mechanisms of drought tolerance include maintenance of turgor through osmotic adjustment (a process which induces solute accumulation in cell), increase in elasticity in cells and decrease in cell size and desiccation by protoplasmic resistance (Sullivan and Ross, 1979; Ugherughe, 1986). The mechanisms that confer drought tolerance by reducing water loss (such as stomatal closure and reduced leaf area) usually result in reduced assimilation of carbon dioxide (El-Sharkway, 2006). Osmotic adjustment increases drought resistance by maintaining plant turgor, but the increased solute concentration responsible for osmotic adjustment may have detrimental effects in addition to energy requirements for osmotic adjustment. Premachandra *et al.* (1994) and Sanchez *et al.* (2001) reported that certain traits that confer tolerance and survival under drought conditions are often associated with reduced photosynthesis and yield potential. It is therefore necessary to understand the genetic basis of such traits as well as their relationships with yield to make them useful in a breeding programme. Crops must balance the mechanisms of escape, avoidance and tolerance in order to be productive (Blum, 2011).

2.4.2.4 Water use efficiency

Development of crop varieties that are efficient in their use of water is the objective of most breeding programmes targeting drought stressed areas (Parry *et al.*, 2005). This attribute often termed water use efficiency has been the subject of many studies. Physiologically, water use efficiency (WUE) is considered as the amount of carbon gained in photosynthesis in exchange for water used in transpiration (Condon *et al.,* 2004). From the agronomists' point of view, WUE is defined as the yield of the harvested product from water made available. On the basis of these definitions, performance of genotypes in terms of water use efficiency is strictly based on the conversion of available moisture into dry matter. Under moisture stressed conditions, certain genotypes of crops adopt survival mechanisms that limit their photosynthetic activities until conditions are more favourable (El-Sharkawy, 2007). Such genotypes often have reduced photosynthetic activity, low stomatal conductance and may also leave more water in the soil than genotypes that maintain biological activity (Condon *et al.*, 2002).

Water use efficiency does not always correspond to high yield under stressed environments as genotypes may utilize water extracted from deeper layers of soil under moisture stressed conditions for purposes other than yield (Monneveux *et al.,* 2013). Okogbenin *et al.* (2003) found that cassava genotypes that were more efficient in extracting moisture from deeper soil layers had lower root yield but higher top growth than those that extracted less water from lower soil layers. Water use efficiency has been indirectly assessed using carbon isotope discrimination ($\Delta^{13}C$) with contrasting results. Cereals with low $\Delta^{13}C$ were found to be 'conservative' in terms of water use and perhaps, in terms of crop growth rate. In the absence of soil water deficit, low $\Delta^{13}C$ genotypes tend to grow slower than high ^{13}C genotypes, resulting in lower total biomass production and yield (Condon and Richards, 1993; Condon *et al.*, 2002). Blum (2005) cautioned that high WUE is a function of reduced water use and not necessarily an improvement in plant productivity. This implies that indiscriminate selection for higher WUE with the assumption that it equates with improved yield under stress might not result in the desired expectation.

2.4.2.5 Reduced plant size

Though plants require water for their growth and tissue expansion, over 90% of the water required by terrestrial plants is not utilized in any biochemical way but lost through transpiration (Morison *et al.*, 2008). In most water limited environments, the plant must control the water loss and prevent tissue dehydration. One of the main factors controlling stomatal water loss at the whole plant level is total leaf area. Plants with large canopies tend to have greater water requirements than plants with small canopies (Blum, 2011). Plant adaptation to moisture stress in dry environments can be obtained by reduced plant size and growth rate (Blum, 2005). This is typical of many dry land plants that abscise older leaves to reduce leaf area and plant water use. Mitchell *et al.* (1998) indicated that reduction in plant size, leaf area, and leaf area index constitute effective mechanisms for limiting the negative effect of drought stress in crop plants. Most crop varieties bred for drought prone environments are characterized by reduced plant size thus reducing the surface area for light interception and hence reduced water loss through transpiration (Holmes and Keiller, 2002). Effect of moisture stress on crop performance depends on the type of crops and the stage of growth. In cereals moisture stress at flowering causes severe flower abscission and hence reduced yield.

2.4.2.6 Stomatal closure

High yielding varieties of most crop plants have been reported to have higher stomatal conductance as a result of their greater transpiration and water use (Reynolds *et al.* 1994). This is because such varieties have larger sink size which eventually leads to earlier leaf senescence under moisture stress compared with varieties with smaller sinks. Higher stomatal conductance results in greater transpiration which leads to greater photosynthesis and water-use (Khanna-Chopra and Sinha, 1988). Thus, sink load and its effect on plants under stress may be an example of the fact that a high yield potential is primarily not compatible with sustainable yield under severe moisture stress.

2.4.2.7 Delayed chlorophyll content depletion

Chlorophyll is one of the major chloroplast components for photosynthesis (Manivannan *et al.*, 2007). The relative chlorophyll content of plants has a positive relationship with the photosynthetic capacity of many crops due to its close association with the photosynthetic enzyme ribulose 1-5 di-phosphate carboxylase (Rubisco) (Arunyanark *et al.*, 2008). For example, flag leaf chlorophyll content of wheat is an indicator of the photosynthetic activity and its stability for the conjugation of assimilate biosynthesis (Bijanzadeh and Emam, 2010). However water deficit leads to an increased depletion and decreased concentration of chlorophyll resulting in leaf colour change since chlorophyll content is highly related to the green colour of leaves (Zaharieva *et al.*, 2001; Izanloo *et al.*, 2008). Several studies have shown that reduction in chlorophyll content occurs as a result of drought in many food and fodder crops like wheat and grasses thereby inhibiting their photosynthetic capacity (Sarker *et al.*, 1999; Jiang and Huang, 2001; Colom and Vazzana, 2003; Li *et al.*, 2004) and hence function (Epron and Dreyer, 1993). It has been found that the ability to maintain stable chlorophyll content under water deficit situations conditions indicates drought tolerance in barley (This *et al.*, 2000) and potato (van der Mescht *et al.*, 1999). Chlorophyll stability during drought might be a promising criterion for selecting for drought tolerance in crops (Arunyanark *et al*., 2008).

Although root yield in cassava genotypes increased with increase in concentration of three leaf chlorophyll components (a, b and ab) under moisture stress (Lahai *et al.*, 2003), little has been done to exploit the genetic variability in cassava for chlorophyll stability for yield improvement. Greater progress in yield advancement is expected since cassava genotypes that maintained their chlorophyll content under moisture stress conditions gave much higher yield than other genotypes.

New methods and tools for quick estimation of chlorophyll content in the leaves of plants have been developed. A portable chlorophyll meter (SPAD meter) that estimates the chlorophyll content of leaves based on greenness has been designed (Haripriya-Anand and Byju, 2008; Byju and Haripriya-Anand, 2009; Almeselmani *et al.*, 2012). The SPAD meter makes instantaneous and non-destructive readings on a plant based on the quantification of light intensity absorbed by the tissue (Almeselmani *et al.*, 2012). Significant positive correlation between the chlorophyll content of the youngest fully expanded leaf and root yield in cassava has been reported (Haripriya-Anand and Byju, 2008; Byju and Haripriya-Anand, 2009). Measurement of chlorophyll content during drought stress can be used as a valuable index for evaluation of plants tolerance to environmental stresses (Paknejad *et al.*, 2007).

2.4.2.8 Stay green

Stay green is a term given to plants that maintain their chlorophyll content under stress due to resistance to premature senescence (Thomas and Smart, 1993; Harris *et al.*, 2007). During moisture stress, stay green varieties are able to maintain their leaves for light interception which results in increased photosynthesis compared with non-stay green varieties (Lenis *et al.*, 2006). Such plants maintained their greenness even under prolonged periods of drought due to stability of their chlorophyll content. Stay green has been extensively used in plant breeding to increase yield potential and yield stability in all environments, including drought-prone areas (Tollenar and Wu, 1999; Campos *et al.*, 2004). Stable chlorophyll content under drought conditions positively correlated with pod yield in groundnut (Arunyanark *et al.*, 2008). Lahai *et al.* (2003) also related root yield in cassava genotypes with increased concentration of leaf chlorophyll under moisture stress but this has not been fully exploited in cassava yield improvement under moisture stress based on leaf chlorophyll content stability.

2.4.2.9 Osmotic adjustment

Osmotic adjustment (OA) is a key mechanism enabling plants under drought stress to maintain water absorption and cell turgor pressure, thus contributing to sustained higher photosynthetic rate and expansion growth. Analysis of OA in wheat under several drought stress conditions has been suggested as an effective selection criterion for drought tolerance especially during the reproductive growth stage (Moinuddin *et al.*, 2005). A number of contrasting reports on the role of OA have been published. For instance, Turner *et al.* (2007) concluded that differences in OA were not associated with yield benefits in a population of chickpea advanced breeding lines. Other studies on OA have indicated that OA cannot be considered equally useful in all crops and/or drought conditions but a general positive association between yield and OA has been reported under severe water stress where yields tend to be low (Serraj and Sinclair, 2002). However this has not been fully exploited in cassava.

2.4.2.10 Carbon isotope discrimination

Rebetzke *et al.* (2002) reported the use carbon isotope discrimination ($\Delta^{13}C$) as a surrogate for water use efficiency to select productive wheat genotypes adapted to drought-prone environments. During diffusion and biochemical fixation of CO_2, the heavier ^{13}C isotope is discriminated against leading to a reduction in the ratio of $^{13}C/^{12}C$ in leaf compared with the normal abundance in the atmosphere. The ratio depends on the balance between diffusion into the leaf and demand by the net CO_2 assimilation rate and gives a measure of transpiration efficiency (Morrison *et al.*, 2008). Drier conditions usually result in less discrimination (less negative). In several C_3 species, ^{13}C is positively correlated with the ratio of internal leaf CO_2 (Ci) concentration to ambient CO_2 concentration (Ca) and negatively associated with transpiration efficiency. High Ci/Ca leads to a higher ^{13}C and a lower transpiration efficiency (Farquhar and Richards, 1984). Selection of low ^{13}C wheat genotypes resulted in increased aboveground biomass and kernel weight. Yield was also found to increase by about 2% under mild stress conditions and up to about 10% under the driest conditions (Rebetzke *et al.*, 2002). Ehleringer (1990) also found that genotypic differences in leaf conductance were positively correlated with ($\Delta^{13}C$) values, irrespective of whether it was measured on the lower or upper leaf surfaces, individual leaves or at whole plant level. There is therefore the need to exploit this relationship in cassava.

2.4.2.11 Abscisic acid (ABA) accumulation

Abscisic acid has been reported to promote drought tolerance in crops (root growth and root hydraulic conductivity through the enhancement of root aquaporins activity (Jacqmard *et al.*, 1995; Sharp and LeNoble, 2001). Abscisic acid can enhance plant performance under drought conditions in the field. Alves and Setter (2004b) recorded substantial amounts of ABA that accumulated rapidly in cassava following exposure to mild moisture stress. Duque and Setter (2013) also evaluating cassava’s response to water stress observed rapid accumulation of ABA in immature leaves which coincided with reduced transpiration and severe leaf abscission. Although ABA accumulation in plants reduces stomatal aperture and hence limits water loss through transpiration (Zhang and Davies, 1990), it also causes growth retardation by reducing leaf area, stomatal closure and reduced photosynthesis. Short term growth retardation by ABA accumulation results from the inhibition of both cell expansion and cell division which often translates into increased root/shoot dry matter ratio under drought stress (Blum, 2011). This adaptive mechanism may lead to reduction in the accumulation of photosynthates which will eventually lead to low yield. Plants' accumulation of ABA as a result of moisture stress can be used as a basis for assessing drought tolerance and yield response in drought prone environments.

2.4.2.12 Leaf retention and abscission in cassava

Throughout its development, the cassava plant sheds older leaves whilst forming new ones. The plant has a leaf life of 15-20 weeks and an optimal leaf area index (LAI) of 4 to 6 (Cock *et al.* 1979) though some cultivars have much shorter leaf life than others. Simulation models and field evaluations have shown that extended leaf life is positively correlated to higher root yields (Tan and Cock, 1979; Lenis *et al.,* 2006). Leaf retention (i.e. stay-green trait) during growth, especially under stress conditions, is associated with higher yields in many other crops such as maize, rice, sorghum, oats and soybean (Thomas and Smart, 1993; Harris *et al.,* 2007). Shorter leaf life in some genotypes results in a suboptimal LAI, which in turn causes reduced root yields especially in non-branching cultivars (Zhang *et al.,* 2010). Some cultivars of cassava shed leaves continuously and produce new ones in their stead. Formation of these new leaves requires a significant metabolic input and creates a competitive sink for photosynthetic assimilates, thus reducing root yields (El-Sharkawy, 2004). In contrast to cereals and determinate legumes, in which reproductive development and seed formation follow vegetative development, photosynthates in cassava have to be allocated for both leaf (source) and storage root (sink) growth simultaneously (Zhang *et al.,* 2010).

2.5 Physiological basis for yield under drought

The physiologically relevant indicators of drought effects are the water content and the water potential of plant tissues (Jones, 2007). These in turn depend on the relative fluxes of water through the plant within the soil-plant-atmosphere continuum (SPAC). Physiological traits are viewed as secondary genetic markers in plant breeding for specific locations where the level of genotype x trait interaction is high (Reynolds and Trethowan, 2007). Although there are a limited number of genes and understanding of the genetic basis of crop adaptation to drought stressed environments (Snape, 2004), physiological traits can be used to dissect stress adaptation into its components. These physiological traits can be applied to specific environments within which they show considerable levels of heritability provided they have close association with genetic markers controlling performance under stress conditions (Reynolds *et al.*, 2005). A good understanding of the physiological and genetic basis of growth and yield adaptation to stress environments is also necessary for setting breeding objectives in marker-assisted selection breeding activities. For these traits to be useful in any breeding programme, the germplasm must be evaluated for these traits and yield in the target environment. Before characterisation the traits can be defined in terms of the phenology of the crop, the specific attributes and the potential contributions of these traits to yield over the crop cycle must be known (Parry *et al.*, 2005).

2.6 Genetic basis of drought tolerance

Drought tolerance is a complex trait which depends on action and interaction of different morphological, physiological and biochemical processes (Babar *et al.*, 2009). Polygenic inheritance of root characters has been reported in cassava (Ekanayake *et al.*, 1985). Long roots and high root numbers have been reported to be controlled by dominant alleles and thick root tip by recessive alleles (Rukundo *et al.*, 2014). Leaf rolling and osmotic adjustment have shown monogenic inheritance (Singh and MacKill, 1991). Tomar and Prasad (1996) reported a drought resistance gene, *Drt1* in rice, which is linked with genes for plant height, pigmentation, hull colour and awn type. The gene has pleiotropic effects on the root system. Similarly in cowpea, drought tolerance has been reported to be controlled by a single dominant gene. Further investigation is needed to understand the genetic basis of morphological and physiological traits contributing to drought tolerance.

2.7 Genes for drought tolerance

Many genes responsible for stressed responses have been isolated and characterized in the in a variety of crop species (Ramanjulu and Bartels, 2002; Cattivelli *et al.*, 2008). The complexity of molecular response to drought in crop plants has also been revealed by transcriptome analyses (Kollipara *et al.*, 2002; Hazen *et al.*, 2005; Buchanan *et al.*, 2005). Studies have shown that plant roots produce chemical signals that are transported to the leaves and shoot when unfavourable environmental conditions such as moisture deficit are encountered (Caliskan, 2009). Physiological response of plants to moisture stress has been associated with the production of aquaporins that form water-selective channels that mediate a rapid trans-membrane water flow in plants (Eisenbarth and Weig, 2005; Jang *et al.*, 2013), According to Jang *et al.* (2013), two aquaporins JcPIP1 and JcPIP2 may be significant regulators of moisture stress response and recovery in *Jatropha sp*. These proteins are also implicated in many other physiological processes that include seed germination, cell elongation, stomatal movement, phloem loading and unloading, reproductive growth, as well as stress responses. Phookaew *et al.* (2014) reported that changes in leaf shape, stomatal closure and relative water content in cassava were related to differential expression of *cassava miR164/MesNAC* and *miR167/MesARF6/8* genes. Research has shown that the gene AVP1 which encodes vacuolar H pyrophosphatase in roots plays an important role in influencing root development through auxin transport resulting in increased root biomass and enhanced recovery from moisture stress condition (Gaxiola *et al.*, 2001; Park *et al.*, 2005). Since robust root systems prevent injury to plants under moisture deficit conditions through enhanced moisture capture (Morrison *et al.*, 2008), targeting genes that enhance root development will result in greater improvement in breeding crops for drought prone environments.

2.8 Breeding for drought tolerance

Conventional breeding is based on genetic variation and uses selection to incorporate superior characteristics into the progeny. For this purpose, two plants possessing desirable traits are selected and then crossed to recombine their genes, so that the offspring has new genetic arrangements. The progeny are tested for the expression of desirable characteristics and selected progeny are maintained in future plant generations (El-Sharkawy, 2007; Cattivelli *et al.*, 2008). In practice, drought tolerance is selected together with plant productivity. Varieties displaying drought tolerance are crossed with drought susceptible but high yielding varieties (Hieng *et al.*, 2004; Lizana *et al.*, 2006).

Three breeding approaches for drought resistance have been evolved. The first is to breed for high yield under optimum (water-stress-free) conditions. Since maximum genetic potential of yield is expected to be realized under optimum condition and a high positive correlation exists between performance in optimum and stress conditions (Johnson and Frey, 1967), a genotype with superior performance under optimum conditions will also yield relatively well under drought conditions. However, the concept of expression of maximum genetic potential in optimum condition is not always successful as genotype by environment interaction may restrict the high yielding genotype from performing well under drought (Okogbenin *et al.*, 2003; Aina *et al.*, 2007b). Thus, a second approach is to breed under actual drought conditions (Hurd, 1971).

The second approach suffers from the problem of year to year variation in the intensity of drought leading to drastic changes in environmental selection pressure on breeding materials.

This is compounded by low heritability of yield under drought making the breeding process complicated and slow (Kirigwi *et al.*, 2004; Pakniyat and Tavakol, 2007). A third approach is to improve drought tolerance in high-yielding genotypes through incorporation of morphological and physiological mechanisms of tolerance. However, this is complicated due to lack of understanding of the physiological and genetic basis of adaptation in drought condition. In contrast, improving the yield potential of an already resistant material may be a more promising approach, provided there is enough genetic variation within such a material (Bidinger *et al.*, 1995). Another approach involves the simultaneous selection for yield and stability in non-stress and in managed stress conditions to select drought-resistant genotype with high yield.

2.8.1 The screening process

Breeding for drought tolerance requires an efficient screening technique, which is fast and capable of evaluating plant performance at the critical developmental stages and capable of screening a large population using only a small samples of plant material (Johnson, 1980). Drought tolerance is the interactive result of different morphological, physiological and biochemical traits and thus, different components could be used as selection criteria for screening (Parry *et al.*, 2005). A combination of different traits of direct importance (leaf rolling, leaf length, leaf angle, root morphology, etc), rather than a single trait, should be used as selection criteria (Mitra, 2001). Field assessment of cassava for relevant physiological traits has been suggested as the most effective way of evaluating drought tolerance (Okogbenin *et al.*, 2013). The main requirement for such field trials is to have appropriate water stress conditions in semi arid regions that can discriminate against the test genotypes. The essence of carrying out phenotyping is to obtain data for the traits that are closely associated with yield for the detection of quantitative trait loci (QTL) (Reynolds and

Trethowan, 2007). Comprehensive and careful field evaluation of mapping populations is sometimes needed in order to provide reliable information on the effectiveness of QTLs, candidate genes and transgenes. Field experiments designed to evaluate genetic differences in drought tolerance are faced with contrasting requirements (Okogbenin *et al.*, 2011). There is a need for a high precision because differences may be small and detailed physiological measurements such as stomatal conductance (Okogbenin *et al.*, 2013) are difficult when large numbers of genotypes are involved. Agronomic practices such as application of nutrients and the control of weeds/pests should be carried out precisely and uniformly to minimize within-replication variability (Edmeades *et al.*, 2004).

2.8.2 Molecular breeding for drought tolerance

The emergence of molecular techniques has contributed significantly to germplasm utilization and enhancement through innovative approaches to plant breeding under stress conditions. Molecular tools such as high-throughput DNA marker genotyping can be used for diversity analysis, genetic linkage mapping, and marker-assisted selection of crops for improved tolerance to drought (Lee, 1995; Mohan *et al.*, 1997; Nguyen *et al.*, 1997). Approaches such as identification and genetic mapping of QTL for specific components are used to dissect the genetic basis of various traits associated with crop performance, including drought tolerance (Ribaut *et al.*, 1997; Crasta *et al.*, 1999).

The application of marker-assisted selection in developing drought resistant genotypes has been useful in developing drought resistant varieties of cassava (Ribaut *et al.*, 1997; Turyagyenda *et al.*, 2013).

2.9 Constraints in breeding for drought tolerance

Advancement in the effectiveness of selection for drought-tolerant cultivars directly for high and stable yield under reduced moisture conditions is slow based on the low heritability of yield as well as the large genotype x environment interaction (Trethowan *et al.*, 2002). This slow progress could also be attributable to lack of efforts through multidisciplinary approach to understand the integrated plant responses to drought and complex genetic control of different mechanisms of drought tolerance. This is compounded by incomplete knowledge about reliable attributes such as indices of drought tolerant, selection criteria and effect of environment on drought-related traits (Paroda, 1986). Attempts to use water-use efficiency to develop more productive crops for drought prone environments have resulted in limited success since most plants maximize water-use efficiency through reduction in transpiration (Parry *et al.*, 2005; Blum, 2005; Blum, 2009). Dry matter production is strongly associated with total transpiration, therefore any reduction in transpiration results in reduced crop growth rate (Udayakumar *et al.*, 1998). Adaptations such as leaf rolling and stomatal closure ensure moisture conservation under water stress conditions but also have negative influence on crop productivity. Leaf rolling reduces light interception whereas stomatal closure prevents entry of carbon dioxide into the leaves, reducing yield (Morrison *et al.*, 2008). Several studies have indicated rapid success through molecular plant breeding using physiological traits to complement conventional breeding for yield (Araus, 2003; Condon *et al.*, 2002; Richards *et al.*, 2002; Reynolds *et al.*, 2009).

2.10 Improving cassava adaptation to drought

Cassava has a huge potential to produce well under marginal ecologies where other crops will fail making it an ideal crop for ensuring food security in the semi-arid and arid tropics (Okogbenin *et al.*, 2013). Wide genetic variability observed in the cassava gene pool offers an opportunity for improved selection gain (Okogbenin *et al.,* 2003). However, a better understanding concerning the genetic variability underlining the mechanisms that account for cassava's improved performance under drought conditions is needed. The magnitude of the genetic variability with respect to mechanisms which range from dehydration avoidance, dehydration tolerance and those linked to optimum growth and metabolism will have to be determined to make rapid and efficient selection possible.

Many physiological traits are used in assessing crops for their response to drought (Bergantin *et al.,* 2004). Physiological and morphological parameters are mostly used as secondary traits where direct selection for yield is difficult under drought stress (Reynolds and Trethowan, 2007). Such traits should be highly and positively associated with yield performance under drought. Okogbenin *et al.* (2013) suggest a number of traits for consideration in drought tolerance in cassava at various stages of the crop's phenology. These include pre-harvest traits such as number of branching levels, length of primary and secondary stems, leaf retention, height of leafless stem, length and width of fully expanded leaf lobes, stomatal conductance and ABA content of leaves and stems, as well as pests and diseases incidence. At harvest, above-ground biomass, storage root fresh weight, number of storage roots, stem diameter, storage root dry matter and storage root starch content are important. For these traits to be useful in an evaluation scheme, they must be heritable and stable across several environments.

Crop performance is affected by genotype x environment interaction which sometimes makes yield potential difficult to determine (Aina *et al.*, 2007b; Egesi *et al.*, 2007b). Several studies in other crops (rice, wheat, maize, chickpea, sugar beet, sorghum, potato) suggest that traits such as root length and carbon isotope differences could be very useful in evaluating genotypes for drought tolerance (Condon *et al.*, 2004; de Souza *et al.*, 2005; Monti *et al.*, 2006; El-Sharkawy, 2007;Wasson *et al.*, 2012). The genetic improvement of crops involves the exploitation of genetic variability in the germplasm (Carvalho and Schaal, 2001; Ojuederie *et al.*, 2014). The level of progress made depends on the magnitude of the diversity that exists within the population (Elias *et al.*, 2001; Montero-Rojas *et al.*, 2011). Genetic diversity can be enhanced through introduction from other sources (Dixon *et al.*, 1992) or through introgression from wild relatives (Agueguia, 1995; Akinbo, 2008).

CHAPTER THREE

3.0 FARMERS' PERCEPTION OF DROUGHT IN CASSAVA CULTIVATION, CONSTRAINTS AND MITIGATION STRATEGIES IN NORTHERN GHANA

3.1 Introduction

Cassava is an important food security crop in the northern parts of Ghana where it serves as a major staple for many households. The crop is mainly cultivated by small scale farmers who plant the cassava in May and harvest in November or December. Farms that are not harvested during this period face the risk of bush fires or destruction by cattle (Adjebeng-Danquah *et al.,* 2012). For this reason, farmers cultivate cassava either as a border crop around yam or as the sole crop for household consumption. Some farmers who have farmlands at distant places cultivate cassava on a large scale to supply to processors. Lack of improved varieties coupled with other constraints has limited the use of cassava as a crop for cultivation on large scale. Farmers have resorted to planting of other crops, due to demand and price, thereby resulting in the reduction in the area for cassava production (Sam and Dapaah, 2009).

Among the major constraints affecting crop production, drought and unpredictable rainfall rank very high. Drought severely impairs plant growth, development and plant production more than any other environmental factor (Shao *et al.,* 2009). Drought in cassava production is one of the major challenges facing farmers in savanna zones of the world (Okogbenin *et al.,* 2003; El-Sharkawy, 2007) and is a serious challenge in the northern region. However, very little work has been done to target cassava's response to drought stress in the region.

To date, only three improved cassava varieties have been specifically released for cultivation in the northern part of Ghana. Most of the high yielding released varieties of cassava were bred for processing into different intermediary forms before they are used. These cultivars often do not meet most farmers' immediate needs (i.e. poundable into fufu), so adoption of these varieties has been low resulting in the continual cultivation of local landraces (Sam and Dapaah, 2009). Low adoption rate of improved crop varieties is attributed to failure of the improved varieties to meet farmers' requirements (Annor-Frempong, 1994). On the other hand, the landraces which are best suited for local dishes (e.g. fufu) are mostly low yielding and highly susceptible to cassava diseases and pests. Improving productivity of the farmer-preferred landraces and acceptability of new cultivars is one of the ways to help farmers and other stakeholders to get the best from the national cassava programme (Manu-Aduening *et al.*, 2014).

In order to devise a new and effective breeding programme, important information about farmers' perceptions of production constraints, their preferences and their criteria for selecting new varieties need to be gathered (Joshi and Bauer, 2006; Efisue *et al.,* 2008). Over the years, farm households have developed different mitigation strategies to address drought. Involving farmers in the identification of their constraints and mitigation strategies has resulted in a much faster breeding process and success rate than strict on-station breeding (Manu-Aduening *et al.*, 2014). For instance, a number of crop varieties (maize, Odendo *et al.*, 2002; cassava, Manu-Aduening *et al.*, 2005; and grain legumes, Gupta, 1985) have been developed through the involvement of farmers and other end users in developing the research agenda based on the identification of the constraints and preferences.

Using semi-structured questionnaires, Asante *et al.* (2013) assessed farmers' preference for rice varietal traits and the implications for research and policy in Ghana. They obtained useful information from the farmers that could enable breeders to develop improved cultivars to boost local production and cut down annual total annual rice imports. Kapinga *et al.* (1997) also indicated that involving farmers accelerates dissemination and adoption of improved technologies. The present study attempts to investigate farmers' perception of drought, identify production constraints and mitigation strategies in the cassava production zones of northern Ghana.

The main objective of the study was to identify farmers' constraints in cassava cultivation with particular emphasis on drought.

The specific objectives were to:

1. Study the cassava production system in the study area,
2. Identify the constraints faced by cassava farmers in the study area,
3. Assess farmers' perception of drought in cassava production and mitigation strategies, and
4. Identify farmers' preferences in new cassava varieties.

3.2 Materials and Methods

3.2.1 The study area

The study was carried out in the Northern region which is located in the Guinea Savannah Agro-ecological zone. This agroecology covers almost two-thirds of the country with an area of 147,900 km^2 (EPA, 2003). The area is characterised by a monomodal rainfall which is erratic and interspersed with intermittent drought which can sometimes last up to one month. Rainfall, temperature and soils differ significantly from those in the southern part of the country (EPA, 2003). The rainy season is also followed by a long dry season of between 5-6 months. Farmers in this area plant cassava at the onset of the first rains which normally start in April and harvest in December and dry the roots for storage. Three cassava producing districts in the Northern region namely, Tolon District (capital, Nyankpala), West Gonja (capital, Damongo) and Salaga district (capital, Salaga) were chosen for the study. Four communities within each of the three cassava producing districts in the region were chosen. These districts are well known cassava production districts in the northern region. The choice of different communities was to capture differences resulting from disparity in cropping systems and cultural practices in cassava production.

3.2.2 Sampling Technique

Information on the major cassava producing areas in Northern region, obtained from the directorates of Ministry of Food and Agriculture (MoFA), was useful in the identification of key cassava producing districts and communities. This guided the development of a sample framework for the survey. The basic focus for the survey was the major cassava producing districts in Northern region.

The sampling process combined purposive and random procedures in three stages. At the first stage, three cassava producing districts from Northern region were purposively selected. These districts were selected based on the area under cassava cultivation. Within each district, the list of cassava producing communities was obtained from which households were randomly selected. Within each household, farmers were then interviewed to obtain information about cassava cultivation practices. Overall the study involved 120 cassava producing households drawn from 12 communities selected from three districts (Table 3.1).

Table 3.1 List of districts and number of cassava producing households selected

Districts	**Communities**				**Number of households**
Tolon (Tolon) (9.4310° N, 1.0649° W)	Cheyohi	Nafarin	Tingoli	Nyankpala	40
East Gonja (Salaga) (8.5509° N, 0.5183° W)	Gbung	Gidanturu	Sisipe	Mariche	40
West Gonja (Damongo) (9.0840° N, 1.8180° W)	Linghintho	Alhassan Kuraa	Mbarupe	Damongo	40
Total					**120**

3.2.3 Data Collection

The core data for the study was obtained from a cross section of cassava producing households. Data was collected using formal interviews with heads of cassava producing households. Information describing household and farm level characteristics was also captured. Other information collected was used to describe household perception about drought and pests as well as constraints and mitigation strategies.

3.2.4 Data Analysis

The study combined both qualitative and quantitative analytical tools. The data was analysed using Statistical Package for Social Scientists (SPSS, 2008). Analysis of the data involved the use of descriptive statistics including frequencies and central tendencies to describe the socioeconomic characteristics of the communities and the households. The Kendall's Coefficient of Concordance (W) was used to test the level of agreement among the ranked constraints and preferences. Kendell's Coefficient of Concordance is a measure of the extent of agreement or disagreement among rankings. The value of 'W' is positive and ranges from a value of one means there is a perfect agreement whilst zero means there is maximum disagreement.

3.3 Results

3.3.1 Demographic characteristics of household heads

The average age of a cassava producing household head in Northern region is 41 years. All the household heads interviewed were males. Majority (93.3%) of the household heads are married whilst single and widowed household heads form 6% and 1%, respectively, of the total. West Gonja and Tolon districts recorded a relatively higher percentage of married household heads (Table 3.2). Majority (88%) of the household heads in Northern region had no basic education. This was consistent across the three sampled districts. West Gonja had the highest level of illiteracy among the sampled districts (Table 3.2). Education enhances technology uptake and decision making processes. Uneducated farmers are not able to read instruction manuals or labels on seed, agrochemicals and fertilizer. However, there are some household heads that have attained primary and secondary education. A typical cassava producing household in Northern region consists of 12 members (Table 3.2). Household members serve as a source of family labour and the economically active members also contribute significantly towards household income. Economically inactive household members have impact on food demand thus increasing the household expenditures. The high expenditures may impact negatively on technology uptake as well as improvement in the livelihood of the household members with respect to education. Islamic religion is the most dominant in the Northern region followed by Christianity. Religion has the potential of impacting negatively on participation in agricultural development projects and adoption of technologies. The average years of farming experience for a typical cassava producer was 26 years. Based on the district disaggregation, farmers in West Gonja are relatively more experienced than those in the other two districts (Table 3.2). Most (98%) of the respondents were natives.

Table 3.2 Demographic characteristics of households

Characteristics	**Districts N = 120**			**Average**
	Tolon	**Salaga**	**West Gonja**	
Age (Years)	42.00	40.00	42.00	41.00
Gender (%)				
• Male	100.00	100.00	100.00	100.00
• Female	0.00	0.00	0.00	0.00
Marital Status of HH head (%)				
• Married	97.50	82.50	100.00	93.30
• Single	2.50	15.00	0.00	5.80
• widowed	0.00	2.50	0.00	0.80
• Separated	0.00	0.00	0.00	0.00
Level of Education (%)				
• None	85.00	77.50	100.00	87.50
• Primary	2.50	10.00	0.00	4.20
• JHS	5.00	2.50	0.00	2.50
• SHS	5.00	10.00	0.00	5.00
• Certificate Diploma	2.50	0.00	0.00	0.80
• Degree	0.00	0.00	0.00	0.00
• Master’s Degree	0.00	0.00	0.00	0.00
Household Size (Number)	13	9	14	12
Religion Status (%)				
• Islamic	85.00	97.50	100.00	94.20
• Christian	15.00	0.00	0.00	5.00
• Traditional	0.00	2.50	0.00	0.80
Years of Farming experience	24	26	30	26
Nativity Status (%)				
• Non-native	0.00	7.50	0.00	2.50
• Native	100.00	92.50	100.00	97.50

3.3.2 Characterization of the cassava production system

3.3.2.1 Farm characteristics of cassava producers

On the average, two members of the household assist the head of the household with farming activities. The results indicated that the average total landholding of a household head in the districts studied is 2.94 hectares (ha) with 1.05 ha under cassava cultivation. Based on district disaggregation, West Gonja controls both the largest landholdings and largest area under cassava cultivation (Table 3.3a). Cassava production is more dominant in terms of area under production in West Gonja relative to the other two districts. Average area under improved cassava varieties is 0.4 ha. About 0.67 ha of land is allocated for cultivation of improved cassava varieties by farmers in Salaga (Table 3.3a). A large proportion (97.5%) of the farmers was found to cultivate local unimproved cassava varieties. Only 5% of the farmers in the Tolon district cultivate improved varieties whilst less than 3% in Salaga cultivate improved varieties and none of the farmers interviewed in the West Gonja. Most of the farmers (97%) rely on their own farms for planting material. Some of the farmers (32%) in Tolon district also depend on the research institutions for planting materials. Most (85%) of the farmers indicated that they were satisfied with their local planting materials. About 96% of the sampled farmers stated that planting materials are readily available from sources such as local farmers, research stations and distant farmers.

Table 3.3a Characteristics of cassava producers

Characteristics	Districts N=120			Average
	Tolon	Salaga	West Gonja	
Family Members that assist on the farm	3.00	2.00	1.00	2.00
Total Landholding (hectares)	2.24	3.20	3.40	2.94
Area under cassava cultivation (hectares)	0.42	0.67	2.07	1.06
Area under improved cassava variety (hectares)	0.35	0.67	0.23	0.40
Cultivation of improve variety (%)				
• Yes	5.00	2.50	0.00	2.50
• No	95.00	97.50	100.00	97.50
Source of planting material (%)				
• Own farm	95.00	94.70	100.00	96.60
• Male neighbour	2.50	0.00	0.00	0.80
• Female neighbour	0.00	0.00	0.00	0.00
• Relatives	0.00	0.00	0.00	0.00
• Farmer group	0.00	2.60	0.00	0.80
• Research station	2.50	2.60	0.00	1.70
• NGO	0.00	0.00	0.00	0.00
• MoFA	0.00	0.00	0.00	0.00
• Other	0.00	0.00	0.00	0.00
Readily available of planting material (%)				
• No	2.50	10.00	0.00	4.20
• Yes	97.50	90.00	100.00	95.80
Source of new material (%)				
• Local farmers	55.00	87.50	100.00	80.80
• Farmers far away	10.00	0.00	0.00	3.30
• Specialized multipliers	2.50	5.00	0.00	2.50
• Extension agents	0.00	0.00	0.00	0.00
• Research Stations	32.50	0.00	0.00	10.80
• Markets	0.00	2.50	0.00	0.80
• MoFA	0.00	5.00	0.00	1.70
Satisfaction with quality of planting material at planting time (%)				
• Satisfied	65.00	90.00	100.00	85.00
• Somewhat satisfied	25.00	0.00	0.00	8.30
• Not satisfied	10.00	10.00	0.00	6.70

As far as decision-making processes of households, cassava farms are owned mostly by men. Decisions on amount of cassava to grow, variety to grow, sale, volume of sale, use of cassava proceeds and sharing of revenue were mainly made by males (Table 3.3b).

Table 3.3b Farm characteristics of cassava producers

Characteristics	**Districts N=120**			**Average**
	Tolon	**Salaga**	**West Gonja**	
Knowledge of a specialized multiplier (%)				
• No	60.00	77.50	100.00	79.20
• Yes	40.00	22.50	0.00	20.80
Ownership of cassava farm (%)				
• Man	100.00	100.00	100.00	100.00
• Woman	0.00	0.00	0.00	0.00
• Children	0.00	0.00	0.00	0.00
Decision on amount of cassava to grow (%)				
• Man	100.00	100.00	100.00	100.00
• Woman	0.00	0.00	0.00	0.00
• Children	0.00	0.00	0.00	0.00
Decision on the variety to grow (%)				
• Man	100.00	100.00	100.00	100.00
• Woman	0.00	0.00	0.00	0.00
• Children	0.00	0.00	0.00	0.00
Decision on sale (%)				
• Man	52.50	100.00	100.00	84.20
• Woman	47.50	0.00	0.00	15.80
• Children	0.00	0.00	0.00	0.00
Decision on volume of sale (%)				
• Man	80.00	100.00	100.00	93.30
• Woman	20.00	0.00	0.00	6.70
• Children	0.00	0.00	0.00	0.00
Decision on the use of cassava proceeds (%)				
• Man	100.00	77.50	100.00	92.50
• Woman	0.00	22.50	0.00	7.50
• Children	0.00	0.00	0.00	0.00
Decision on sharing of revenue (%)				
• Man	100.00	97.50	100.00	99.20
• Woman	0.00	2.50	0.00	0.80
• Children	0.00	0.00	0.00	0.00

Cassava was found to be cultivated as an upland crop (Table 3.3c). The lowland ecology usually retains water which is not suitable for root and tuber crops. Selection of cassava varieties by farmers in Northern region depends on the poundability of the crop. About 67% of the sampled farmers prefer cassava varieties that are poundable since they are in high demand on the market. However, farmers in West Gonja do not prefer cassava that is poundable. This may be due to the end use of the crop and the preference of the customers. The majority (74.2%) of the farm households in Northern region plant and harvest their cassava in April and December respectively (Table 3.3c). However, variation exists in the time of harvesting across the three districts. In West Gonja, planting of cassava usually takes place in March. Fertilizer is not commonly used for cassava production among farmers in Northern region. Cassava production is largely rain-fed but a few farmers use irrigation. According to the majority (73%) of the farmers, planting material can last for one year but 17% believe that planting material can last for over five years.

Table 3.3c Cassava production system

Characteristics	**Districts N = 120**			**Average**
	Tolon	**Salaga**	**West Gonja**	
Ecology for cassava cultivation				
• Upland	100.00	100.00	100.00	100.00
• Lowland	0.00	0.00	0.00	0.00
Selection criterion of cassava variety				
• Unpoundable	0.00	32.50	100.00	33.00
• Poundable	100.00	67.50	0.00	67.00
Month of planting cassava (%)				
• February	2.50	2.50	10.00	5.00
• March	12.50	17.50	37.50	22.50
• April	65.00	72.50	27.50	55.00
• May	20.00	2.50	15.00	12.50
• June	0.00	2.50	10.00	4.20
• July	0.00	2.50	0.00	0.80
Month of harvesting cassava (%)				
• April	0.00	5.00	0.00	1.70
• September	0.00	0.00	2.50	0.80
• October	0.00	0.00	17.50	5.80
• November	2.50	12.50	37.50	17.50
• December	97.50	82.50	42.50	74.20
Do you apply fertilizer (%)				
• No	100.00	100.00	100.00	100.00
• Yes	0.00	0.00	0.00	0.00
Do you use irrigation (%)				
• No	95.00	97.50	100.00	97.50
• Yes	5.00	2.50	0.00	2.50
Length of storage of planting materials (%)				
• Less than 1 year	27.50	0.00	100.00	9.20
• 1 year	35.00	85.00	0.00	73.30
• 2-4 years	0.00	2.50	0.00	0.80
• Over 5 years	37.50	12.50	0.00	16.70

3.3.3 Constraints in cassava production

Based on the rankings of the constraints, lack of credit was the major challenge facing most cassava farmers in the study area (Table 3.4). Drought was ranked as the second most constraining factor followed by lack of improved varieties, diseases and pests, weed infestation, difficulty in obtaining planting material, high labour cost and floods in that order. Access to land was the least constraining factor in cassava production. The Kendall's value of 0.296 indicated that there is 30% agreement among the respondents in terms of ranking of the constraints. The relatively lower value of agreement can be explained by the differences in the ranking of the constraints by the farmers.

Table 3.4 Ranking of importance of constraints in cassava production

Constraints	**Mean rank***
Lack of credit	2.56
Drought/inadequate rainfall	3.20
Lack of improved varieties	5.31
Diseases and Pests	5.72
Weed infestation	6.21
Difficulty in obtaining plant material	6.34
High labour cost	6.59
Flood	6.77
Low soil fertility	7.02
Low market price	7.42
Access to land	8.86
Number of farmers	80
Kendall's W[a]	0.296
Chi-square	236.778
Df.	10
Assymp. Sig.	0.000

*** = Least mean rank indicates most important constraint**

3.3.3.1 Perception of drought in cassava production

Fifty-five per cent (55%) of the sampled farmers agreed that drought is a major challenge in cassava cultivation while 24% strongly agree with the statement (Table 3.5). All the farmers in West Gonja agreed that drought is a major challenge in cassava cultivation. Most farmers have experienced changes in the pattern of rainfall (97.5%) and drought (95.8%) over the past ten years (Table 3.5). Generally, it was agreed by 71.4% of the farmers that drought impacts negatively on cassava production. However, 80% of the farmers in Salaga district disagreed with this observation. More than half of them (57.5%) were either indifferent or disagreed that drought can impact negatively on yield of cassava probably due to the widely held view that cassava is drought tolerant.

Severity of drought was believed to be increasing by 38% of the sampled farmers (Table 3.5). However, a large number of farmers (92.5%) in the Salaga district believed the severity of drought was decreasing. It is possible that the varieties of cassava cultivated in this district are drought tolerant thus drought has impacted the yield and volume of production less.

Table 3.5 Perception of drought in cassava production

Characteristics	**Districts N = 120**			**Average**
	Tolon	**Salaga**	**West Gonja**	
Perception of drought as a major challenge in cassava cultivation (%)				
• Strongly agree	40.00	32.50	0.00	24.20
• Agree	55.00	10.00	100.00	55.00
• Indifferent	0.00	7.50	0.00	2.50
• Disagree	2.50	35.00	0.00	12.50
• Strongly disagree	2.50	15.00	0.00	5.80
Change in the pattern of rainfall over the past ten years (%)				
• No	0.00	7.50	0.00	2.50
• Yes	100.00	92.50	100.00	97.50
Experience of drought in the past ten years (%)				
• No	7.50	5.00	0.00	4.20
• Yes	92.50	95.00	100.00	95.80
Has drought affected cassava production (%)				
• No	5.10	80.00	0.00	28.60
• Yes	94.90	20.00	100.00	71.40
Severity of drought (%)				
• Increasing	65.00	5.00	45.00	38.30
• Decreasing	12.50	92.50	2.50	35.80
• Unchanged	22.50	2.50	52.50	25.80

3.3.3.2 Mitigation strategies for drought in cassava production

Different strategies are employed by the different farmers in the studied districts (Table 3.6). About 41% of the total number of farmers interviewed employ early planting as a strategy to mitigate the effect of drought (Table 3.6). Some farmers (19.17%) also use their own varieties which they believe are drought tolerant. Afforestation (9.17%), delayed weed control (9.17%), mulching (8.33%), improving soil fertility (8.33%) were the other strategies used by farmers to combat drought in the Northern region.

Table 3.6 Mitigation strategies against drought

Mitigation measures	**Salaga**		**Tolon**		**West Gonja**		**Total**	
	No. of farmers	**%**	**No. of farmers**	**%**	**No. of farmers**	**%**	**No. of farmers**	**%**
Irrigation	2	5.00	2	5.00	2	5.00	6	5.00
Improving fertility	6	15.00	2	5.00	2	5.00	10	8.33
Delayed weed control	5	12.50	5	12.50	1	2.50	11	9.17
Mulching/ loosening soil	3	7.50	6	15.00	1	2.50	10	8.33
Improved / drought tolerant variety	6	15.00	8	20.00	9	22.50	23	19.17
Early planting	13	32.50	14	35.00	22	55.00	49	40.83
Afforestation	5	12.50	2	5.00	4	10.00	11	9.17
TOTAL	**40**	**100.00**	**40**	**100.00**	**40**	**100.00**	**120**	**100.00**

3.3.4 Farmers preferences for improved cassava varieties

The factors that influenced the selection of cassava varieties in Northern region are presented in Table 3.7. The Kendall's Coefficient of Concordance 'W' was 0.203 and significant at 1% level indicating 20% agreement between the respondents in the ranking of the factors that influenced their choice of cassava varieties.

High yield after 12 months, earliness (usually six months), marketability and plant type were the four most important factors considered by the smallholder cassava farmers in the selection of the preferred cassava varieties in Northern region (Table 3.7). Easy access to planting material and resistance to pests and diseases were the least important factors in the cassava varietal selection process. Yield is one of the major factors that influence farmers' to adopt a particular crop variety. Most of these smallholder farmers are resource poor and will normally not commit their resources to a variety whose potential yield is uncertain. Yield is one of the desired attributes for new varieties of crops that are developed by research institutions. Earliness is also very important, especially in an area where drought is a major challenge to crop survival, however earliness comes with a yield penalty. Marketing is one of the major challenges of smallholder farmers in Ghana, especially where crops grown are not market oriented. Plant type in terms of the canopy formation is also an important factor in the selection of a cassava variety.

Table 3.7 Ranking of factors influencing selection of cassava varieties

Influential factors			**Mean rank***
High yield after 12 months			2.12
Earliness (Six month)			3.10
Easily marketable			3.60
Plant type			3.66
Easy access to planting material			3.86
Resistance to pest and diseases			4.66
Number of farmers	120	Df.	5
Kendall's W^a	0.203	Assymp. Sig.	0.000
Chi-square	122.08		

*** = Least mean rank indicates most important preference**

3.3.5 Pests and diseases infestation in cassava production

Most of the farmers (67%) had observed the infestation of pests and diseases on the farm (Table 3.8). In Tolon, 95% indicated that they had observed pests and disease infestation but

56.4% of the farmers in the Salaga district had not observed any pests and diseases incidence. The extent of infestation was also found to be increasing according to the 55.3% of the farmers in Tolon whilst 97% of the farmers in the Salaga district responded that the incidence has been decreasing. In the West Gonja district only 12% of the farmers had observed increase in the pattern of pests and disease infestation whilst 48% had observed decrease in the pattern. Majority (86.2%) of the farmers indicated that they obtain information on pests and diseases control from their colleague local farmers. Only 8.8% of the farmers named research stations as their source of information of pests and diseases control.

Pest attacks typically occur at the flowering stage according to 31.6% of the farmers in Tolon, 11.8% in Salaga and 64% in West Gonja. However, in Salaga district attacks usually occur immediately after sprouting (41.2%). In the Tolon district, most of the pests, mainly goats and sheep, generally chew the leaves of the plants. Cassava mealy bugs also appear during the dry season causing the cassava plants to become bunchy at the growing points. Control of pests is by the adoption and use of good agricultural practices (35.6%) such as timely and regular weeding, clearing of bushes around the crop and other sanitary methods. Local control methods, such as the use of neem extract (41.1%), are commonly used by farmers in West Gonja (88%) to control pests (Table 3.8). On the average, a typical farmer travels a distance of 20.28 km to seek technical assistance on pest control.

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Table 3.8 Pests and diseases infestation in cassava production

Characteristics	Districts			Average
	Tolon	Salaga	West Gonja	
Observation of pest and disease infestation (%)				
• No	5.00	56.40	37.50	32.80
• Yes	95.00	43.60	62.50	67.20
Pattern of infestation (%)				
• Increasing	55.30	2.70	12.00	25.00
• Decreasing	23.70	97.30	48.00	57.00
• Unchanged	21.00	0.00	40.00	18.00
Source of information on pests and diseases control (%)				
• Local Farmer	59.30	100.00	100.00	86.20
• Farmers far away	14.80	0.00	0.00	5.00
• Research stations	25.90	0.00	0.00	8.80
Stage of pest attack (%)				
• Immediately after sprouting	15.80	41.20	4.00	18.00
• Vegetative stage	26.30	23.50	0.00	14.80
• Flowering stage	31.60	11.80	64.00	39.30
• Matured stage	26.30	23.50	32.00	27.90
Mode of attack (%)				
• Chew the leaves	42.40	50.00	68.00	53.10
• Lay eggs on the plant	57.60	50.00	32.00	46.20
Control Strategy (%)				
• Neem extract	22.90	0.00	88.00	41.10
• Insecticide	8.60	15.40	0.00	6.80
• Cultural practices	40.00	84.60	4.00	35.60
• Pest resistant varieties	17.10	0.00	4.00	9.60
• Chemical application	8.60	0.00	4.00	5.50
• Other	2.90	0.00	0.00	1.40
Distance to AEA (Km)	4.80	43.13	6.00	20.28

3.3.6 Post-production practices in cassava production

Post-production practices are an essential part of the cassava value chain. All (100) the farmers sampled in the various districts indicated that they engaged in some form of processing and processed their cassava in 2012 (Table 3.9).

Table 3.9 Post-production practices in cassava cultivation

Characteristics	**Districts N = 120**			**Average**
	Tolon	**Salaga**	**West Gonja**	
Do you process cassava (%)				
• No	0.00	0.00	0.00	0.00
• Yes	100.00	100.00	100.00	100.00
Did you process cassava in 2012 (%)				
• No	0.00	0.00	0.00	0.00
• Yes	100.00	100.00	100.00	100.00

3.3.7 Preference of processed cassava

Different forms of cassava were preferred for processing by the farmers in the Tolon district (Table 3.10). The Kendall's 'W' was found to be 0.510 and significant at 1% level indicating 51% agreement between the respondents in the ranking of the preferences of the various forms of processed cassava. The most preferred processed form of cassava in Tolon district was *kokonte* (powdered form of dried cassava chips) followed by *gari* and cassava dough in that order. Cassava chips were the least preferred product of cassava. In the case of the Salaga district, the most preferred processed form is *kokonte* (powdered form of dried cassava chips) followed by cassava dough and chips in that order. *Gari* was the least preferred product of cassava. Kendall's 'W' was 0.419 and significant at 1% level indicating that there is 42% agreement between the respondents in the ranking of the preferences of the various forms of processed cassava. The most preferred form of processed cassava in West Gonja district is *Kokonte* followed by cassava dough and *gari* in that order. Flour was the least preferred product of cassava. The Kendall's 'W' is found to be 0.726 and significant at 1% level indicating that there is 73% agreement between the respondents in the ranking of the preferences of the various forms of processed cassava.

Table 3.10 Farmers' preferences for processed cassava in the different districts

Cassava products	**Districts**		
	Tolon	**Salaga**	**West Gonja**
	Mean rank*	**Mean rank**	**Mean rank**
Kokonte	1.18	1.56	1.12
Gari	3.08	4.44	3.65
Cassava dough	3.18	2.83	2.08
Flour	3.30	3.10	4.31
Chips	4.28	3.07	3.85
Number of farmers	40	40	26
Kendall's W	0.510	0.419	0.726
Chi-square	81.524	68.644	75.477
Df.	4	4	4
Assymp. Sig.	0.000	0.000	0.000

*** = Least mean rank indicates most important preference**

3.3.8 Uses of cassava

The average production volume of cassava is 22 bags out of which 17 bags are sold. Quantity consumed and given out as gifts, on the average, are five bags and two bags, respectively. Production volume and sale were higher in the Salaga district relative to the other two districts. West Gonja recorded the lowest level of household consumption of cassava (Table 3.11).

Table 3.11 Cassava production and uses

Characteristics	**Districts N = 120**			
	Tolon	**Salaga**	**West Gonja**	**Average**
Quantity of cassava produced (bags)	11.74	14.85	12.00	22.10
Quantity of cassava consumed (bags)	5.99	5.31	1.40	5.44
Quantity of cassava sold (bags)	4.20	10.44	5.90	17.16
Quantity of cassava gift (bags)	1.36	2.13	0.50	1.55

3.3.9 Market information and decisions on cassava production

Producers of cassava in Northern region relied mostly on other farmers, local markets and radio in that order of preference for information on market price of cassava. Other farmers were the dominant source of information on market price for producers in Salaga and West Gonja. Producers in Tolon depend largely on the local market for information on agricultural prices (Table 3.12a). Majority (66%) of the farmers preferred to sell their produce at home. Though community markets are the most preferred market for the majority (67%) of farmers for the sale of cassava in Northern region, some prefer the big town markets. Big markets located in townships were the second most preferred market for producers in the Salaga district. For farmers in Tolon district, neighbouring and big town markets are also key market outlets (Table 3.12a). In terms of market contact, farmers themselves served as the method of market contact for majority (78%) of cassava producers.

Table 3.12a Market information and decision on cassava production

Characteristics	**Districts**			**Average**
	Tolon	**Salaga**	**West Gonja**	
Main source of information for market price (%)				
• Radio	2.50	5.00	0.00	2.50
• Other farmer	35.00	62.50	100.00	65.80
• Local market	62.50	30.00	0.00	30.80
• Other	0.00	2.50	0.00	0.80
Marketing outlet for sale of produce mostly (%)				
• At home	15.00	82.50	100.00	65.80
• Neighbouring market	67.50	15.00	0.00	27.50
• Big market in town	17.50	2.50	0.00	6.70
Preferred market outlet for cassava disposal (%)				
• `home	40.00	60.00	100.00	66.70
• Neighbouring market	37.50	0.00	0.00	12.50
• Big market in town	15.00	40.00	0.00	18.30
• NA	7.50	0.00	0.00	2.50
Method of market contact (%)				
• By myself	90.00	42.50	100.00	77.50
• Neighbour	5.00	30.00	0.00	11.70
• Other farmers	5.00	27.50	0.00	10.80

Traders (100%) were the most preferred choice for sale of cassava across all the three districts in Northern region. Bicycle (42%) was the main mode of transporting produce to the market. The use of motor tricycles (87%) was also observed for transporting produce to the market especially in Tolon district. Farmers (52.5%) in Salaga district mostly prefer car/truck for carting cassava to the market. Cassava was usually sold in December at a price of GH₵42 per bag (100kg). Average distance covered by a farmer across districts was 2.75 km to the nearest market. Farmers in the Tolon district usually travel 13.77 km to access the nearest market (Table 3.12b).

Table 3.12b Marketing of cassava products in the different districts

Characteristics	**Districts N = 120**			**Average**
	Tolon	**Salaga**	**West Gonja**	
Main buyer of cassava (%)				
• Traders	100.00	100.00	100.00	100.00
• Established agents	0.00	0.00	0.00	0.00
• Marketing cooperatives	0.00	0.00	0.00	0.00
• Company	0.00	0.00	0.00	0.00
• Government	0.00	0.00	0.00	0.00
Mode of transportation (%)				
• Walking	7.70	17.50	0.00	8.40
• Bicycle	5.10	22.50	97.50	42.00
• Motor bike	0.00	5.00	2.50	2.50
• Bus/Small van	0.00	2.50	0.00	0.80
• Car/truck	0.00	52.50	0.00	17.60
• Motor tricycle	87.20	0.00	0.00	28.60
Preferred month of cassava sale (%)				
• February	7.90	18.40	0.00	8.60
• March	10.50	10.50	0.00	6.90
• April	0.00	5.30	0.00	1.70
• May	5.30	0.00	0.00	1.70
• June	39.50	0.00	0.00	12.90
• July	0.00	57.90	0.00	19.00
• October	0.00	0.00	5.00	1.70
• November	7.90	2.60	25.00	12.10
• December	28.90	5.30	70.00	35.30
Price of Cassava/Bag (GH₵)	33.00	26.00	67.75	42.00
Distance to nearest market (Km)	13.77	0.16	4.00	2.75

3.4 Discussion

The study found that farmers in the selected districts were relatively young with an average age of 41 years. This is because farming is a major occupation of the area and people are exposed to it very early in their lives. This suggests that farmers can work productively for the next two (2) decades, hence, with the right investment, the future of cassava production in Northern Ghana looks very positive. All the household heads interviewed were males which is a common practice in the northern part of Ghana, where women only become household heads in the absence of their husbands. Majority of the household heads were married. The importance attached to marriage makes it common for girls to be betrothed for marriage at a very young age.

Contrary to perception that cassava is only a “border crop” in the Northern Region, the findings of this study indicated that, out of the average total landholding of a household head in the districts studied (2.94 ha), up to 1.05 ha of it is put under cassava cultivation which means that cassava is considered as a major crop among the farmers interviewed. Cassava production was more dominant in West Gonja relative to the other two districts in terms of area under production. This is possibly due to the fact that its ecology is located within the Guinea Savanna and the Forest Transition Zones (EPA, 2003) which is good for cassava production. Majority (97.5%) of the farmers cultivated local unimproved cassava varieties possibly due to the fact that only three improved cassava varieties have been released for the Guinea Savanna ecology since 2003 (Sam and Dapaah, 2009). These varieties may either be out of reach to these farmers or they failed to meet their preferences (Manu-Aduening *et al.*, 2006). Although improved crop varieties may be high yielding, they may not be attractive to farmers unless they possess some crop-specific traits that farmers consider important (Asrat *et al.*, 2009). Decisions on cassava cultivation, sale and uses rest mostly on the household heads who happen to be males most of the time. This implies that acceptability of the crop by males will boost its production in the region. Experienced farmers who have participated in several agricultural development projects normally serve as nodal points for good agricultural practices. This has implications for cassava technology transfer.

In terms of constraints, the farmers ranked lack of credit as the number one constraint facing cassava production. The long duration nature of the crop coupled with its scale of production in the region makes it unattractive as a venture. Drought was ranked as the second most constraining factor facing cassava production among majority of the farmers in the districts. This is typical of savanna zones of the world that experience terminal and intermittent drought during most parts of the year (Okogbenin *et al.*, 2003). Though cassava has been widely considered as a drought tolerant crop, over 70% of the farmers agreed that drought was a major challenge in cassava cultivation. Most of the farmers in the West Gonja district had experienced changes in the rainfall pattern over the years. However, most of the farmers in the Salaga district did not agree that drought can impact negatively on yield of cassava. This is because, unlike other crops, cassava has the ability to give appreciable yields even in marginal ecologies, therefore total crop failure due to drought is not experienced by most farmers (El-Sharkawy, 2007). But up to 80% yield loss is possible in cassava depending on the time of the drought (Aina *et al.*, 2009).

The perception of negative effect of drought was found to vary with districts. Salaga and West Gonja districts which lie in the Guinea Savanna and Forest Transition Belt have vegetation similar to the forest zones but experience monomodal rainfall pattern and high temperatures (EPA, 2003). Some common mitigation strategies employed by the farmers include early planting, and also the cultivation of improved varieties. Association of farmers with non-governmental organizations has also exposed them to interventions such as afforestation and reduced deforestation (Martey *et al.*, 2014).

Lack of improved varieties and diseases and pests infestation were also considered as some of the major constraints faced by the farmers. This agrees with earlier reports that most farmer-preferred varieties are prone to pests and disease especially cassava mosaic disease (Manu-Aduening *et al.*, 2006). Most of the times improved varieties failed to meet farmers' preferences leading to low adoption and even total rejection of such varieties. However Smale *et al*. (2001) indicated that farmers choose crop varieties based on attributes that can overcome their production constraints, meet their consumption preferences and market requirements. Farmers' adoption decisions are therefore not only driven by profit maximisation but rather on complex processes that are affected by several socio-economic and psychological variables (Traxler and Byerlee, 1993; Willock *et al.* 1999) as were found in this study.

Improved varieties are also out of reach of most farmers especially those who are located in faraway communities. Planting materials are also difficult to come by even in communities where they have been previously distributed. Difficulty in obtaining planting materials of improved varieties was also identified as one of the challenges due to poor distributing network and also the short storage period of planting materials of cassava. Access to land was the least constraining factor in cassava production due to the fact that most of the inhabitants are natives and relied so much on family members for land for cultivation. Parts of the Northern region are prone to floods particularly areas close to the White and Black Volta rivers that experience annual overflows whenever the Bagre Dam in Burkina Faso is opened.

Farmers' preferences for improved varieties were, in the order of importance, high yield (after 12 months), earliness (six months), marketability and plant type. Root yield and its characteristics have been the objective for cultivation of varieties by most farmers (Nweke *et al.*, 1994) in Africa. Most of these farmers are resource poor and will normally not commit their resources to a variety whose potential yield is uncertain. However, the preference for early maturing variety or high yielding one depends on the location and the prevailing environmental conditions (Annor-Frempong, 1994; Okogbenin *et al.*, 2003). Annor-Frempong (1994) indicated that one of the reasons for the rejection of cassava varieties by farmers is late-bulking. Farmers usually opt for early maturing cassava varieties in areas of uncertain rainfall particularly in savanna regions (Nweke *et al.*, 1994). Manu-Aduening *et al*. (2005) also found that farmers' criteria for accepting a cassava variety depended on production characteristics such as disease and pest resistance, high yielding, early maturity and adaptability to harsh environments.

Plant type has been a very important criterion for farmers in any cultivation system. Farmers mostly cultivate more than one crop on a piece of land and therefore choose varieties that are either non-branching or late branching to prevent the shading of other intercrops (Njukwe *et al.* 2013). The canopy formation usually prevents the growth of weeds which compete with plants for soil nutrients and cause yield reduction. Some farmers often choose early branching genotypes to control weeds. Leaf retention has been one of the most important plant traits to select when breeding for drought tolerance (Lenis *et al.*, 2006; El-Sharkawy, 2007).

Easy access to planting material and resistance to pests and diseases were the least important factors in the cassava varietal selection process by the farmers. This is because most farmers rely on their own planting materials or obtain some from family members. Though pests and diseases are common problems associated with cassava production in the Northern region

(Asante, 2010), most of the farmers were not familiar with pests and diseases in cassava unlike other crops like vegetables. This is contrary to the findings of Manu-Aduening *et al.* (2006) and Acheampong *et al.* (2013) who found pests and diseases resistance as one of the major considerations in the choice of cassava varieties.

Farmers also preferred to process their cassava into *kokonte* ahead of gari and cassava dough probably due to the ease of processing and storage of *kokonte* unlike the other two products. As observed by Acheampong *et al.* (2013), poor value chain and lack of storage facilities in Ghana cause farmers to delay harvesting as a storage method but this is not possible in northern Ghana due to the annual bush fires and destruction by cattle. Farmers take advantage of the dry season and dry all the harvested cassava for storage.

Majority of the farmers preferred to sell their produce at home due to high cost incurred in the transport to markets. However, the emergence of projects like Millennium Challenge Account (MCA), Northern Rural Growth Programme (NRGP), and AGRA Soil Health Project aim at improving the business skills of Farmer Based Organizations (FBOs) in the northern region (Martey *et al.*, 2014).

3.5 Conclusion

The present study sought to fill the gap of knowledge and also serve as foundation for future research. The study revealed that two members of the household assist with farming activities. An average total landholding of a household head in Northern region of Ghana is 2.94 ha with 1.06 ha under cassava cultivation. Local farmers, research stations and distant farmers are the main sources of new planting materials. Cassava is mostly cultivated in the upland ecology and planting material usually lasts for a year. In terms of the constraints facing cassava production, lack of credit was the major challenge facing most cassava farmers in the study area. Drought was the second major challenge whereas access to land was the least constraining factor in cassava production. Pests and diseases are also major problems for cassava producers.

Common mitigating strategies adopted by the majority of the farmers include early planting at the onset of the rains, use of drought resistant varieties, use of improved varieties, mulching, manuring and afforestation.

Factors that influenced the choice of preferred cassava varieties were high yield, early maturity, easy marketability and good plant type. The average production volume of cassava is 22 bags out of which 17 bags are sold. Producers of cassava rely mostly on other farmers, local market and radio in that order of preference for information on market price of cassava. Community market is the most preferred market outlet for the majority of farmers.

3.6 Implications for research

Breeding efforts should focus on development of high yielding cassava varieties through farmer-participatory selection that are drought tolerant, resistant to pests and diseases. Varieties developed in this way will be easily adopted and disseminated among farmers for improved cassava production in the northern parts of Ghana. More agricultural extension agents are needed to provide technical assistance for improved cultivation of cassava in the region. Additionally, research on climate smart agriculture to boost farming in the Guinea Savanna Agroecology which occupies about 30% of the entire land area in Ghana is needed. Credit facilities in the form of subsidized inputs should be provided for farmers through the farmer based organization systems.

CHAPTER FOUR

4.0 AGRONOMIC PERFORMANCE AND GENETIC DIVERSITY ASSESSMENT OF CASSAVA GENOTYPES IN THE GUINEA SAVANNA ECOLOGY OF GHANA

4.1 Introduction

Genetic diversity evaluation and further characterization of cassava (*Manihot esculenta* Crantz) germplasm is a useful strategy for its improvement (Elias *et al.*, 2001; Montero-Rojas *et al*, 2011). Genetic improvement of any crop including cassava depends on the existence of useful genetic variation within the germplasm for the trait of interest (Carvalho and Schaal, 2001; Ojuederie *et al.*, 2014). Knowledge of genetic diversity among the breeding materials can help ensure long term genetic gain (Messmer *et al.*, 1993). Broad genetic diversity is needed for genetic improvement and must be properly assembled and evaluated to enhance the chances for selecting best performing genotypes for any trait of interest (Savita, 2006). Aina *et al.* (2009) indicated that progress in cassava yield performance could be made by utilizing the vast genotypic variability present in different cassava genotypes for different traits under varying environmental conditions like drought.

Genetic diversity of cassava can be broadened through hybridisation with wild and related species (Agueguia, 1995; Akinbo, 2008) or through introductions from local or exotic varieties (Dixon *et al.*, 1992). Useful genes from wild relatives of cassava can be introgressed in a hybridisation programme to generate more variability, but the heterozygous nature of the crop makes this difficult. Genes for high protein content and pest resistance have been successfully introgressed from inter-specific hybrids of *Manihot esculenta* ssp *flabellifolia* into cultivated cassava (Akinbo, 2008). Germplasm collection from other centres of origin can also be used to broaden the genetic base for evaluation in the target environment. Local germplasm, particularly adapted landraces from farmers' fields, are valuable genetic resources for crop improvement (Aina *et al.*, 2009; Ojuederie *et al.*, 2014).

After collection, germplasm needs to be characterised to remove duplicate accessions and obtain a genetically distinct core representative sample for effective breeding. Characterisation can be done at both morphological and molecular levels. Morphological traits have been used to effectively characterise several crop genotypes, particularly in stressful environments (Carvalho, 2004; Dakogre, 2008; Asare *et al.*, 2011; Sathyanarayana *et al.*, 2012; Tewodros, 2013; Onaga *et al.*, 2013). Morphological evaluation provides very useful information for identification of genetic variation and correlation of agronomic traits (Nassar, 2005). Due to their fast and easy assessment, morphological traits are useful for preliminary evaluation and or assessing the extent of diversity (Asare *et al.*, 2011). However they are highly influenced by the environment (Al-Fares and Abu-Qaoud, 2012). Molecular markers are thus used to complement the information generated from morphological markers (Okogbenin *et al.*, 2008; Zhang *et al.*, 2008; Kawuki *et al.*, 2009; Asare *et al.*, 2011). Available molecular markers for assessing genetic diversity include random amplified polymorphic DNA (RAPD; Rimoldi *et al.*, 2010), amplified fragment length polymorphism (AFLP; Benesi *et al.*, 2010), allozymes (Ocampo *et al.*, 1992), simple sequence repeats (SSRs; Chavarriaga-Aguirre *et al.*, 1998), single nucleotide polymorphism markers (SNPs; Kizito *et al.*, 2005; Ferguson *et al.*, 2011) and diversity array technology markers (DArT; Xia *et al.* 2005). SSRs are highly variable and can be used to generate useful genetic information for genetic analysis of plants. SSRs are codominant in nature and are very useful for molecular characterisation of heterozygous crops like cassava (Chavarriaga-Aguirre *et al.*, 1998). SSRS have been successfully used to assess genetic diversity between cassava accessions and their wild relatives (Roa *et al.*, 2000; Asare *et al.*, 2011; Essuma *et al.*, 2012).

Agronomic improvement of cassava involves selecting elite genotypes under varying environmental conditions for the highest possible root yield (Ntawuruhunga and Dixon, 2010). However, it is more difficult to assess root yield than other phenotypically observable traits in large populations, especially in drought prone environments, due to its multigenic nature and high environmental influence (Akinwale *et al.*, 2010). Complex traits need to be characterised in the target environments and the overall variability partitioned into its heritable and non- heritable components. This provides breeders with useful information on the relative contributions of these components to overall crop performance (Kumar *et al.*, 1999) and suggests the methods to use in developing efficient selection schemes (Nyquist, 1991).

The objective of this study was to assess the genetic variability within a collection of local and exotic cassava genotypes.

The specific objectives were to:

1. Assess diversity among local and exotic cassava genotypes based on morphological traits and simple sequence repeat markers
2. Identify traits that account for genetic variability among the germplasm

4.2 Materials and Methods

4.2.1 Location of the experiment

The trial was conducted in the research field of the Savanna Agricultural Research Institute located at Nyankpala (9^{o}25’N, 0^{o}58’W) in the Guinea Savannah Agroecological Zone of Ghana. The Guinea Savannah Zone covers over one third of the entire land area of Ghana and is characterised by high temperature and low humidity during most parts of the year. The rainfall pattern is monomodal and erratic with an annual mean of 1100 mm which mostly begins in period between April - May and ends in October. The area is also characterised by a long dry season (4-6 months) which normally begins in November and lasts till April. Intermittent dry spells often lasting up to two weeks also occur during the growing season.

4.2.2. Germplasm used for the study

A total of 150 cassava genotypes were used for the study. These included 74 local genotypes collected from farmers' fields in the Northern Region (Guinea Savanna Agro Ecology), Brong-Ahafo and Ashanti regions (Forest Zones) of Ghana. Seventy-six exotic genotypes including drought tolerant populations were obtained from the CSIR-Crops Research Institute (Kumasi), International Institute of Tropical Agriculture (Nigeria) and the International Center for Tropical Agriculture (Columbia) (Table 4.1).

Table 4.1 List of cassava genotypes used for the study

Local genotypes		**Exotic genotypes**	
DM 001	_*Biabasse_	96/1643	*01/0046
ADE 2000/0107	*SAA 002	*96/1708	01/0061
ATR 004	*DM 002	*96/409	*01/0069
*ATR007	DAA 2000/004	97/0783	01/0085
*AFS 2000/023	*Debor	97/0857A	01/0090
*AFS 2000/043	DMA 2000/031	97/0879	01/0091
AFS 2000/071	*Essiabayaa	*97/1856	*BAN 001
*AFS 2000/131	Gbese	*97/4769	*01/0093
ATR001	*SAA 003	98/0002	01/0098
ATR 008	KAA 90/061	*98/0505	01/0111
NWA 001	*KSI 2000/092	*CTSIA 1	*01/0114
AWA 004	*KSI 2000/126	*CTSIA 110	*01/0134
AW 2000/053	*KSI 2000/191	*CTSIA 112	01/0152
AW 2000/075	SAA 001	*CTSIA 131	*01/0169
Badu bankye	*KW 2000/53	*CTSIA 133	*01/0220
*Bankye brodie	*Kwanwoma	*CTSIA 162	01/0265
Bankye broni	*NWA 004	*CTSIA 230	01/0267
ATR 003	Kwasia bedi	*CTSIA 45	*01/1088
NWA 003	ATR 005	*CTSIA 48	*01/1412
*BD 96/009	*SAA 004	*CTSIA 65	01/1663
*BD 96/021	*OFF 2000/019	*CTSIA 72	01/1797
*BD 96/040	*OFF 2000/023	*CTSIA 76	*02/0540
BD 96/057	OFF 2000/093	*CTSIA 8	*191/02324
BD 96/087	OFF 2000/134	*CTSIA 90	192/0057
*BD 96/093	*OFF 2000/145	*00/0093	*I9I934
BD 96/114	OFF 2000/25	*00/0140	*2000/0388
BD 96/136	ATR010	*00/0203	92/0067
BD 96/141	_*Pontisange_	*00/0338	*94/0006
*BD 96/154	DM 003	*00/0354	94/0020
BD 96/2075	SW 2000/187	*00/0364	95/0166
*ATR002	TA 97/008	001/0104	96/0603
ATR 010	*TA 97/054	01/0040	*96/0708
*TA 97/137	UCC 2001/209	*98/0581	*MM 96/1751
Tolodo	*UCC 2001/449	*98/2132	MM 96/5280
*UCC 2001/104	*UCC 2001/464	*98/2226	TME 4
*UCC 2001/111	*AWA 001`	*99/0240	*TME 419
*UCC 2001/113	DM 005	*99/0554	*TME 435
		*MM 94/JW1	*TME 693

*** = genotypes selected for the molecular diversity studies**

4.2.3 Experimental design

The land was ploughed, harrowed and the trial was laid out in a 15 x 10 alpha lattice design with three replications before mounds were raised for planting. Cassava cuttings measuring 25-30 cm were planted on top of the mounds according to Ekanayake (1996). Each plot was made up of five plants with intra row spacing of one metre between plants. Adjacent plants were also one metre apart. Weeding was done as and when necessary.

4.2.4 Data collection

4.2.4.1 Agronomic and morphological characterization

Twenty eight agronomic and morphological descriptors (Table 4.2) from standard cassava descriptors of IITA modified by Fukuda *et al.* (2010) were used to characterise the 150 cassava genotypes. Data were taken at three, six, nine and 12 months after planting (Appendix 4.1). Data collected at harvesting (12 months after planting) included above ground biomass (t/ha), root yield (t/ha), number of roots per plant and root dry matter content (%). Harvest index was estimated as the ratio of root yield to total biomass. Mean root weight (g) was also estimated as the total root weight divided by the number of roots per plot.

Table 4.2 Morphological traits used to characterize the cassava genotypes

Qualitative traits	Quantitative traits
Apical leaf colour	Plant height
Colour of root pulp	Height at branching
External colour of root	Number of leaves/plant
Petiole colour	Number of leaf lobes
Root constrictions	Angle at branching
Colour of root cortex	Length of petiole
Root shape	Root yield
Texture of root epidermis	Harvest index
Colour of end branches	Number of roots/plant
Colour of stem exterior	Dry matter content
Distance between leaf scars	
Growth habit of stem	
Habit of branching	
Levels of branching	
Pubescence	
Root peduncle	
Shape of central leaf lobe	
Shape of plant	

4.2.4.2 Root dry matter content

Roots were first chopped into pieces (about 1cm thick) and mixed thoroughly. Afterwards 100g of a sample was taken and dried at 80^{o}C for 48 hours and weighed. Dry matter content was obtained by expressing the dry weight as a percentage of the fresh weight of the sample taken.

4.2.4.3 Assessment of cassava mosaic disease severity.

This was scored using a scale of 1-5 where 1= no symptom and 5= highly diseased plants (Msikita *et al.*, 2000).

4.2.4.4 Molecular characterisation

The molecular assessment involved characterization of 89 cassava genotypes selected from the morphological characterisation. This was done using 36 simple sequence repeat (SSR) primers. This activity was carried out at the Biotechnology Laboratory of CSIR-Savanna Agricultural Research Institute (SARI), Nyankpala.

4.2.4.4.1 Genomic DNA extraction

Genomic DNA was extracted from the 89 cassava genotypes using CTAB method described by Doyle and Doyle (1990) with slight modifications. Healthy cassava cuttings were raised in pots for two weeks after which the youngest fully expanded leaves were picked into an ice chest and sent to the laboratory for DNA extraction.

About 20 mg of the leaf sample from each plant was taken and ground in 2.0 ml Eppendorf tubes into fine powder with liquid nitrogen. 800 µl of 2% CTAB and 0.5 µl of 0.1% mercaptoethanol were added. The samples were incubated in a sand bath at 65^0C for 30 minutes with intermittent vortexing. The samples were then cooled at room temperature after which equal volume (800 µl) of chloroform isoamyl alcohol (24:1) was added. The tube was inverted several times to ensure that a thorough mixture was obtained. The tubes were then centrifuged at 14000 rpm for 15 minutes. Equal volume of chloroform isoamyl alcohol solution was added to the samples in clean 1.5 ml Eppendorf tubes and centrifuged at 14000 rpm for 15 minutes. Nucleic acids were precipitated by adding two thirds volume of ice cold isopropanol (400 µl) and shaken gently. Precipitation was enhanced by storing the samples in a fridge at 20°C overnight. Pelleting of nucleic acids was done by centrifuging at 14000 rpm for 5 minutes. The isopropanol was decanted and the pellet was washed with 500 µl of washing buffer. The washing buffer was decanted and the pellet was washed in 400 µl of ethanol (80%) and then centrifuged at 6000 rpm for 4 minutes. The ethanol was decanted and the pellet was dried. The DNA was suspended in 100 µl of TE buffer and centrifuged at high speed for 30 seconds and stored at4^{0}C until ready for use. DNA of each accession was confirmed by electrophoresis on 2% agarose gel which revealed positive results.

4.2.4.4.2 SSR (microsatellite) markers and PCR amplification

A total of 36 simple sequence repeat primers (SSR), widely distributed across the cassava genome (Mba *et al.*, 2001), were used for the study (Table 4.3). They were procured from Metabion International AG (Germany). Polymerase chain reactions (PCR) were carried out in a Techne Thermalcycler (TC- 412) in a 10µl reaction mixture in 96-well plates. PCR master mix kits (KAPA 2G Fast ReadyMix with dye) procured from KAPA Biosystems (Pty) Ltd (South Africa) was used for the amplification. The kit 2X PCR master mix containing KAPA2G Fast DNA Polymerase (0.2 U per 10µl reaction), KAPA2 Fast PCR buffer, dNTPs (0.2mM each at 1X), $MgCl_2$ (1.5mM at 1X), stabilizers and loading dye. One micro litre of genomic DNA and 0.5µl each of forward and reverse primers were added to the PCR kits for DNA amplification. PCR was subjected to initial denaturation at 95°C for 3 min, followed by cycles of 95°C for 10 sec, 52°C for 10 sec and 72°C for 10 sec. The reaction was repeated for 35 cycles and a final extension at 72°C for 10 minutes was carried out. The reactions were then held at 4°C until electrophoresis.

Table 4.2 SSR primers used for the experiment

Primer name	Sequence (5'-3')	Expected band size (bp)
NS 189	F: TGGGCTGTTCGTGATCCTTA R: CATGAGTTTAAAAATTATCACATCCG	106-124
NS 376	F: TCAAGACCCTTGCTTTGGTT R: GGACTATCAAGGCGCAAAAG	213-233
NS 911	F: CACGACGTTGTAAAACGAC R: TGTTGTTCAGACGATGTCCAA	90-150
SSRY 4	F: TGAGAAGGAAACTGCTTGCAC R: CAGCAAGACCATCACCAGTTT	278-320
SSRY 5	F: GGAAACTGCTTGCACAAAGA R: CAGCAAGACCATCACCAGTTT	70-150
SSRY 9	F: AACTGTCAAACCATTCTACTTGC R: GCCAGCAAGGTTTGCTACAT	245-285
SSRY 12	F: TCACCGTTAATTGTAGTCTGCG R: GCGAGGTTCAAATATGCGAT	220-290
SSRY 19	F: CCAGAAACTGAAATGCATCG R: AACATGTGCGACAGTGATTG	190-250
SSRY 20	F: GTACATCACCACCAACGGGC R: AGAGCGGTGGGGCGAAGAGC	146-188
SSRY 21	F: GGCTTCATCATGGAAAAACC R: CAATGCTTTACGGAAGAGCC	120-230
SSRY 34	F: AGTGGAAATAAGCCATGTGATG R: CCCATAATTGATGCCAGGTT	288-306
SSRY 45	F: CGTTGATAAAGTGGAAAGAGCA R: ACTCCACTCCCGATGCTCGC	
SSRY 48	F: AAGGAACACCTCTCCTAGAATCA R: CCAGCTGTATGTTGAGTGAGC	
SSRY 50	F: TCAAACAAGAATTAGCAGAACTGG R: TGAGATTTCGTAATATTCATTTCACTT	
SSRY 59	F: ACAGCTCTAAAAACTGCAGCC R: AACGTAGGCCCTAACTAACCC	130-180
SSRY 63	F: TGACTAGCAGACACGGTTTCA R: GCTAACAGTCCAATAACGATAAGG	
SSRY 64	F: ACCACAAACATAGGCACGAG R: CACCCAATTCACCAATTACCA	192-220
SSRY 69	F: CCTTGGCAGAGATGAATTAGAG R: GGGGCATTCTACATGATCAATAA	180-270
SSRY 78	F: GGTAGATCTGGATCGAGGAGG R: CAATCGAAACCGACGATACA	
SSRY 82	F: GGAATTCTTTGCTTATGATGCC R: TTCCTTTACAATTCTGGACGC	166-208
SSRY 103	F: TGTAAGGCATTCCAAGAATTATCA R: TCTCCTGTGAAAAGTGCATGA	274-308
SSRY 106	F: CATTGGACTTCCTACAAATATGAAT R: TGATGGAAAGTGGTTATGTCCTT	268-302
SSRY 120	F: CCTGCCACAATATTGAAATGG R: CAACAATTGGACTAAGCAGCA	150-174

Table 4.2 cont'd

Primer name	Sequence (5'-3')	Expected band size (bp)
SSRY 135	F: TTCCAGACCTGTTCCACCAT R: ATTGCAGGGATTATTGCTCG	230-265
SSRY 147	F: ATAGAGCAGAAGTGCAGGCG R: CTAACGCACACGACTACGGA	118-136
SSRY 148	F: TGAAACTGTTTGCAAATTACGA R: TCCAGTTCACATGTAGTTGGCT	90-140
SSRY 151	F: TGAAAATCTCACTGGCATTATTT R: TCATAAAGCTCGTGATTTCCA	160-240
SSRY 155	F: TGATGAAATTCAAAGCACCA R: CGCCTACCACTGCCATAAAC	130-180
SSRY 161	F: CCGCTTAACTCCTTGCTGTC R: CAAGTGGATGAGCTACGCAA	200-240
SSRY 164	F: GCAATGCAGTGAACCATCTTT R: CGTTTGTCCTTTCTGATGTTC	156-204
SSRY 169	F: TCAGAATCATCTACCTTGGCA R: AAGACAATCATTTTGTGCTCCA	70-130
SSRY 175	F: CGACAAGTCGTATATGTAGTATTCACG R: GCAGAGGTGGCTAACGAGAC	100-156
SSRY 177	F: CGATCTCAGTCGATACCCAAG R: CACTCCGTTGCAGGCATTA	244-286
SSRY 180	F: TGCACACGTTCTGTTTCCAT R: ATGCCTCCACGTCCAGATAC	131-145
SSRY 181	F: TGTGACAATTTTCAGATAGCTTCA R: CACCATCGGCATTAAACTTTG	130-230
SSRY 182	F: ACAATTCATCATGAGTCATCAACT R: CCGTTATTGTTCCTGGTCCT	190-260

4.2.4.4.3 Gel electrophoresis

The PCR products obtained were electrophoresed in horizontal polyacrylamide (6%) and ethidium bromide gels. The tracking dye in the PCR premix (KAPA 2G) made visual tracking of the PCR products through the gel easier. Approximately 10 µl of the amplified products and a 50 bp and 100 bp molecular ladder (Ladder Plus) obtained from NBS Biologicals Ltd, Cambridge, UK were electrophoresed at 120V for 150 minutes using Galileo Bioscience (81-2325) horizontal tank. The molecular ladder was loaded into lane one and the DNA of the cassava genotypes were loaded in the adjacent lanes. The gels were stained in

100 ml 1X TE buffer with ethidium bromide (3 µl) for 30 minutes and visualized by illumination on Bench top UV transilluminator. The gels were photographed under UV light.

4.2.5 Data analysis

4.2.5.1 Agronomic and morphological data

Factorial analysis was performed to determine the grouping of the genotypes using DARwin software programme version 5 (Perrier and Jacquemoud-Collet, 2006). Dissimilarity among genotypes was estimated using Sokal and Sneath 'n1' modality within DARwin 5. Principal component analysis of the 28 morphological traits including root yield was performed to examine the percentage contribution of each trait to the total genetic variation using GenStat version 12.1 (Payne *et al.*, 2009). The agronomic data on growth and yield was subjected to analysis of variance for alpha lattice using PROC GLM in SAS (SAS, 2009). Pearson correlation analysis was performed to estimate the relationship among traits.

4.2.5.2 Molecular data

The DNA bands were scored as either present (1) or absent (0) for each of the genotypes by visual inspection. Loci were considered polymorphic if more than one allele was detected. PowerMarker version 3.25 (Liu and Muse, 2005) was used to generate allele frequency, number of alleles, gene diversity, heterozygosity and polymorphism information content (PIC). Genotype associations were analysed with DARwin 5 using the simple matching coefficient and neighbour-joining algorithim for confirmation of major nodes.

The calculation of the PIC was based on the equation:

$\text{PIC} = 1 - \sum P_i^2$

Where P_i= the frequency of the i^{th} allele.

4.2.5.3 Estimation of variance components

Variance components of the different agronomic traits were estimated using the mean squares following the procedures of Akinwale *et al.* (2010). Broad sense heritability, genetic advance and genetic advance as percentage of mean were estimated according to Tsegaye *et al.* (2007) as follows:

$\sigma^2_p = \sigma^2_g + \sigma^2_e$,

$$\sigma^2_g = \frac{MSg - MSe}{r}$$

Where:

σ^2_p = Phenotypic variance

σ^2_g = Genotypic variance

σ^2_e= Environmental variance (error mean square)

r = number of replications

Genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) were estimated as:

$$\text{GCV } (\%) = \frac{\sqrt{\sigma^2_g}}{\bar{X}} \text{ x } 100$$

$$\text{PCV } (\%) = \frac{\sqrt{\sigma^2_p}}{\bar{X}} \text{ x } 100$$

Where: $\bar{X}$ = grand mean

Broad sense heritability was estimated as:

$H^2 = \sigma^2_g / \sigma^2_p$

Where:

H^2 = broad sense heritability

Genetic advance expected under selection assuming a selection intensity of 5% was estimated as:

$GA = (K)\sigma_A H^2$

Where: GA = expected genetic advance

K = Selection differential (2.06 at 5% selection intensity)

σ_A= Phenotypic standard deviation

Genetic advance as a percentage of mean (GAM) was also estimated using the formula:

$GAM = (GA/ \overline{X})* 100$

4.3 Results

4.3.1 Morphological diversity

4.3.1.1 Factorial analysis

The cassava genotypes were genetically diverse for the 28 morphological traits used for the assessment. The genotypes were separated into four quadrants, each containing at least one genotype from all the sources (Fig. 4.1). Quadrant A contained genotypes obtained from all the three sources; the International Center for Tropical Agriculture (CIAT; green), International Institute of Tropical Agriculture (IITA; red) and local sources from Ghana (blue). Quadrant B was made up predominantly of genotypes obtained from local sources in Ghana with only two (TME 4 and TME 435) from IITA and one from CIAT (CTSIA 65). The genotypes obtained from IITA dominated in Quadrant C with only eight coming from local sources in Ghana and one from CIAT. Quadrant D was also made up of genotypes from local sources and IITA with only one genotype from CIAT appearing in this group. There were exceptions however, since some few genotypes overlapped in the quadrants outside the sources from which majority of their counterparts were obtained. Some of the genotypes (96/2226, 191/02234 and TA97/054) appeared at the extreme ends of the four axes indicating that they were far distinct from the other genotypes they appeared in the same quadrants with. Analysis of the principal components was carried out to identify the important traits that contributed most of the variations in the genotypes.

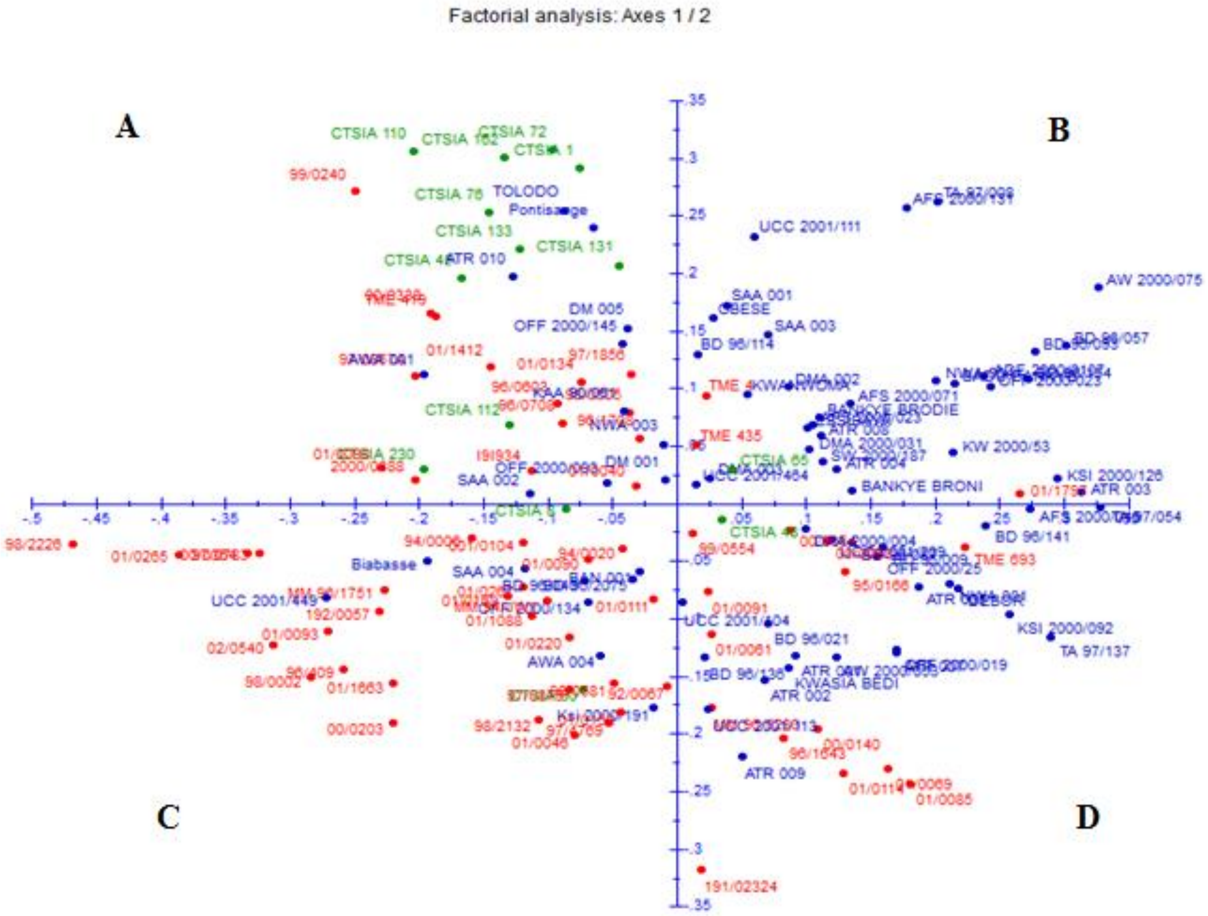


Fig. 4.1 Factorial analysis of 150 cassava genotypes from different sources (Red = IITA, Blue = Local and Green = CIAT) using morphological traits

4.3.1.2 Principal component analysis

Principal component analysis of the 18 qualitative traits revealed that the first six axes (PC1 – PC6) cumulatively accounted for 54.83% of the total variation observed among the genotypes (Table 4.3). Traits with eigen values greater than one were considered as contributing significantly to the variation among the genotypes. The first PC axis with an eigen value of 2.56 accounted for 12.78% of the variation. The traits that contributed most of the variation were root constriction, colour of stem exterior, distance between leaf scars and growing habit. The second PC also contributed 10.93% of the total variation and contained colour of root cortex, texture of root epidermis and colour of end branches. The third PC with 1.8% contribution was associated with petiole colour and shape of plant. The fourth PC axis contributed 1.6% of the total variation and was associated with habit of branching and root peduncle. The fifth and sixth PCs contributed 1.49 and 1.26% respectively and were associated with external root colour, petiole colour and shape of central leaf lobe.

Table 4.3 Principal component analysis of 18 qualitative traits showing their contributions to the total variation among 150 cassava genotypes

Trait	PC1	PC2	PC3	PC4	PC5	PC6
Apical leaf colour	0.255	0.019	-0.218	**0.338**	0.098	0.253
Colour of root pulp	0.213	0.024	0.201	0.213	-0.177	-0.249
External colour of root	0.083	0.226	0.194	0.066	**-0.400**	0.460
Petiole colour	-0.218	0.203	**0.300**	0.397	0.364	0.017
Root constrictions	**-0.305**	-0.275	-0.168	-0.055	0.140	0.074
Colour of root cortex	-0.172	**0.398**	0.074	-0.214	-0.161	0.111
Root shape	-0.068	-0.098	0.023	-0.051	0.269	0.293
Texture of root epidermis	-0.159	**0.304**	0.134	0.080	-0.402	0.204
Colour of end branches	-0.257	**0.311**	0.143	0.331	0.348	0.086
Colour of stem exterior	**0.415**	0.161	0.202	-0.220	0.269	0.094
Distance between leaf scars	**0.421**	0.255	0.173	-0.137	0.256	-0.049
Growth habit of stem	**0.308**	0.009	0.006	0.089	-0.078	-0.271
Habit of branching	0.088	0.006	0.227	**-0.319**	-0.068	-0.008
Levels of branching	0.113	0.289	-0.181	-0.071	0.166	-0.016
Pubescence	0.272	-0.289	0.045	0.148	0.038	0.270
Root peduncle	-0.151	0.098	0.000	**-0.380**	0.281	0.065
Shape of central leaf lobe	0.119	-0.194	-0.058	-0.132	0.067	**0.577**
Shape of plant	-0.182	-0.082	**0.363**	-0.350	0.031	-0.077
Eigen values	2.557	2.186	1.866	1.600	1.495	1.264
%Variance	12.78	10.93	9.33	8.00	7.47	6.32
%Cumulative variance	12.78	23.71	33.04	41.04	48.51	54.83

Figures in bold represent significant traits in the various principal components

Principal component analysis using 10 quantitative traits (Table 4.4) indicated that the first three principal components (PC1, PC2 and PC3) contributed 55.68% of the total variation observed among the genotypes. PC1 contributed 22.68% of the total variation and was associated with root yield, number of roots per plant, harvest index and number of leaves. The second PC contributed 20.36% of the total variation and was associated the height at branching, plant height, number of leaf lobes and length of petiole. The third PC axis with a contribution of 12.64% was associated with plant height, angle at branching and root dry matter content.

Table 4.4 Principal component analysis of 10 quantitative traits showing their contributions to the total variation among 150 cassava genotypes

Trait	PC1	PC2	PC3	PC4	PC5	PC6
Plant height	0.032	**0.521**	0.314	0.375	0.149	0.140
Height at branching	-0.105	**0.562**	0.127	0.086	0.300	0.129
Number of leaves/plant	**0.388**	-0.128	0.362	0.128	-0.499	0.037
Number of leaf lobes	-0.167	**0.376**	-0.001	-0.577	-0.060	-0.078
Angle at branching	-0.003	-0.081	**0.687**	-0.242	0.173	-0.595
Length of petiole	-0.150	**0.379**	-0.185	-0.263	-0.611	-0.123
Root yield	**0.545**	0.146	0.042	-0.260	-0.067	0.053
Harvest index	**0.411**	-0.044	-0.259	-0.408	0.469	0.034
Number of roots/plant	**0.521**	0.200	0.030	0.073	-0.081	0.164
Dry matter content	0.224	0.204	**-0.422**	0.367	0.023	-0.746
Eigen values	2.268	2.036	1.264	1.142	0.987	0.725
%Variance	22.68	20.36	12.64	11.42	9.87	7.25
%Cumulative variance	22.68	43.04	55.68	67.1	76.97	84.22

Figures in bold represent significant traits in the various principal components

4.3.2 Molecular diversity

Out of the 36 SSR markers used for the initial screening of the germplasm, 35 of them were polymorphic and were used for the analysis. A total of 167 alleles with a mean of 4.77 alleles per locus were generated by the 35 simple sequence repeat markers (SSR) (Table 4.5). Allele frequency ranged from 0.32 to 0.99 with an average of 0.62. Allele number ranged from 2 to 10 alleles per locus. Gene diversity varied from 0.03 to 0.81 with primers SSRY 48 and SSRY 164 obtaining the lowest and highest gene diversity, respectively. Primer SSRY 180 had the highest heterozygosity of 0.97 with SSRY 48 obtaining the lowest heterozygosity of

0.03. Polymorphism information content (PIC) ranged 0.03 to 0.78 with a mean of 0.45. SSRY 164 was the most polymorphic marker as it generated the highest PIC value of 0.78.

Table 4.5 Allele frequency, allele number, gene diversity, heterozygosity and polymorphism information content (PIC) values generated by the molecular analysis

Marker	Allele Frequency	Allele No.	Gene Diversity	Heterozygosity	PIC
NS-189	0.67	5.00	0.49	0.24	0.43
NS-376	0.66	5.00	0.52	0.50	0.48
SSRY-4	0.68	3.00	0.47	0.54	0.40
SSRY-5	0.45	3.00	0.59	0.36	0.51
SSRY-9	0.33	6.00	0.76	0.44	0.72
SSRY-12	0.52	5.00	0.53	0.24	0.43
SSRY-19	0.34	6.00	0.76	0.59	0.72
SSRY-20	0.70	7.00	0.49	0.35	0.47
SSRY-21	0.60	4.00	0.57	0.48	0.51
SSRY-34	0.92	3.00	0.15	0.11	0.14
SSRY-45	0.57	5.00	0.57	0.75	0.51
SSRY-48	0.99	3.00	0.03	0.03	0.03
SSRY-50	0.60	6.00	0.59	0.30	0.54
SSRY-59	0.47	5.00	0.57	0.18	0.48
SSRY-63	0.75	5.00	0.42	0.10	0.40
SSRY-64	0.58	5.00	0.58	0.38	0.52
SSRY-69	0.42	6.00	0.70	0.77	0.65
SSRY-78	0.69	5.00	0.48	0.35	0.43
SSRY-82	0.61	3.00	0.50	0.49	0.40
SSRY-103	0.53	6.00	0.54	0.86	0.44
SSRY-106	0.66	5.00	0.50	0.46	0.45
SSRY-120	0.67	3.00	0.49	0.22	0.44
SSRY-135	0.76	3.00	0.38	0.37	0.33
SSRY-147	0.95	3.00	0.10	0.07	0.10
SSRY-148	0.93	2.00	0.12	0.11	0.12
SSRY-151	0.45	8.00	0.70	0.75	0.66
SSRY-155	0.78	5.00	0.37	0.38	0.34
SSRY-161	0.59	6.00	0.61	0.54	0.57
SSRY-164	0.32	10.00	0.81	0.61	0.78
SSRY-169	0.88	5.00	0.22	0.10	0.21
SSRY-175	0.45	4.00	0.63	0.53	0.55
SSRY-177	0.49	4.00	0.57	0.36	0.48
SSRY-180	0.51	5.00	0.61	0.97	0.55
SSRY-181	0.63	3.00	0.54	0.62	0.48
SSRY-182	0.57	5.00	0.61	0.86	0.56
Mean	**0.62**	**4.77**	**0.55**	**0.43**	**0.45**
SE	0.17	1.61	0.19	0.24	0.16

4.3.2.1 Cluster analysis

Cluster analysis performed with Darwin software and adopting the neighbour joining analysis showed that the genotypes were grouped into seven clusters (Fig. 4.2). Cluster one was made up of 15 genotypes dominated by genotypes from IITA with only three (KW2000/53, Essiabayaa and Debor) from Ghana and one from CIAT (CTSIA 48). Cluster two was made up of 14 genotypes mainly from Ghana, IITA and CIAT. Cluster three was also made up of nine genotypes, one from CIAT, two from IITA and six from Ghana. Of the 12 genotypes in cluster four, only one came from IITA (TME 419) with no genotype from CIAT appearing here. Cluster five had 16 genotypes, three from Ghana, four from IITA and nine from CIAT. Cluster six also had 16 genotypes which were mostly dominated by genotypes from IITA with only one genotype coming from CIAT. Cluster seven contained seven genotypes, one from IITA, three from Ghana and three from CIAT.

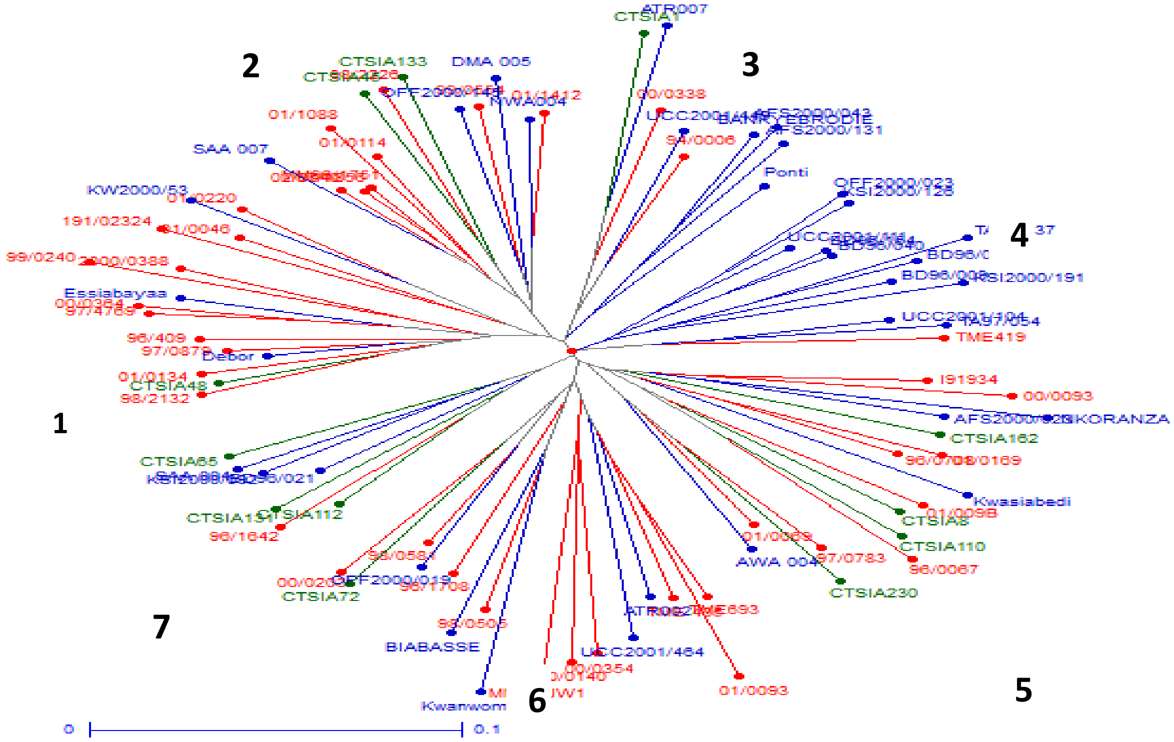


Fig. 4.2 Dendrogram showing the relationship between 89 cassava genotypes from Ghana (Blue), IITA (Red) and CIAT (Green) based on neighbour-joining analysis and simple matching coefficient

4.3.3 Agronomic traits

4.3.3.1 Analysis of variance

Analysis of variance indicated very highly significant (P<0.001) genotype effect for all the traits measured except severity of cassava mosaic disease (Tables 4.6 and 4.7). This indicates the existence of significant genetic variability for growth and root yield for further improvement.

Table 4.6 Mean squares for growth parameters measured

Source	**D.f.**	**Av_Lev**	**CMD**	**Plt ht (cm)**	**htatbran**
Rep	2	2245.60	2.34	6498.35	775.00
Blk(Rep)	27	989.60	0.34	978.38	45.00
Genotype	149	2743.90***	0.76NS	2207.65***	1089***
Error	262	665.10	665.00	275.00	205.00

NS= not significant, *** = significant at P< 0.001, Av_Levs = average number of leaves/plant, CMD_SC = cassava mosaic disease severity, Plt_ht (cm) = plant height (cm), Htatbran = height at branching (cm)

Table 4.7 Mean squares for yield and yield components

Source	**D.f.**	**Rtyld(t/ha)**	**Rtno/plt**	**MRW(g)**	**HI**	**DM%**
Rep	2	437.51	52.85	335636.78	0.03785	34.13
Blk(Rep)	27	66.57	18.5	26686.094	0.00945	8.64
Genotype	149	119.55***	9.87***	22311.81***	0.021***	32.87***
Error	262	32.332	1.870	9024.410	0.004	9.080

*** = significant at P< 0.001, Rtyld (t/ha) = root yield (t/ha), Rtno/plt = root number per plant, MRW (g) = mean root weight (g), HI = harvest index, DM (%) = dry matter content (%).

4.3.3.2 Mean performance of genotypes based on sources

The genotypes from CIAT had the highest average plant height (175.88 cm) followed by those from local sources (144.94 cm) with IITA genotypes being the shortest (126.12 cm) (Table 4.8). Genotypes from IITA were also early branching with average height at branching of 48.26 cm compared with local (60.87 cm) and CIAT (73.74 cm) among the group. Genotypes from CIAT had the highest average number of leaves per plant (83.58) followed by IITA (72.70) and local genotypes (54.43). Severity of cassava mosaic disease was highest for local genotypes (1.75) compared with CIAT (1.38) and IITA (1.42). The highest average root yield was produced by genotypes from IITA (20.23 t/ha) followed by CIAT (18.94 t/ha) and local (17.34 t/ha). Genotypes from CIAT also had more root numbers per plant (8.38) compared with IITA (6.38) and local genotypes (5.83). Average dry matter content was highest for the genotypes from CIAT (36.15%) followed by local genotypes (32.68%) and IITA (29.84%). Genotypes from IITA had the highest mean root weight (323.81 g) followed by local (307.74 g) and CIAT (232.32 g). Harvest index was highest for genotypes from IITA (0.59) followed by CIAT (0.57) and local genotypes (0.55).

Table 4.8 Average performance of groups of genotypes from the different sources

Traits	**Local (n=74)**	**CIAT (n=14)**	**IITA (n=62)**	**Mean**
Plt_ht	144.94	175.88	126.12	148.98
Htatbran (cm)	60.87	73.74	48.26	60.96
Leafno/plant	54.43	83.58	72.70	70.24
CMD (1-5)*	1.75	1.38	1.42	1.52
Rtyld (t/ha)	17.34	18.94	20.23	18.83
Rtno/plt	5.83	8.38	6.38	6.86
MRW (g)	307.74	232.32	323.81	287.95
DM (%)	32.68	36.15	29.84	32.89
HI	0.55	0.57	0.59	0.57

* 1= no symptom, 5 = highly diseased plants. Plt_ht (cm) = plant height (cm), Htatbran = height at branching (cm), Leafno= average number of leaves/plant, CMD = cassava mosaic disease score, Rtyld (t/ha) = root yield (t/ha), Rtno/plt = root number per plant, MRW (g) = mean root weight (g), DM (%) = dry matter content (%), HI = harvest index

4.3.3.3 Mean performance of genotypes

Significant ($P<0.05$) genetic variation was observed for root yield, dry matter content, harvest index and plant height. The best 15 and worst 15 genotypes are presented in Table 4.9. The highest root yield was obtained from MM96/1751 (36.1 t/ha) with 01/0061 giving the least root yield of 3.99 t/ha. Root dry matter content ranged between 21.1% for 01/1163 and 39.12 % for CTSIA 8 with a mean of 31.85%. Mean harvest index for all the 150 genotypes was 0.57. Genotype 01/0169 had the highest harvest index (0.77) with 01/0061 having the least (0.19%). The highest plant height (211.70 cm) was recorded from CTSIA 133 with 96/0708 having the shortest plant height (81.3 cm). Average number of leaves per plant also varied during the different months (Fig. 4.3). The average number of leaves per plant recorded in September (three months after planting) increased marginally in November before it started to decline in December, January with least being recorded in February before it started to increase again in March and April. Since leaf retention was one of the objectives for assessment of the genotypes in the study, the best performing genotypes during the months of low average leaf retention would be good candidates for selection.

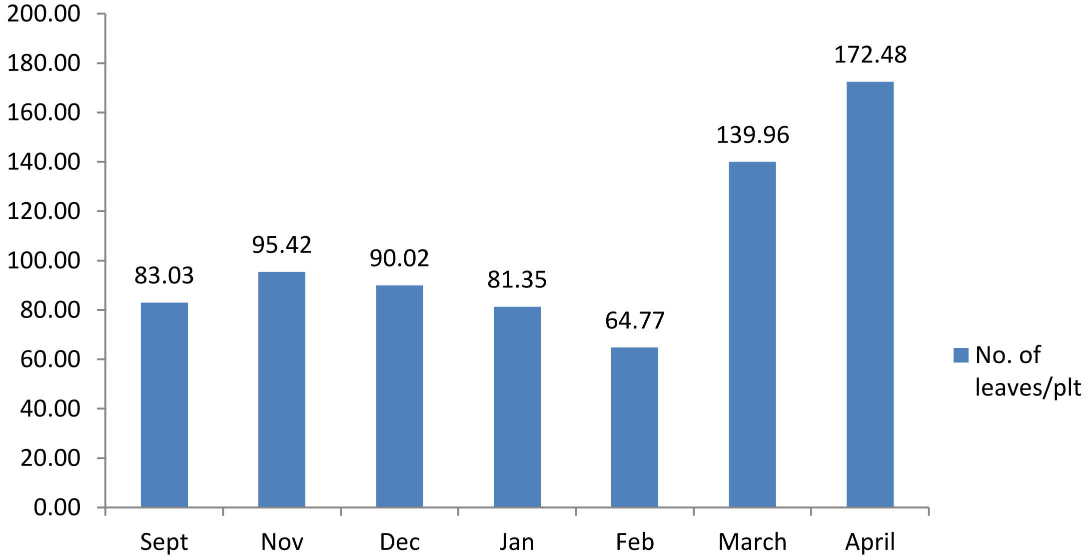


Fig. 4.3 Average number of leaves per plant at different months

Table 4.9 Mean performance of top 15 and bottom 15 of cassava genotypes for root yield, dry matter content, harvest index and plant height

	Genotypes	**Root yield (t/ha)**	**Genotypes**	**Dry matter content (%)**	**Genotypes**	**HI**	**Genotypes**	**Plant height (cm)**
1	MM 96/1751	36.10	CTSIA 8	39.12	01/0169	0.77	CTSIA 133	211.70
2	ATR 002	33.43	CTSIA 45	38.36	00/0203	0.75	CTSIA 76	205.00
3	UCC 2001/449	31.87	96/409	37.65	98/0002	0.72	*Pontisange*	203.70
4	ATR 007	31.10	96/1708	37.46	2000/0388	0.71	CTSIA 65	192.70
5	TME 419	30.99	CTSIA 112	37.41	98/2132	0.71	ATR 007	191.70
6	00/0203	30.32	CTSIA 110	37.32	MM 96/1751	0.71	TME 419	190.30
7	TME 435	29.54	CTSIA 230	37.15	94/0006	0.70	MM 96/1751	188.70
8	98/2132	29.10	ATR 002	36.69	00/0338	0.70	AFS 2000/071	188.70
9	NWA 004	29.06	00/0338	36.56	TME 419	0.70	NWA 004	184.30
10	01/0169	28.76	Bankye broni	36.51	01/0134	0.70	CTSIA 110	184.30
11	99/0240	28.49	97/0857A	36.38	I9I934	0.69	OFF 2000/093	183.70
12	01/0069	28.21	CTSIA 65	36.27	TME 4	0.69	TA 97/008	181.30
13	98/0002	27.76	CTSIA 76	36.13	ATR 001	0.69	Bankye brodie	179.00
14	SAA 004	27.43	Kwasia bedi	35.89	97/0857A	0.69	CTSIA 72	178.70
15	ATR 001	27.32	00/0354	35.72	99/0240	0.68	ATR 007	178.00
	”	”	”	”	”	”	”	”
	”	”	”	”	”	”	”	”
136	BD 96/114	9.23	01/0091	27.55	BD 96/009	0.46	BAN 001	101.30
137	KSI 2000/191	9.15	01/0114	27.32	DAA 2000/004	0.45	01/0220	100.70
138	DMA 2000/031	9.15	01/0061	27.28	CTSIA 110	0.44	97/0783	99.70
139	01/0111	9.04	95/0166	27.22	UCC 2001/464	0.44	02/0540	96.90
140	UCC 2001/113	8.54	BD 96/009	27.22	CTSIA 8	0.44	Tolodo	96.70
141	DAA 2000/004	8.10	97/1856	27.14	AFS 2000/023	0.44	NWA 003	96.70
142	UCC 2001/464	7.82	02/0540	26.87	BD 96/141	0.44	01/0267	96.30
143	BD 96/141	7.15	01/0169	26.37	01/0152	0.42	01/0040	91.70
144	BD 96/009	6.99	001/0104	26.09	01/0111	0.42	97/4769	91.30
145	OFF 2000/25	6.99	00/0093	24.52	01/1663	0.41	01/0169	90.00
146	BD 96/040	6.99	96/0603	24.36	BD 96/2075	0.41	98/0505	87.70
147	192/0057	6.87	97/0783	22.38	KAA 90/061	0.40	00/0364	86.70
148	01/0152	6.26	192/0057	22.27	02/0540	0.39	01/1412	84.00
149	NWA 003	4.76	01/1088	21.67	DMA 2000/031	0.37	192/0057	81.70
150	01/0061	3.99	01/1663	21.10	01/0061	0.19	96/0708	81.30
	Grand mean	18.69		31.85		0.57		140.19
	SE	3.44		1.74		0.04		10.64

4.3.3.4 Estimates of variance components

Genetic variances for number of leaves per plant, plant height, height at branching, number of roots per plant and harvest index were higher than their corresponding error variances (Table

4.10). The error variances of cassava mosaic disease severity (CMD), root yield, mean root weight and dry matter content had lower genetic variances than their error variances.. Phenotypic coefficient of variation (PCV) was higher than the genotypic coefficient of variation for all the traits. The lowest PCV (13.1%) was observed for root dry matter content with cassava mosaic disease (CMD) severity showing the highest (73.48%). In the case of genotypic coefficient of variation, dry matter content again had the lowest (9.1%) with CMD severity showing the highest of 64.4%. The magnitude of the differences between the GCV for the different traits and their respective PCV was wide for CMD severity, mean root weight (g), root yield (t/ha), height at first branching (cm) and number of roots per plant. However, narrow differences were observed for dry matter content, harvest index, plant height (cm) and height at branching (cm). Broad sense heritability estimates ranged between 31% for mean root weight and 66% for plant height (Table 4.10). High broad sense heritability estimates were obtained for number of roots per plant (54.7%), number of leaves per plant (55.9%), height at first branching (57.5), HI (59.3) and plant height (66.3%). Low broad sense heritability estimates were also observed for mean root weight (31.4%), CMD severity (39.9%), root yield (45.9%) and root dry matter content (48.1%). Estimates of genetic advance varied from 0.13 for harvest index to 80.91 g for mean root weight. Genetic advance as a percentage of mean (GAM) also ranged between 13% for dry matter content to 64.79% for number of leaves per plant.

Table 4.10 Estimates of variance components, broad sense heritability, GCV and PCV, GA and GAM of nine cassava traits evaluated under rain fed conditions in the Guinea Savannah Zone of Ghana

Traits	σ^2_g	σ^2_e	σ^2_p	H^2	PCV	GCV	GA	GAM
Leafno/plt	747.9	611	1358.97	55.97	57.65	42.35	41.87	64.79
CMD	0.54	0.81	1.35	39.92	73.48	46.42	0.96	60.51
Plt_ht (cm)	667.6	339.8	1007.4	66.26	22.64	18.43	43.39	30.95
Htatbran	314.7	233.3	548	57.47	41.09	31.13	27.73	48.68
Rtyld(t/ha)	30.14	35.53	65.67	45.89	43.35	29.37	7.67	41.05
Rtno/plt	2.86	2.37	5.24	54.68	36.39	26.91	2.58	41.04
MRW (g)	4893.33	10674.00	15567.33	31.43	40.58	22.75	80.91	26.31
DM%	8.38	9.04	17.42	48.10	13.10	9.09	4.14	13.00
HI	0.0062	0.0043	0.0105	59.26	17.94	13.81	0.13	21.93

Leafno/plt = average number of leaves/plant, CMD = cassava mosaic disease severity, Plt_ht (cm) = plant height (cm), Htatbran = height at branching (cm), Rtyld (t/ha) = root yield (t/ha), Rtno/plt = number of storage roots per plant, MRW (g) = mean root weight (g), DM (%)=dry matter content (%), HI = harvest index, σ^2_g = genotypic variance, σ^2_e = Error variance, σ^2_p = Phenotypic variance, H^2= broad sense heritability, PCV = Phenotypic coefficient of variation, GCV = Genotypic coefficient of variation, GA = genetic advance, GAM = genetic advance as percentage of the mean

4.3.3.5 Pearson correlation among traits

Correlation analysis performed on the traits also revealed very high significant (P<0.001) differences among them (Table 4.11). Apart from number of leaves per plant and root yield, the correlations between cassava mosaic disease severity and all other traits were insignificant (P>0.05). Root yield, which is the ultimate aim of cassava breeding, was positively correlated with all the traits except height at branching and root dry matter content. Number of roots per plant (r = 0.57), mean root weight (r = 0.59), HI (r = 0.54) and number of leaves per plant (r = 0.54) had high correlation with storage root yield. The correlations between root dry matter content and most of the traits were not significant (P> 0.05) except for plant height (r = 0.2), height at branching (0.18) and number of roots per plant (r = 0.15). Number of roots per plant was also significantly correlated with all the other traits. Among the growth parameters, plant height was positively correlated with root dry matter content (r = 0.20) and significantly (P<0.01) but negatively correlated with harvest index (r = 0.15). Mean root weight (g), which indicates the size of roots formed, was also associated with a number of traits such as average number of leaves per plant (r = 0.21), height index (r = 0.31) and root yield (r = 0.59). Very highly significant (P<0.001) negative correlation was also observed between mean root weight and number of storage roots per plant.

Table 4.11 Pearson correlation coefficients for eight cassava traits evaluated among 150 cassava genotypes

CMD	1	-							
Leafno/plt	2	-0.10*	-						
Plt_ht (cm)	3	-0.01NS	0.16**	-					
Htatbran	4	0.03NS	-0.19***	0.55***	-				
Rtyld(t/ha)	5	-0.11*	0.54***	0.23***	0.05NS	-			
RtNo/plt	6	-0.07NS	0.44***	0.26***	0.10*	0.57***	-		
MRW (g)	7	-0.04NS	0.21***	0.06NS	-0.02NS	0.59***	-0.22***	-	
HI	8	-0.09NS	0.11*	-0.15**	-0.02NS	0.54***	0.35***	0.31***	-
DM%	9	-0.02NS	-0.02NS	0.20***	0.18***	0.01NS	0.15**	-0.11*	0.07NS
		1	2	3	4	5	6	7	8

*, **,*** = significant at P< 0.05, P< 0.01 and P< 0.001 respectively, NS = not significant (P> 0.05), CMD = Cassava mosaic severity, Leafno/plt = average number of leaves/plant, Plt_ht (cm) = plant height (cm), Htatbran = height at branching (cm), Rtyld (t/ha) = root yield (t/ha), Rtno/plt = root number per plant, MRW (g) = mean root weight (g), DM (%)=dry matter content (%), HI = harvest index

4.4 Discussion

4.4.1 Genetic diversity using morphological traits

Principal component analysis of both the qualitative and quantitative traits revealed that the genotypes were morphologically diverse for traits such as distance between leaf scars, colour of stem exterior, colour of end branches, petiole length, shape of plant, growth habit and habit of branching. These traits are distinct and vary with different genotypes hence will be useful in selection. In the case of the quantitative traits, plant height which reflects the growth rate of the plant, height at branching, number of leaf lobes, root yield and harvest index were the important characteristics that distinguished the genotypes. Quantitative traits are polygenically controlled and are higly influenced by the environment (Kang, 1998; Piepho, 2000; Aina *et al.*, 2009; Ntawuruhunga and Dixon, 2010). They are therefore are very important characteristics to consider in breeding for drought tolerance in cassava since they were found to contribute to its survival mechanisms. Nasser *et al.* (2010) working with progeny of interspecific hybrid of *M. glaziovii* with cultivated cassava in Brazil found that brown stem colour was associated with drought tolerance. This makes this phenotype a good trait to consider in assessing several cassava genotypes for drought tolerance.

The height that cassava plants attain at maturity reflects its growth habit during the season (Okogbenin *et al.,* 2013). Early branching helps to develop dense canopy, cover the soil and capture as much sunlight as possible thereby preventing soil heating and water loss through evaporation. Tan and Cock (1979) associated branching habit with root yield in cassava and indicated that it could be used as a determinant for root yield. The morphological variability observed for this trait corroborates earlier studies by Raghu *et al.* (2007) and Asare *et al.* (2011).

4.4.2. Genetic diversity using SSR markers

The high level of polymorphism exhibited by the markers was an indication of the level of genetic variability within *Manihot esculenta* Crantz (Kawano *et al.,* 1978). Huff *et al*. (1993) stated that the average number of primers required to adequately assess genetic diversity in crops differ and depends on the level of out-crossing within the species. For example, crop species that are highly inbred require larger number of primers than crop species that are naturally heterogeneous like *Manihot esculenta* Crantz. An average of 4.77 alleles per locus was detected by these SSR primers. This finding is similar to the mean number of alleles detected per locus in previous studies on cassava (Raghu *et al.*, 2007; Siqueira *et al.*, 2009; Essuma *et al.*, 2012). Heterozygosity levels, which varied from 0.03 to 0.97 with a mean of 0.43, deviated from the findings of Essuma *et al*. (2012) who observed a heterozygosity range of 0.47 to 0.66 with a mean of 0.57 when they assessed the genetic diversity of 64 cassava accessions using 26 SSR markers. High level of heterozygosity observed within the genotypes studied can be attributed to their diverse origins and probably hybridization of the exotic accessions from IITA and CIAT. Polymorphism information content (PIC) values obtained in this study were similar to results obtained by Fregene *et al*. (2003), Raghu *et al*. (2007) and Asare *et al*. (2011) and were high enough to detect genetic variability in the population.

Cluster analysis using SSR allelic data indicated considerable genetic diversity among the 89 cassava genotypes studied. This variability shown by the SSR primers indicated that genetic diversity study using molecular characterization was more effective in detecting genetic divergence than morphological characters. The genotypes were grouped into seven diverse clusters. Apart from cluster four, the remaining six clusters contained at least one genotype from local, IITA or CIAT sources indicating that the genotypes shared common alleles. Although some of the genotypes from the same source clustered together, the clusters were not constituted based on location or origin. Asare *et al.* (2011) also found similar groupings of genotypes irrespective of their origins. The wide genetic variability existing in the genotypes provides an opportunity for genes to be combined through controlled hybridization to create a broader genetic base for yield improvement.

4.4.3. Growth and yield parameters

The estimates of the variance components revealed significant genetic effects probably due to the different sources from which the genotypes were obtained (Zanklan, 2003; Sathyanarayana *et al.*, 2012). This indicates the existence of significant genetic variability within the population for selection. Similar observations have been made in sweet potato (Tsegaye *et al.*, 2007), aerial yam (Tewodros, 2013), rice (Singh *et al.*, 2013) and cassava (Tewodros *et al.*, 2013). Wide genetic variation was observed between the different agronomic traits namely root yield, dry matter content, plant height and harvest index. The ranking of genotypes varied with the different traits as some produced high root yield with some having better dry matter, harvest index and plant height. This indicates a rich source of variability for these traits for possible genetic combination for improvement.

Estimates of genetic parameters in a germplasm collection can serve as basis for comparing response to selection and the expected level of progress (Nyquist, 1991; Lankey and Lee, 1993; Kumar *et al.*, 1999). A large proportion of the phenotypic variances of HI, plant height, height at branching, number of roots per plant and number of leaves per plant were accounted for by the genetic components indicating inherent genetic variation for these traits. However, root yield, mean root weight and CMD severity were more influenced by the environmental factors as their observed genetic variances were lower than the error variances. Similar results were obtained by Tsegaye *et al.* (2007) and Tewodros *et al.* (2013) who recorded lower genotypic variance for yield traits in sweet potato and cassava, respectively.

Analysis of the magnitude of the variability among most of the traits indicated narrow differences between their genotypic coefficients of variation and their respective phenotypic coefficients of variation. The narrow differences suggest that the observed variability was mainly due to genetic effects (Tsegaye *et al.*, 2007; Okwuagwu *et al.*, 2008; Singh *et al.*, 2013).

Broad sense heritability, which indicates the repeatability of the performance for a trait in future generations (Sabesan *et al.*, 2009), was high for most of the traits including average number of leaves per plant, harvest index and root yield (t/ha). However broad sense heritability alone does not give a full indication of genetic gain that can be made with selection (Singh *et al.*, 2013; Pradeepkumar *et al.*, 2001). Genetic advance as a percentage of the mean performance of the different traits also revealed that much progress could be made for all the traits of interests. Traits such as average number of leaves per plant and root yield combined high broad sense heritability with high genetic advance as percentage of mean. This implies that selection of genotypes based on these traits could result in high selection gain is subsequent generations.

4.4.4 Phenotypic correlation

Association between characters provides an understanding of the basis of the complexity of yield and suggests ways of improving yield through indirect selection (Singh *et al.*, 2013). The estimates of the phenotypic correlation indicated strong association between root yield and all the traits measured except height at branching and root dry matter content. The magnitude of the association between root yield and dry matter content was insignificant indicating that the dry matter content can be improved without compromising on the yield performance (Aina *et al.*, 2007c). Cassava mosaic disease had a significant negative influence on root yield and number of leaves per plant. Earlier studies on cassava mosaic diseases (Egesi *et al.*, 2007a; Akinbo, 2008) have associated it with significant yield reduction due to reduction in leaf area and hence light interception. Root number per plant and mean root weight, which indicate the size of roots, were also positively and significantly correlated with root yield. This implies that high root number coupled with increased root sizes will result in yield improvement in cassava as observed by Aina *et al.* (2007c). Leaf retention or “stay green” under moisture stress conditions has been reported to be very useful for improving the performance of several crops, particularly cassava (Lenis *et al.*, 2006; El-Sharkawy, 2007). From this study, a strong significant positive correlation was found between leaf retention, root yield and number of roots per plant. Root yield was positively correlated with mean root weight and root number. Other selection indices can be used in indirect selection for improvement in these traits. Harvest index, which indicates the accumulation of dry matter into the economic parts of the plant (Alves, 2002; El-Sharkawy, 2004) was also found to be positively correlated with root yield. However, it is not an indication of high yield potential. For instance, a less vigorous, short cassava plant with a vigorous root system may have a high harvest index but not high root yield *per se*. For this reason, a yield standard should be set and genotypes that exceed such a target with desirable harvest index should be selected (Aina *et al.*, 2007c).

4.5 Conclusion

The study revealed significant variation for all the traits studied. The growth rate and branching habit of the genotypes which accounted for a large proportion of the genetic variability observed among the genotypes used for the study. The existence of high genetic diversity in the population was demonstrated by the SSR markers. However, the genotypes did not cluster based on the sources from which they were obtained as they did when morphological traits were used to group them. It is possible that these genotypes were related by ancestry or had narrow genetic base.

High broad sense heritability and genetic advance as a percentage of mean were also observed for most of the traits indicating the potential for genetic improvement. The analysis of phenotypic correlations also indicated positive associations among the traits and with root yield and yield components. The wide genetic variability observed among the various traits also suggests the possibility for making significant progress in the breeding programme if genotypes are selected from this population. A combination of wide genetic variability, strong genotypic variances, high broad sense heritability and significant phenotypic association between traits were also identified from the study. This provides opportunity for selection in further studies of the mechanism of leaf retention and activity, chlorophyll and stability over time and dry matter accumulation pattern under different environmental conditions.

CHAPTER FIVE

GENETIC VARIABILITY IN ABSCISIC ACID CONTENT, CARBON ISOTOPE DISCRIMINATION AND ROOT BULKING IN CASSAVA UNDER IRRIGATION AND NO IRRIGATION

5.1 Introduction

Cassava (*Manihot esculenta* Crantz) has the ability to grow in marginal ecologies where other crops fail (Okogbenin *et al.*, 2003; El-Sharkawy, 2007). Several studies have attributed cassava's ability to grow in these ecologies to its hardiness and ability to tolerate dry conditions through enhanced water use efficiency (El-Sharkawy and Cock 1984; Okogbenin *et al.*, 2003; El-Sharkawy, 2004). Effective identification of physiological traits linked to water use efficiency in cassava has been very difficult (El-Sharkawy, 2007). Various physiological and morphological mechanisms are used by cassava for survival under stress conditions which can be exploited (El-Sharkawy and Cadavid, 2002; El-Sharkawy, 2007).

The use of physiological and agronomic traits that are easily identifiable in breeding programmes (Araus *et al.*, 2002) is very effective for improving yield under abiotic stress conditions. Such traits can be used for indirect selection for yield. However, yield is a complex trait which results from interaction among several traits and their interaction with the environment whether optimal or stressful (Aina *et al.*, 2009). In some cases, direct selection for yield may simultaneously involve other secondary traits that have little to do with drought-tolerance. A better understanding of traits that are required for adaptation and productivity is therefore important (Monneveux *et al.*, 2013). Yield improvement under drought stress in various crops has been successfully achieved by using indirect selection for traits such as anthesis-silking interval in maize (Edmeades *et al.*, 2000), abscisic acid accumulation, leaf retention, stem starch accumulation (in wheat), chlorophyll content stability, stomatal conductance, canopy temperature and carbon isotope discrimination (Condon *et al.*, 2004; Lenis *et al.*, 2006; Cattivelli *et al.*, 2008).

Early root yield (bulking) in cassava has also been identified as a very important trait in drought tolerance (Nweke *et al.*, 1994; Okogbenin *et al.*, 2013). Genotypes that are able to bulk early before the on set of mosture stress are likely to suffer less damage than late bulking genotypes (Okogbenin and Fregene, 2002; Okogbenin *et al.*, 2008). However, genetic variability for these physiological traits in cassava have not been properly established. Monneveux *et al.* (2013) suggested that traits that have been exploited to improve cereals and other crops can be exploited in root crops. In cassava, abscisic acid (ABA) content has been linked to drought tolerance (Alves and Setter, 2004b; Duque and Setter, 2013). Abscisic acid promotes drought tolerance in crops through stimulation of root growth and hydraulic conductivity (Jacqmard *et al.*, 1995; Sharp and LeNoble, 2001). ABA accumulation in plants reduces stomatal aperture, promotes leaf abscission and hence limits water loss through transpiration (Zhang and Davies, 1990). However, there is scanty information regarding the genetic variability in the role of ABA content in survival and its relationship with cassava root yield under field conditions. Reports have associated leaf retention in cassava with high root yield improvement (Lenis *et al.*, 2006) through enhanced capture of large proportion of the photosynthetically active radiation (Okogbenin *et al.*, 2013). Carbon isotope discrimination which involves the preferential assimilation of the lighter carbon atom (^{12}C) to the heavier isotope (^{13}C) has been used to assess transpiration and water use efficiency in crops (Condon *et al.*, 2004). Carbon isotope discrimination has also been linked with chlorophyll content and the activities of the photosynthetic enzyme ribulose 1-5 diphosphate carboxylase (Arunyanark *et al.*, 2008). Drought has been found to degrade chlorophyll content in several crops (Karimidazeh *et al.*, 2011; Almeselmani *et al.*, 2012). Ability to maintain stable chlorophyll content under drought stress can be used as an index for drought tolerance.

Stable chlorophyll content under drought stress has been linked with improved yield for several crops including barley, wheat and potato (van der Mescht *et al.*, 1999; This *et al.*, 2000; Monneveux *et al.*, 2013). Improved yield in wheat was found to be linked with improved chlorophyll content and retention under drought stress and increased stomatal conductance (Delgado *et al.*, 1994). To develop a drought tolerant cassava variety, there is the need to understand the genetic basis of the crop's improved performance under drought stress and the pattern of dry matter accumulation.

The aim of this study was to assess the genetic variability in ABA content and carbon isotope discrimination as well as their relationships with storage root bulking under limited moisture conditions.

The objectives were to:

1. Determine the genetic variability in abscisic acid content under irrigation and no irrigation,
2. Determine the genetic variability in carbon isotope discrimination ($\Delta^{13}C$), chlorophyll content and stomatal conductance in cassava under irrigation and no irrigation,
3. Assess the effect of irrigation and no irrigation on stomatal conductance, chlorophyll content and root yield,
4. Determine the relationship between ABA, carbon isotope ratio, root yield and yield components, and
5. Determine the relationship between early dry matter accumulation and final root yield.

5.2 Materials and Methods

5.2.1. Study site

The characteristics of the study site are as described in section 4.2.1 of Chapter four of this Thesis.

5.2.2 Planting material and experimental design

Twenty cassava genotypes were selected from the preliminary evaluation (Chapter four) and used in this study (Table 5.1). These genotypes were selected based on root yield, dry matter content, harvest index and plant height. They were made up of six local landraces collected from farmers' fields, seven drought tolerant genotypes collected from the International Institute of Tropical Agriculture (IITA) and seven from the International Center for Tropical Agriculture (CIAT), Columbia. Randomised complete block design with three replications was used for the experiment under irrigation and no irrigation. A plot consisted of four rows with ten plants in a row giving a population of 40 plants in each plot.

Table 5.1 List of cassava genotypes used in the study

Genotype	Source	Genotype	Source
ATR 002	Local	00/0203	IITA
ATR 007	Local	96/1708	IITA
NWA 004	Local	I91934	IITA
*Pontisange**	Local	CTSIA 45	CIAT
*Biabasse**	Local	CTSIA 48	CIAT
UCC2001/449	Local	CTSIA 65	CIAT
TME 419	IITA	CTSIA 72	CIAT
TME 435	IITA	CTSIA 112	CIAT
96/409	IITA	CTSIA 230	CIAT
MM96/1751	IITA	CTSIA 110	CIAT

*Local farmer-preferred varieties

5.2.3 Land preparation and planting

The land was first slashed, ploughed and harrowed. Ridges were manually raised one metre apart for planting. Mature cassava cuttings measuring 25-30 cm were planted on the top of ridges at an angle of 45^o (Ekanayake, 1996) using within row spacing of one metre between plants. No fertilizer was applied to the trials but weeds were controlled as and when necessary. Reshaping of ridges was done to prevent exposure of the roots.

5.2.4 Irrigation regimes

At the beginning of the dry season (end of November), supplementary irrigation was applied using a drip irrigation system. The irrigation commenced when visible signs of moisture stress begun to appear on the plants and evaporation exceeded precipitation. No irrigation was applied to drought stressed plots. Drip laterals were laid at a spacing of one metre apart. Drip holes spaced at 30 cm interval on each line had a discharge capacity of 1.6 l/hr. This gave a discharge rate of 5.33 litres/m^2/hour. Water was supplied twice a week for four hours each day until May, 2014 when the rains stabilised.

5.2.5 Data collection

5.2.5.1 Growth parameters

Monthly data were recorded on growth parameters commencing at three months after planting. These included plant height (cm), stem girth (cm), number of leaves per plant, number of branches per plant, width of central leaf lobe (cm) and length of central leaf lobe (cm).

5.2.5.2 Abscisic acid (ABA)

Abscisic acid content (ABA) was estimated using reverse chromatography according to the procedure described in Duque and Setter (2013) below:

Three leaf disks were taken from the youngest fully expanded leaves using a 6 mm-diameter cork borer from plants in both irrigation and no irrigation plots between the hours of 10:00 and 11:00 am during March, 2014. Leaf disks were quickly put in separate wells in a 96-well plate filled with 300 µl of 80% methanol (v/v). The set up was placed on a heating mat (about 35°C) to evaporate the methanol. After complete drying, the samples packaged in transparent polythene bag and were shipped to the physiology laboratory of Cornell University, U.S.A. for ABA determination. On arrival, the samples in the 96-well plates were opened and the ABA separated with C_{18} reverse-phase chromatography (Setter and Para, 2010). ABA fractions were dried at room temperature after which they were redissolved in 100 µl of distilled water and 10 µl aliquots were analysed by enzyme-linked immunosorbant assay (ELISA) for ABA according to Setter *et al.* (2001).

5.2.5.3 Carbon isotope ratios ($\Delta^{13}C$) determination

Carbon isotope ratios have been associated with water use efficiency in crops. In order to determine the genetic variability in the efficiency of dry matter accumulation under limited moisture conditions, carbon isotope ratios were estimated. At the beginning of the dry season, the growing points of the plants in the two central rows of plots under irrigation and no irrigation plots were marked for sampling later. It was assumed that at this period genotypes would vary in their assimilation of carbon for dry matter accumulation. At harvest, samples were taken from above the marked stem portions. These samples were dried and ground into fine powder and packaged in sealable plastic bags before being shipped to the Cornell Isotope Laboratory for carbon isotope ratio estimation. About 2.5 to 3 mg of ground plant sample was weighed into tin capsules and fed into a Carlo Erba NC2500 (Italy) elemental analyzer coupled to a Thermo Scientific Delta V (Germany) isotope ratio mass spectrometer. The samples were combusted at 1000^{o}C to determine the amplitudes. To ensure accuracy and precision of the instrument, an in-house standard was analysed after every 10 samples. The delta value (Δ^{13}C) was corrected against a primary reference scale. The primary reference scale was Vienna Pee Dee Belemite.

5.2.5.4 Stomatal conductance and leaf temperature

Cassava plants have been found to partially close their stomata (El-Sharkawy, 2007) in response to mild stress resulting in reduced stomatal conductance and increase in leaf temperature. Stomatal conductance is the measure of the rate of passage of carbon dioxide (CO_2) or water vapour through the stomata of the leaf (Decagon, 2008). Stomatal conductance was measured to establish the genetic variation in the sensitivity of the different genotypes under limited moisture. Stomatal conductance (mmol/m^{2}s^{-1}) and leaf temperature (^{o}C) were simultaneously measured using a leaf porometer (Decagon services, U.S.A.). Data collection commenced in October, 2013 when the plants were four months old and continued until April, 2014. The readings were taken from the abaxial portion of the third fully expanded leaf on two plants from each plot between the hours of 10:00 – 13:00 each day.

5.2.5.5. Chlorophyll content

Leaf chlorophyll content was measured using the SPAD chlorophyll meter. Four plants from each plot were taken for the readings. Three parts of each plant consisting of the top (third fully expanded leaf), the middle part and the bottom leaf were evaluated. The mean of the three regions was computed to represent the chlorophyll content for each plant. Data collection commenced at three months after planting.

5.2.5.6 Photosynthetically active radiation (PAR)

The amount of photosynthetically active radiation (PAR) was measured using the sunflecks ceptometer (Decagon Services, U.S.A.). Ten readings were taken under the plant canopy to determine how much light passed through the canopy unto the soil surface. Another set of 10 readings were taken above the canopy to know the amount of incoming solar radiation. The averages of these readings were computed to represent the reading for the plot. The amount of PAR was estimated as the difference between the readings taken in the open minus the reading taken under the plant canopy.

The percentage of PAR (%PAR) was estimated as:

$$\%\mathrm{PAR} = \frac{\text{PAR captured}}{\text{Total incoming radiation}} \times 100$$

5.2.5.7 Fresh root yield (t/ha) and yield components:

Four sequential harvests were done at six, eight, ten and at twelve months after planting under both irrigation and no irrigation. At each harvest, 10 roots were selected from four plants and measured from one tip to the other with a tape measure to determine root length (cm). Root girth (cm) was also determined by measuring the widest portion of the same roots using vernier callipers. Root length/girth ratio was also calculated. Number of storage roots per plant was also recorded. Mean root weight (g) was determined from the weight of roots divided by the total number of roots harvested from each plot.

5.2.5.8 Root dry matter content

This was estimated following the procedure described under Section 4.2.4.2 in Chapter four of this Thesis.

5.2.5.9 Soil moisture monitoring

Soil moisture was monitored using a probe but access tubes were first installed in each replication under both irrigation and no irrigation treatment plots to facilitate the readings. The access tube was inserted up to a depth of one metre to facilitate the readings with the probe. Soil moisture was monitored by inserting a portable soil moisture probe, Delta-T Profile Probe type PR2 (Delta-T Devices Ltd, UK) following the user manual. The probe which was one metre in length was equipped with A Delta-T HH2 Moisture Meter for making the readings. Readings were taken from 25 cm and 50 cm below the soil surface from six months after planting at the beginning of the dry season.

5.2.6 Data analysis

General analyses of variance were performed for all traits using the GenStat statistical package (Payne *et al.,* 2009). Genotypes and irrigation regimes were considered as factors to assess the genotypic response to drought stress. To estimate genetic variability in root yield at different times under irrigation and no irrigation, harvest time, genotypes and their interactions were considered as independent factors. Pearson's correlation was used to determine associations among physiological traits and with root yield. Significant differences between genotypes under irrigation and no irrigation were detected using their standard errors of differences. Two sample t-test was performed to compare the mean performance of all genotypes under irrigation and no irrigation using the GenStat version 12.1 (Payne *et al.,* 2009).

5.3 Results

5.3.1 Weather conditions during the period of the experiment

Total rainfall recorded over the experimental period was 1181.1 mm whilst that of evaporation was 1823.26 mm (Table 5.2). In addition, a total of 853.3 mm of water was applied to the irrigated plots. This gave a total quantity of 2034.43 mm of water for use by the plants under irrigation. Monthly fluctuations in rainfall, evaporation, relative humidity and temperature were observed during the period indicated (Table 5.3). The highest amount of rainfall (217.4 mm) was recorded in August, 2013 whilst no rain was recorded in November and December, 2013. Average minimum temperature and maximum temperature were 24.16 and 33.67 ^{o}C, respectively with mean of 28.71 ^{o}C, recorded for the entire season. The highest monthly evaporation (223.32 mm) was recorded in March, 2014 which also had the highest temperature (37.5 ^{o}C). There were fluctuations in the distribution of rainfall and evaporation (Fig. 5.1a). Monthly evaporation exceeded rainfall from November, 2013 to May, 2014. Relative humidity also declined from September, 2013 till February, 2014 before it started to rise again. Temperature fluctuations were also observed over the period of the experiment (Fig. 5.1b).

Table 5.2 Total water use and evaporation under irrigation and no irrigation

	Irrigation	**No irrigation**
Irrigation water applied (mm)	853.33	0.00
Amount of rainfall (mm)	1181.1	1181.10
Total water supplied	2034.43	1181.10
Evaporation (mm)	1823.26	1823.26

Table 5.3 Rainfall, evaporation, temperature and relative humidity during the period of the experiment

Months	Rainfall (mm)	Evaporation (mm)	Temperature (ºC)			Relative humidity (%)		
			Min	**Max**	**Mean**	**Min**	**Max**	**Mean**
Jun-13	161.9	111.02	24.3	31.1	27.8	68.0	89.0	79.0
Jul-13	203.8	89.2	23.6	29.7	26.7	75.0	93.0	84.0
Aug-13	217.4	78.86	22.9	28.9	25.9	75.0	93.0	84.0
Sep-13	164.1	77.64	22.6	30.2	26.4	74.0	93.0	79.0
Oct-13	119.7	97.72	23.2	32.0	27.6	68.0	90.0	79.0
Nov-13	23.3	122.88	22.9	35.0	29.0	53.0	83.0	68.0
Dec-13	0	167.69	19.6	35.5	27.5	52.0	68.0	60.0
Jan-14	0	185.04	26.8	35.9	28.4	36.0	56.0	46.0
Feb-14	2.4	202.2	23.0	36.8	29.9	32.0	55.0	44.0
Mar-14	25.7	223.32	26.2	37.5	31.9	43.0	67.0	55.0
Apr-14	50.7	176.45	26.6	36.4	31.5	53.0	81.0	67.0
May-14	45.6	174.16	26.8	35.5	31.2	56.0	83.0	70.0
Jun-14	166.5	117.08	25.6	33.2	29.4	64.0	88.0	76.0
Average	**90.85**	**140.25**	**24.16**	**33.67**	**28.71**	**57.6**	**79.9**	**68.5**
Total	**1181.1**	**1823.26**						

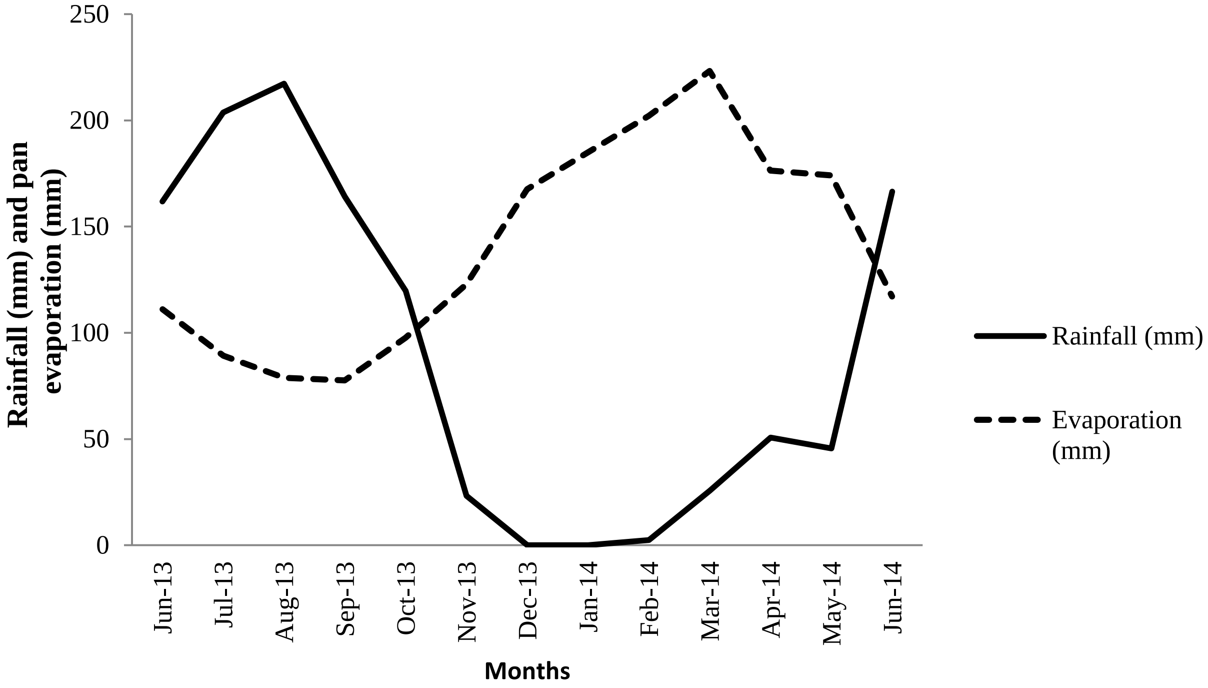


Fig. 5.1a Monthly rainfall distribution and evaporation during the period of the experiment (June, 2013 –June, 2014).

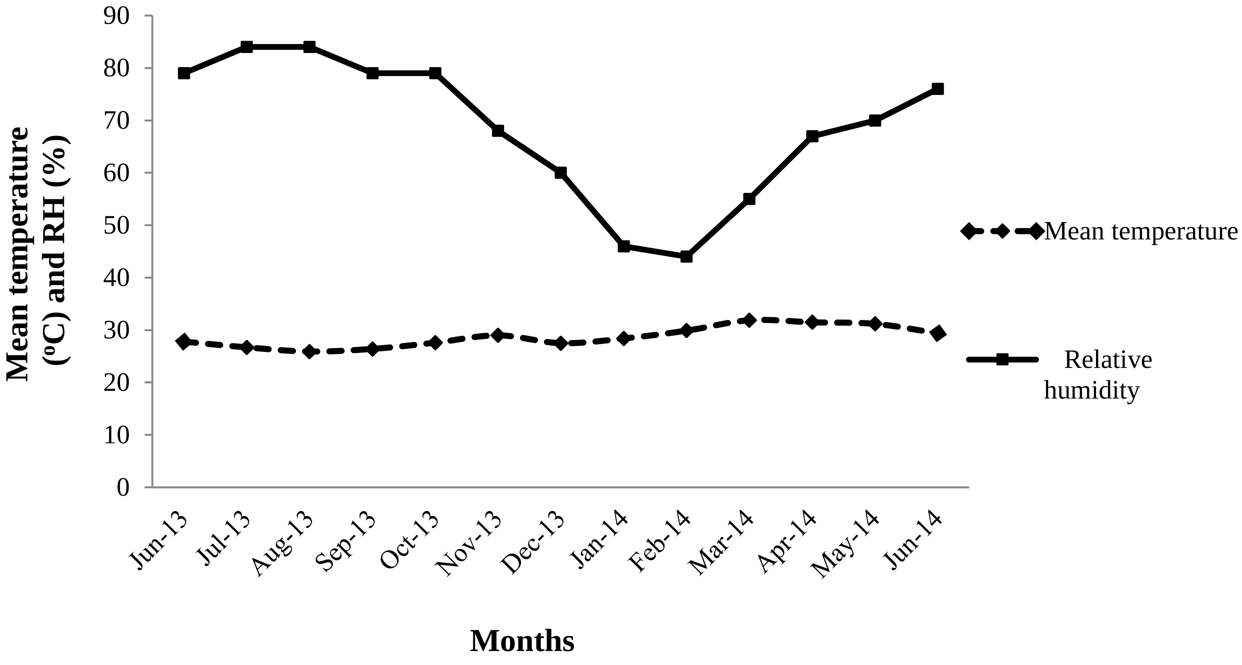


Fig. 5.1b Relative humidity and mean temperature during the period of the experiment (June, 2013 –June, 2014).

5.3.2 Soil moisture content

Results of the soil moisture content (%) at the two depths from October, 2013 to May, 2014 under irrigation and no irrigation are presented in Fig. 5.2. Apart from the month of October, soil moisture contents were higher under irrigation than under no irrigation. The decline in soil moisture was also faster under no irrigation than under irrigation. Moisture content at 50 cm depth was higher under irrigation from October to December. From January to May, soil moisture content at 25 cm depth was higher than the moisture content at 50 cm due the irrigation water supplied.

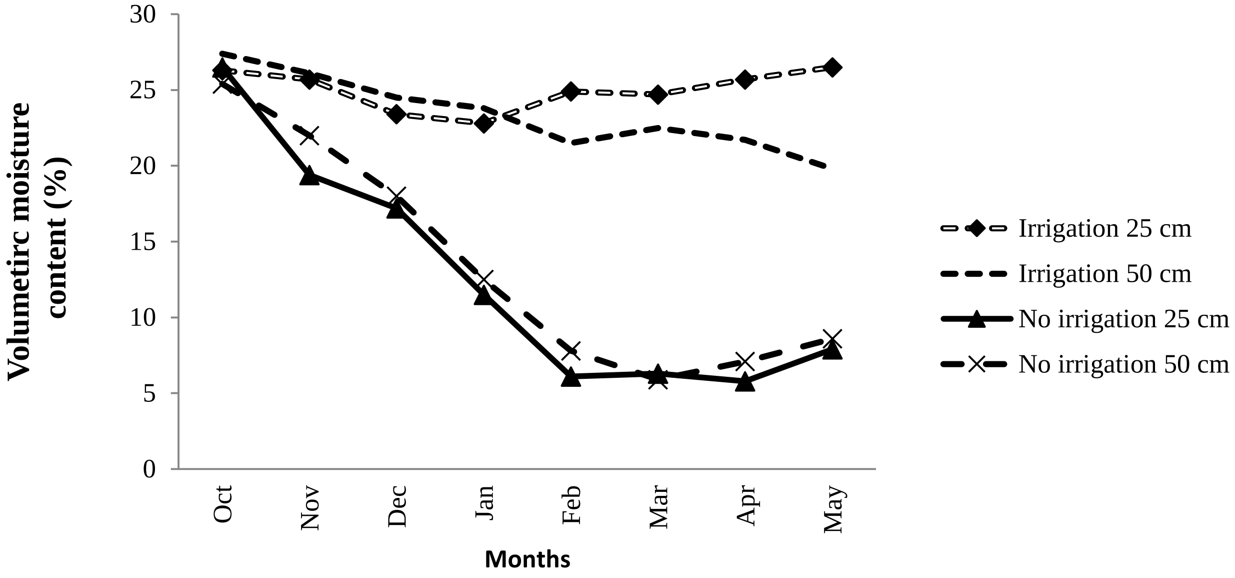


Fig. 5.2 Soil moisture content (%) at 25 and 50 cm under irrigation and no irrigation from October, 2013 to May, 2014.

5.3.3 Mean squares for abscisic acid content (ABA), carbon isotope (Δ^{13}C) and intercepted solar radiation under irrigation and no irrigation

Highly significant (P<0.01) genotype and very highly significant (P<0.001) irrigation treatment effects were observed for ABA (Table 5.4). The interaction of genotype and irrigation effect was significant (P>0.05). In the case of Δ^{13}C, significant (P<0.05) genotype effect was observed but the effects of irrigation and the interaction with genotype were not significant (P>0.05). Percentage of photosynthetically active radiation (%PAR) captured was highly significant (P<0.01) for genotype and very highly significant (P<0.001) for irrigation but their interaction was also not significant (P>0.05).

Table 5.4 Mean squares for abscisic acid (ABA) content, carbon isotope ratio ($\Delta^{13}C$) and percentage of captured radiation (%PAR) of 20 cassava genotypes under irrigation and no irrigation

Source of variation	d.f.	ABA (pmol/mm^2)	$\Delta^{13}C$ (‰)	%PAR
Genotype (G)	19	0.066**	0.197*	342.4**
Treatment (I)	1	4.618***	0.237NS	7512.1***
GxI	19	0.088NS	0.056NS	87.1NS
Error	78	0.057	0.108	137.9

*, **, *** = significant at $P<0.05$, $P<0.01$, and $P<0.001$ respectively. NS = Not significant ($P>0.05$).

5.3.4 Analysis of variance for physiological and growth traits

In the analysis of the growth and physiological parameters, genotype, irrigation treatment and harvesting time of roots were considered as factors. Very highly significant ($P<0.001$) genotype effects were seen on all traits except leaf temperature (°C) (Table 5.5). Irrigation treatment had a highly significant ($P<0.01$) effect on all physiological traits except leaf chlorophyll content. The time of harvest had significant effect ($P<0.05$) on leaf chlorophyll content and very highly significant effect ($P<0.001$) on all traits except width of central lobe which was significant at $P<0.01$. Apart from leaf chlorophyll content and leaf temperature (°C), significant interaction was observed for all the other traits. Effect of combined interaction between genotype, irrigation treatment and harvest time on all the traits was insignificant ($P>0.05$).

Table 5.5 Mean squares for physiological and growth traits

Source of variation	df	Chrl	St_con (mmol/m2s-1)	L_temp (oC)	Plt_ht (cm)	Levs/plt	Lo_length (cm)	Lo_width (cm)
Genotype (G)	19	490.3***	4114***	2.23NS	14570.0***	10207.0***	19.44***	3.65***
Irrigation (I)	1	403.6NS	528636***	288.93***	122268.0***	90191.7***	373.90***	7.53***
Harvest time (H)	3	632.9*	184786***	19.76***	4859.9***	100462.7***	249.33***	1.56**
GxI	19	362.7**	1311NS	1.92NS	1329.9***	991.6*	5.29***	0.51NS
GxH	57	136.3NS	1828NS	1.07NS	184.7NS	866.2*	1.95NS	0.35NS
IxH	3	56.4NS	142174***	3.43NS	2052.5***	11519.4***	49.72***	1.31*
GxIxH	57	181.8NS	1718NS	1.43NS	104.4NS	282.5NS	1.87NS	0.35NS
Error	308	182.1	1450	2.03	350.4	580.2	1.71	0.37

*, **, *** = significant at $P<0.05$, $P<0.01$, and $P<0.001$ respectively. NS = Not significant ($P>0.05$). Chrl = leaf chlorophyll content, St_con (mmol/m^{2}s) = stomatal conductance, L_temp (°C) = leaf temperature, Plt_ht (cm) = plant height, No.Levs/plt = number of leaves per plant, Lo_length (cm) = length of central leaf lobe, Lo_width (cm) = width of central leaf lobe

5.3.5 Mean squares for root yield and yield components

Very highly significant (P<0.001) genotype and irrigation treatment effects were observed for root yield (t/ha) and all yield components (Table 5.6). With the exception of root number per plant, harvest time had very high significant effect (P<0.001) on root yield and yield components. Very highly significant (P<0.001) genotype by irrigation treatment effect was again observed on root yield (t/ha) and above ground biomass (t/ha). Genotype x irrigation treatment effect was highly significant (P<0.01) for harvest index and significant (P<0.05) for number of roots per plant but the effect on mean root weight (g), root girth (cm) and root length (cm) was not significant (P>0.05). Interaction of genotype and harvest time effect was insignificant (P>0.05) for yield and all yield components except root girth and dry matter content. Effect of harvest time x irrigation treatment interaction was also insignificant (P>0.05) for all traits except root length (cm) and root number per plant. However, genotype by treatment by harvest time interaction effects for all the root yield and yield components were not significant (P>0.05).

Table 5.6 Mean squares for root yield and yield components

Source of variation	**Df**	**Rt_yld (t/ha)**	**AGB (t/ha)**	**HI**	**MRW (g)**	**Rt_girth (cm)**	**Rt_length (cm)**	**Rt_no/plt**	**DM%**
Genotype (G)	19	195.86***	60.83***	0.094***	47741***	5.61***	443.69***	37.29***	140.18***
Irrigation (I)	1	2047.91***	2733.22***	0.039***	269826***	93.69***	3235.29***	192.22***	87.85***
Harvest time (H)	3	2705.53***	2101.14***	0.216***	392571***	143.83***	3709.37***	3.40NS	880.85***
GxI	19	23.91***	23.65***	0.007**	6158NS	0.72NS	33.39NS	8.04*	10.52NS
GxH	57	12.012NS	5.98NS	0.003NS	3757NS	1.13***	32.85NS	3.02NS	11.96**
IxH	3	660.14***	93.64***	0.210***	191277***	24.82***	53.06NS	3.57NS	550.24***
GxIxH	57	6.99NS	6.724NS	0.003NS	4471NS	0.68NS	34.52NS	2.98NS	7.764NS
Error	308	9.21	7.95	0.003	3881	0.6	33.4	4.86	7.46

*, **, *** = P<0.05, P<0.01, and P<0.001, NS = Not significant (P>0.05). Rt_yld (t/ha) = root yield (t/ha), AGB (t/ha) = above ground biomas (t/ha), HI = harvest index, MRW (g) = mean root weight (g), Rt_girth (cm) = root girth (cm), Rt_length (cm) = root length (cm), Rt_no/plt =root number per plant, DM% = root dry matter content (%).

5.3.6 Relationship between traits

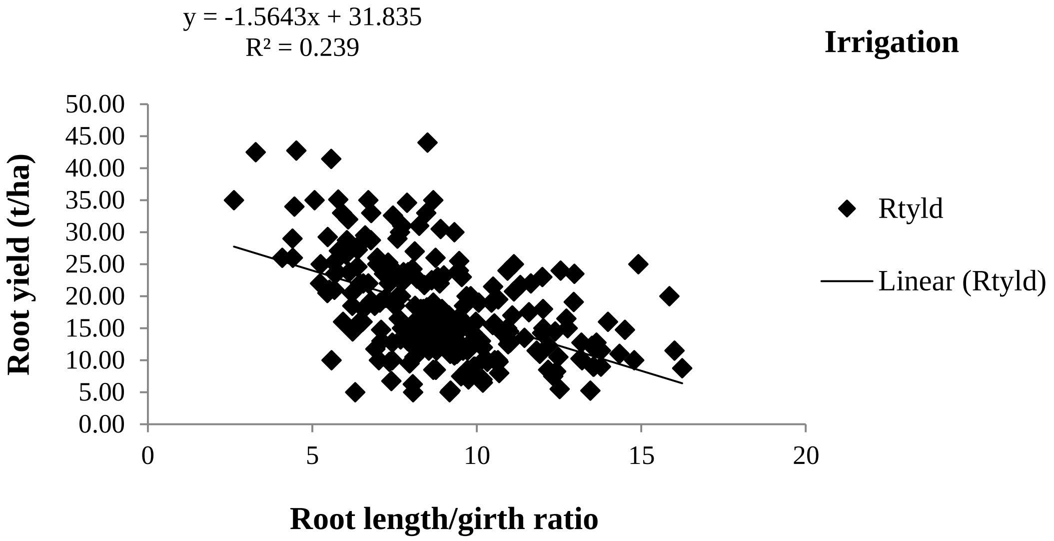
Abscisic acid content was negatively correlated with root yield and a number of traits associated with root yield (Table 5.7). For instance, root yield was significantly and positively correlated with root girth (cm), stomatal conductance, percentage of captured photosynthecally active radiation (%PAR), above ground biomass (t/ha), mean root weight (g), harvest index and dry matter content. All these traits were significantly and negatively correlated with ABA content. The correlation between ABA with number of leaves per plant was not significant ($P>0.05$).

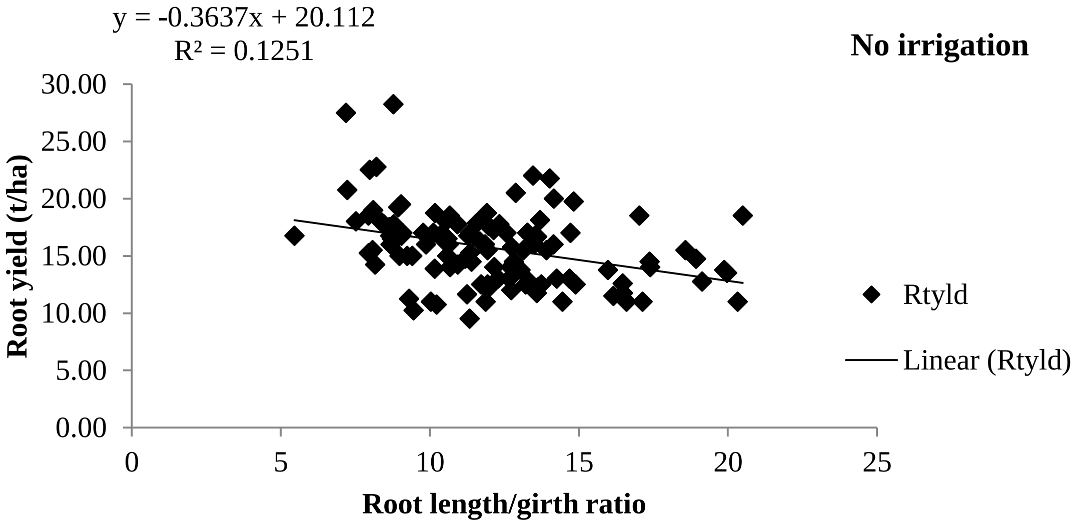
Carbon isotope ratio ($\Delta^{13}C$) had a weak and insignificant ($P>0.05$) correlation with root yield but was significantly correlated with root girth and above ground biomass which are both positively correlated with root yield. Proportion of captured radiation (%PAR) was very highly significant ($P<0.001$) and positively correlated with stomatal conductance, root yield, mean root weight, root girth and harvest index. Highly significant negative correlation was observed between %PAR and ABA content, and root length/girth ratio. Harvest index was positively and significantly correlated with stomatal conductance, mean root weight and root girth. Root yield was positively correlated with root girth but negatively correlated with root length. Root length/ root girth ratio was derived to determine whether dry matter allocation was correlated with root extension or expansion. Root length/girth ratio was negatively correlated with most of the traits that are positively correlated with root yield. There was no correlation between root length/girth ratio and $\Delta^{13}C$ (‰). However, the root length/girth ratio was significantly and negatively correlated with all the traits except ABA content whose correlation was positive. Analysis of the relationship between root length/girth ratio under no irrigation, irrigation and combined analysis gave a negative slope for the relationships (Fig. 5.3). The coefficients of determination (r^2) were 0.239 under irrigation, 0.125 under no irrigation and 0.303 in the combined analysis.

Table 5.7 Phenotypic correlations between Δ^{13}C, ABA, stomatal conductance, root yield and yield components of 20 cassava genotypes

Δ^{13}C (‰)	1	1												
ABA	2	-0.16NS	1											
St_con	3	-0.23**	-0.24**	1										
AGB (t/ha)	4	0.20*	-0.20*	-0.23**	1									
% PAR	5	-0.03NS	-0.23**	0.31***	0.11NS									
Rtyld (t/ha)	6	0.09NS	-0.45***	0.28**	0.41***	0.49***	1							
MRW (g)	7	0.05NS	-0.46***	0.47***	0.09*	0.58***	0.71***	1						
Rt_girth	8	0.24**	-0.34***	0.33***	0.17*	0.51***	0.77***	0.64***	1					
Rt_length	9	-0.09NS	0.17NS	-0.03NS	-0.21*	-0.16NS	-0.11NS	-0.01NS	-0.17NS	1				
HI	10	-0.02NS	-0.43***	0.50***	-0.21*	0.51***	0.71***	0.76***	0.61***	0.07NS	1			
DM%	11	-0.15NS	-0.33***	0.33***	0.21*	0.24**	0.23**	0.26**	0.21*	-0.15NS	0.17NS	1		
L/G	12	-0.10NS	0.39***	-0.30**	-0.27**	-0.51***	-0.61***	-0.57***	-0.70***	0.69***	-0.47***	-0.25**	1	
Levs/plt	13	0.13NS	-0.15NS	-0.05NS	0.59***	0.19*	0.45***	0.21*	0.22**	-0.21*	0.11NS	0.35***	-0.31***	1
Chlr	14	-0.12NS	0.06NS	-0.04NS	0.03NS	-0.08NS	-0.05NS	-0.13NS	-0.14NS	0.15NS	-0.07NS	-0.03NS	-0.05NS	-0.01NS
		1	2	3	4	5	6	7	8	9	10	11	12	13

*,**,***= significant at P<0.05, P<0.01 and P<0.001 respectively, NS = not significant (P>0.05), %_13C (‰) = Carbon isotope ratio, ABA (pmol/mm^2) = Abscisic acid content, St_con (mmol/m^{2}s^{-1}) = stomatal conductance, AGB (t/ha) = above ground biomas yield, %PAR = Percentage of captured photosynthetically active radiation, Rtyld (t/ha) = root yield, MRW (g) =mean storage root weight, Rt_girth (cm) = root girth, Rt_length (cm) = root length, HI = harvest index, DM% root dry matter content, L/G = Root length : girth ratio, Levs/plt =Number of leaves per plant, Chlr = Leaf chlorophyll content





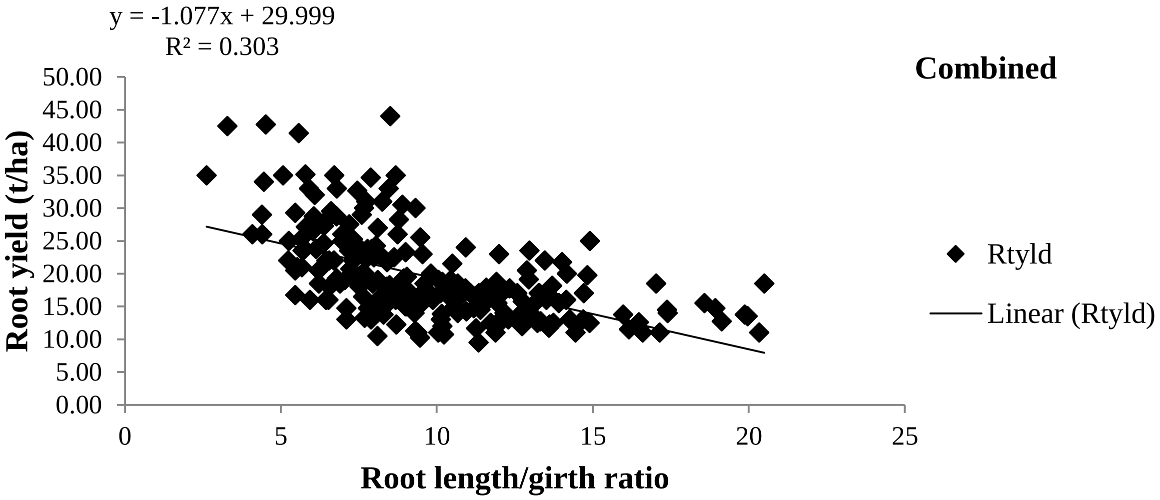


Fig. 5.3 Root length/girth ratio under irrigation, no irrigation and combined analysis

5.3.7 Performance of genotypes

5.3.7.1. Carbon isotope ratio (Δ^{13}C), abscisic acid (ABA) content and photosynthetically active radiation.

Though moisture stress had significant effect on ABA content and percentage of intercepted solar radiation, variable responses of genotypes were observed (Table 5.8). Under no irrigation, CTSIA 230 had the lowest Δ^{13}C ratio (-25.87‰) whilst CTSIA 112 had the highest (-26.79 ‰). The highest Δ^{13}C ratio under irrigation was again exhibited by CTSIA 112 (-26.69‰) and the lowest of -25.97‰ by MM 96/1751. Means of all genotypes under no irrigation and irrigation were not significantly different according to the t-test (P=0.167).

Both genotype and irrigation effects were significant for ABA content but their interaction was not significant. Moisture stress significantly influenced mean ABA content in the different genotypes. Under no irrigation, *Biabasse* accumulated the highest amount of ABA (0.93 pmol/mm^2) while TME 419 accumulated the least amount (0.32 pmol/mm^2). Under irrigation, ABA content ranged from 0.07pmol/mm^2 for ATR002 to 0.54 pmol/mm^2 for I91934.

The proportion of the photosynthetically active radiation (%PAR) significantly varied among the genotypes and the treatments. It was used as an indicator of leaf retention during the stress period. The %PAR under no irrigation varied from 4.9% to 33.69% for CTSIA 45 and *Pontisange*, respectively. However, under irrigation, the proportion of captured PAR varied from 23.23% for CTSIA 112 to 52.1% for *Biabasse*.

Table 5.8 Genotype x irrigation effect on abscisic acid (ABA) content, carbon isotope ratio (Δ^{13}C) and percentage of intercepted solar radiation (%PAR) of 20 cassava genotypes

Genotypes	**Δ^{13}C (‰)**		**ABA (pmol/mm^2)**		**%PAR**	
	Irrigation	**No irrigation**	**Irrigation**	**No irrigation**	**Irrigation**	**No irrigation**
00/0203	-26.23	-26.15	0.09	0.53	46.28	26.51
96/1708	-26.42	-26.54	0.23	0.50	38.70	25.97
96/409	-26.34	-26.36	0.23	0.75	38.39	33.59
ATR 002	-26.27	-26.48	0.33	0.83	38.22	28.09
ATR 007	-26.03	-26.42	0.07	0.90	24.12	22.46
*Biabasse**	-26.15	-26.44	0.27	0.93	52.10	27.87
CTSIA 110	-26.52	-26.52	0.34	0.47	24.66	13.94
CTSIA 112	-26.69	-26.79	0.22	0.84	23.23	22.38
CTSIA 230	-26.18	-25.87	0.33	0.63	37.54	17.71
CTSIA 45	-26.25	-26.23	0.40	0.67	28.29	4.90
CTSIA 48	-26.31	-26.35	0.29	0.35	41.89	24.56
CTSIA 65	-26.37	-26.16	0.49	0.68	37.44	14.73
CTSIA 72	-26.22	-26.31	0.27	0.78	40.12	25.72
I91934	-26.04	-25.98	0.54	0.60	49.73	23.22
MM 96/1751	-25.97	-25.94	0.23	0.34	33.60	18.58
NWA 004	-26.32	-26.4	0.21	0.59	31.54	8.74
*Pontisange**	-26.17	-26.43	0.11	0.78	42.92	33.69
TME 419	-26.05	-26.2	0.25	0.32	50.92	27.93
TME 435	-26.17	-26.5	0.26	0.84	51.84	32.42
UCC 2001/449	-26.06	-26.51	0.19	0.85	36.74	19.30
Mean	**-26.24**	**-26.33**	**0.27**	**0.66**	**38.41**	**22.62**
SED	**-0.23**	**-0.30**	**0.07**	**0.14**	**7.99**	**5.16**
t (cal)(means)	1.41NS		7.76		5.91	
$t_{0.05(2), 38}$	2.024		2.024		2.024	

* Local farmer-preferred varieties, NS = not significant (P = 0.167).

5.3.7.2 Stomatal conductance, leaf temperature and leaf chlorophyll content

Stomatal conductance was significantly (P<0.001) influenced by genotype and moisture stress (Table 5.9). Mean stomatal conductance values for all genotypes under no irrigation and irrigation were 122.12 mmol/m^{2}s^{-1} and 178.98 mmol/m^{2}s^{-1}, respectively. Under irrigation, Stomatal conductance ranged from 157.00 mmol/m^{2}s^{-1} (TME 419) to 208.9

mmol/m^{2}s^{-1} (CTSIA 112). The genotypes showed variable responses under no irrigation. A range of 104.00 mmol/m^{2}s^{-1} to 143.80 mmol/m^{2}s^{-1} was observed for CTSIA 230 and *Pontisange*, respectively. Analysis of stomatal conductance over the period of the experiment indicated low values for the months of January, February and March (Fig. 5.4). Overall, average stomatal conductance was maintained at a higher rate under irrigation than under moisture stress.

The genotypes also had higher average leaf temperature under no irrigation than under irrigation (Table 5.9). Average leaf temperature for all genotypes was 34.16^{o}C under irrigation which was significantly ($P<0.001$) lower than the mean for all genotypes under no irrigation (34.86^{o}C). The differences observed among genotypes under moisture stress were not significant among the genotypes. However, differential responses of the genotypes were observed under irrigation. TME 435 had the lowest leaf temperature of 32.05^{o}C and CTSIA 72 had the highest of 35.18^{o}C. Leaf temperature fluctuations were observed during the period of the study (Fig. 5.5).

Leaf chlorophyll content was lower under irrigation than no irrigation but not significantly different according to the t-test (Table 5.9). The mean chlorophyll content of all genotypes under irrigation was 49.09 whilst that under no irrigation was 50.87. However, significant genetic variation was observed under irrigation and no irrigation. Chlorophyll content under irrigation ranged from 40.11 (*Biabasse*) to 60.13 (CTSIA 48). Again, CTSIA 48 had the highest chlorophyll content (61.15) under no irrigation which was significantly ($P<0.05$) different from most of the other genotypes including NWA 004 (40.98).

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Table 5.9 Genotype x irrigation effect on stomatal conductance, leaf temperature and chlorophyll content of 20 cassava genotypes

Genotypes	**Stomatal conductance (mmol/m^{2}s^{-1})**		**Leaf temp (°C)**		**Chlorophyll content**	
	Irrigation	**No irrigation**	**Irrigation**	**No irrigation**	**Irrigation**	**No irrigation**
00/0203	181.1	120.7	33.97	35.20	45.63	57.8
96/1708	185.7	117.8	34.29	35.88	51.49	46.62
96/409	178.4	127.0	34.24	33.93	42.60	46.38
ATR 002	182.5	113.0	34.20	34.91	43.71	44.06
ATR 007	174.9	114.5	33.95	35.05	46.37	42.74
*Biabasse**	165.0	116.7	33.78	35.18	40.11	46.03
CTSIA 110	180.7	130.2	34.00	36.03	48.86	50.57
CTSIA 112	208.9	104.1	34.03	35.42	49.43	55.70
CTSIA 230	181.2	104.0	33.93	35.02	46.73	51.44
CTSIA 45	182.1	111.5	34.45	35.13	53.03	49.21
CTSIA 48	195.5	114.0	34.21	35.32	60.13	61.15
CTSIA 65	176.9	124.4	34.59	33.87	55.48	58.12
CTSIA 72	183.2	119.4	34.37	35.46	54.23	60.36
I91934	164.1	140.0	34.33	35.35	52.15	52.70
MM 96/1751	193.7	118.5	34.19	35.18	51.23	48.84
NWA 004	168.4	112.3	34.73	34.02	41.63	40.98
*Pontisange**	185.1	143.8	34.16	34.38	50.55	51.78
TME 419	157.0	133.6	33.89	34.28	50.23	54.34
TME 435	173.7	135.5	33.90	33.48	52.74	48.89
UCC 2001/449	161.4	141.5	34.08	34.05	45.47	49.78
Mean	**178.98**	**122.12**	**34.16**	**34.86**	**49.09**	**50.87**
SED	**16.34**	**24.42**	**2.40**	**0.72**	**4.57**	**4.662**
t (cal)(means)	8.19		5.28		NS	
$t_{0.05(2), 38}$	2.024		2.024		2.024	

* Local farmer-preferred varieties, NS=not significant (P= 0.302)

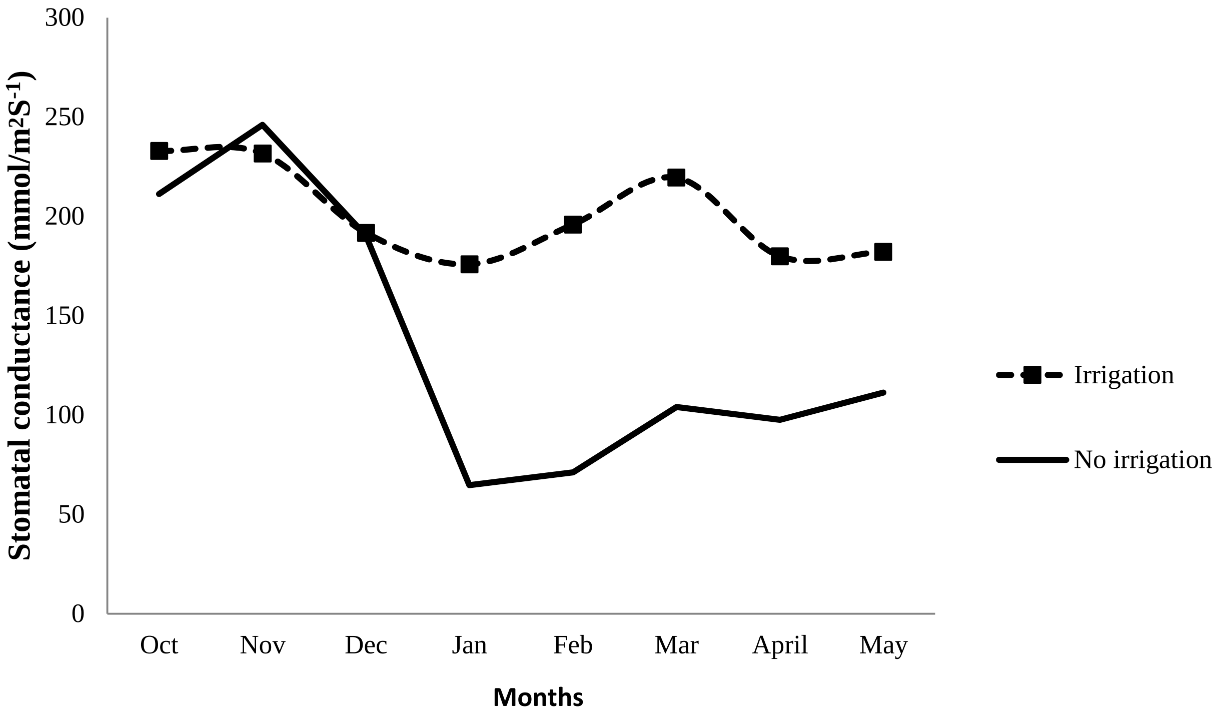


Fig. 5.4 Variation in stomatal conductance (mmol/m^{2}s^{-1}) from October to May under irrigation and no irrigation

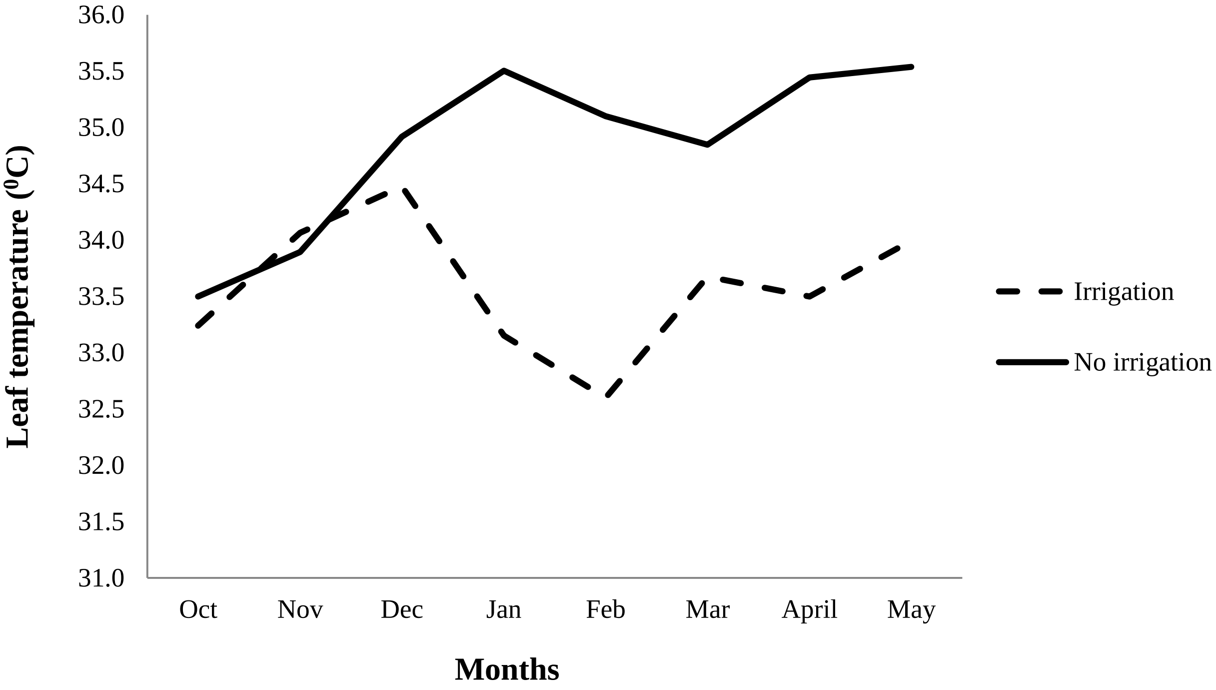


Fig. 5.5 Leaf temperature (°C) variability under irrigation and no irrigation from October to May

5.3.7.3 Plant height, leaf production, expansion of central leaf lobe

Plant growth was significantly affected by moisture stress. Rate of increase in plant height (cm) was reduced during the dry months (Fig. 5.6). Significant ($P<0.05$) variations were observed among genotypes under irrigation and no irrigation (Table 5.10). Average plant height (cm) at harvest for all genotypes was 125.87 and 163.18 cm under no irrigation and irrigation, respectively. CTSIA 72 had the tallest plants, 236.8 cm, while ATR 002 had the shortest, 121.3 cm at harvest. Under no irrigation, CTSIA 110 had the tallest plants (171.7 cm) compared to 96/1708 which had the shortest (88.50 cm).

Rate of new leaf production varied over the different months being particularly higher under irrigation than under no irrigation (Fig. 5.7). The average number of leaf scars per plant was however higher under no irrigation than under irrigation. The highest number of leaf scars per plant was recorded in January, when the weather was hot (Fig. 5.8). Genotypes differed significantly in number of leaves per plant (Table 5.10). Average number of leaves per plant was 118.49 under irrigation and 40.84 under no irrigation. I91934 retained more leaves under both conditions than all the other genotypes. MM96/1751 had the least number of leaves per plant under both conditions.

Leaf sizes were very highly significantly ($P<0.001$) affected by moisture stress and genotypes differed in their response as can be seen from the width and length of the central leaf lobes. Genotypes varied in the extent to which they were affected (Table 5.10) when the sizes were compared under both conditions. Under irrigation, TME 419 had the longest central leaf lobe of 13.1 cm as compared to the shortest of 7.65 cm for CTSIA 112. Under no irrigation, CTSIA 110 had the longest central leaf lobe length of 7.77 cm while CTISA 72 had the shortest lobe central leaf length of 5.28 cm. Average central leaf lobe widths (cm) at harvest for all genotypes were 2.58 cm and 1.91 cm under irrigation and no irrigation, respectively. TME 419 had the widest lobes with CTSIA 110 having the smallest central leaf lobe width under irrigation. Central leaf Lobe width under no irrigation was generally low with a range from 1.27 cm to 2.28 cm.

Table 5.10 Plant height, number of leaves/plant and dimensions of central leaf lobe of 20 cassava genotypes under irrigation and no irrigation

Genotypes	Plant height (cm)		Leaves/plant		Central leaf lobe length (cm)		Central leaf lobe width (cm)	
	Irri	**No irri**	**Irri**	**No irri**	**Irri**	**No irri**	**Irri**	**No irri**
00/0203	123.80	90.00	142.60	25.40	7.68	6.12	2.35	1.85
96/1708	121.90	88.50	84.60	17.60	8.57	6.38	2.10	1.90
96/409	153.20	121.60	119.70	29.80	9.80	5.85	3.33	1.92
ATR 002	121.30	110.60	116.00	61.90	8.87	6.00	2.30	1.93
ATR 007	180.80	144.80	98.80	39.20	8.20	5.83	2.42	2.17
*Biabasse**	136.80	116.80	113.40	47.20	8.47	6.17	2.48	2.28
CTSIA 110	212.80	171.70	138.70	58.30	11.93	7.77	1.32	1.30
CTSIA 112	187.30	136.90	127.30	39.50	7.65	5.43	2.42	1.97
CTSIA 230	197.30	148.20	181.80	61.20	9.67	6.87	1.70	1.52
CTSIA 45	159.20	120.60	121.50	53.40	10.83	6.70	1.70	1.27
CTSIA 48	127.90	116.50	117.80	39.10	9.35	5.87	2.92	2.03
CTSIA 65	224.80	161.40	105.40	47.30	9.78	6.33	2.72	2.28
CTSIA 72	236.80	147.80	87.60	31.10	8.83	5.28	2.65	1.72
I91934	136.60	106.50	190.00	80.70	8.48	5.83	2.57	1.90
MM 96/1751	156.60	112.00	74.70	12.10	11.13	5.33	3.12	1.75
NWA 004	172.30	132.70	98.40	31.40	8.95	5.70	2.92	2.00
*Pontisange**	152.50	149.40	89.80	26.10	10.73	5.78	3.07	2.05
TME 419	168.10	112.30	97.80	45.60	13.10	7.12	3.85	2.42
TME 435	135.20	113.30	122.10	43.80	10.27	6.28	3.20	2.13
UCC 2001/449	158.30	115.80	141.70	26.10	9.75	6.93	2.45	1.83
Mean	**163.18**	**125.87**	**118.50**	**40.80**	**9.60**	**6.18**	**2.58**	**1.91**
SED	**23.21**	**16.52**	**18.95**	**11.32**	**1.045**	**0.786**	**0.544**	**0.481**
t (cal)(means)	4.06		10.11		9.86		4.44	
$t_{0.05(2), 38}$	2.024		2.024		2.024		2.024	

* Local farmer-preferred varieties, Irri = irrigation, No irri = no irrigation

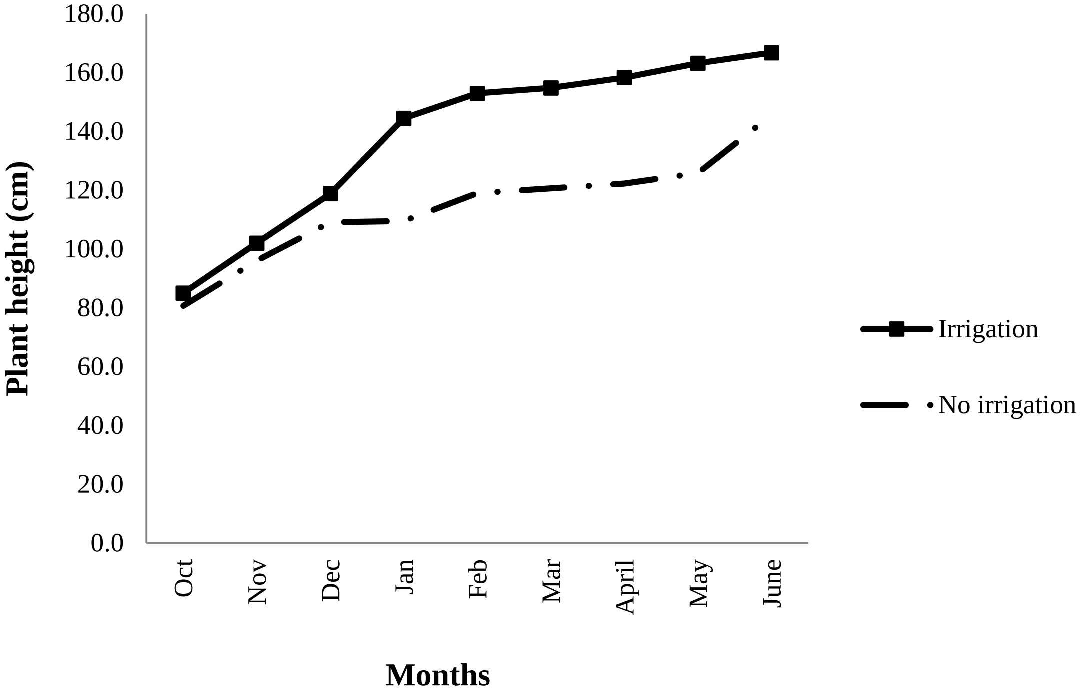


Fig. 5.6 Mean plant height (cm) at different months under irrigation and no irrigation

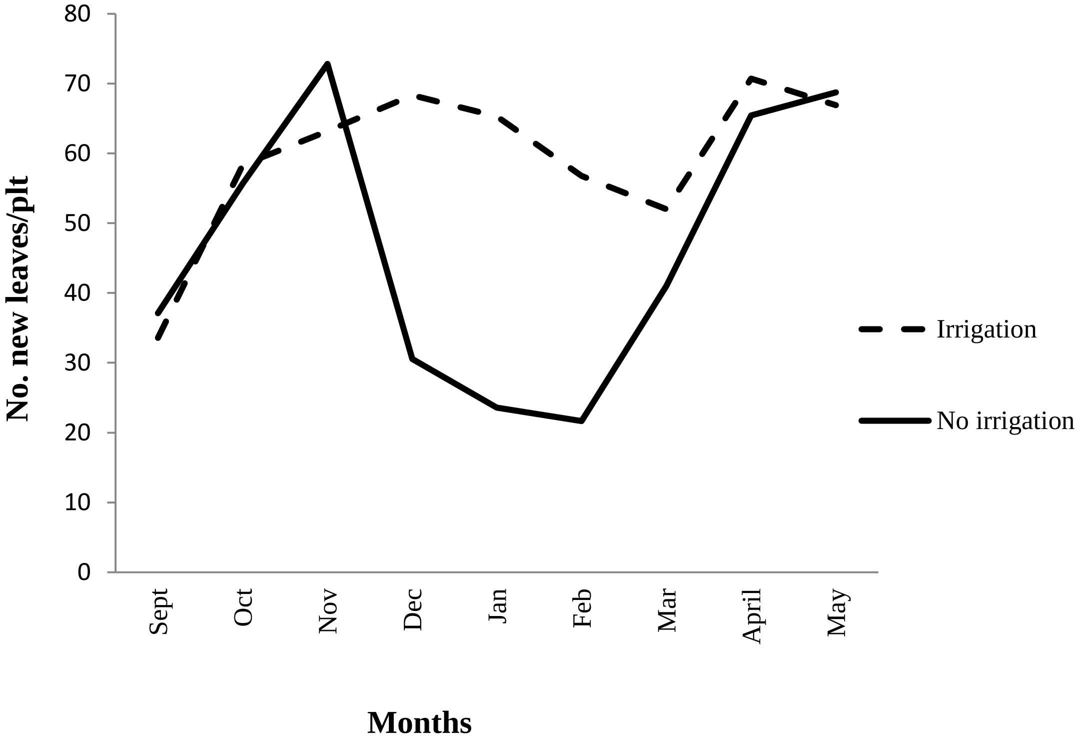


Fig. 5.7 Average number of new leaves/plant under irrigation and no irrigation at different months.

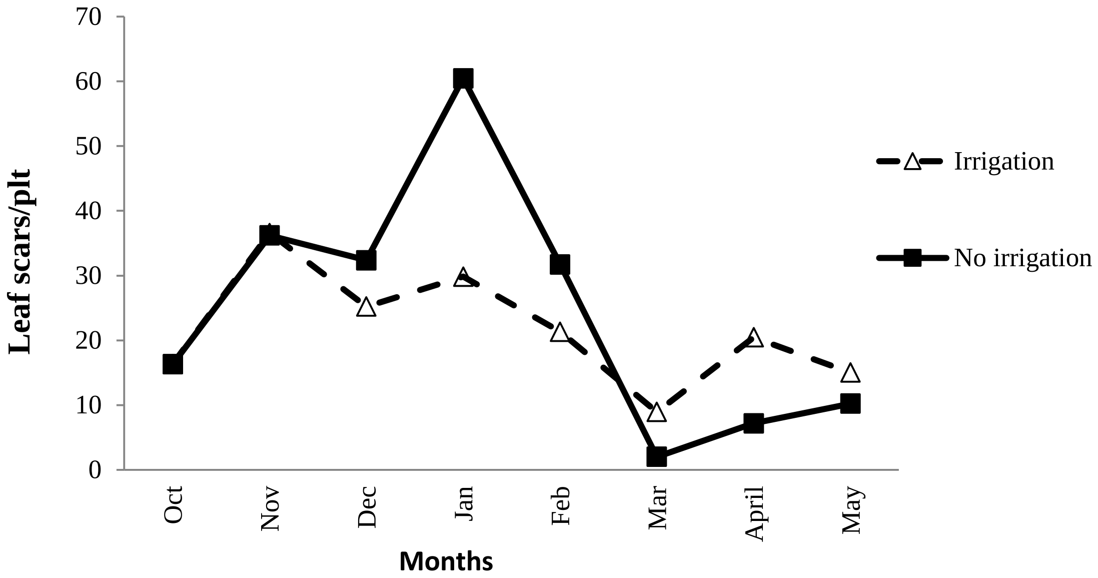


Fig. 5.8 Average number of leaf scars/plant under irrigation and no irrigation at different months

5.3.7.4 Root yield and yield components at 12 months after planting

Fresh root yield was significantly (P<0.05) affected by genotype and moisture stress (Table 5.11). Average root yields were 16.39 and 26.58 t/ha under no irrigation and irrigation, respectively. Genetic variation was observed for root yield under both conditions. Five genotypes (96/1708, I91934, TME 419, 00/0203 and UCC2001/449) had significantly higher root yield than the best local farmer preferred variety, *Pontisange* under irrigation. Two genotypes, I91934 and UCC2001/449 also had significantly higher root yield under no irrigation than *Pontisange*. Genotype 96/1708 had the highest root yield under irrigation (38.25 t/ha) whilst CTSIA 48 had the lowest yield (19.0 t/ha). Under no irrigation, I91934 had the highest yield (21.67 t/ha) and CTSIA 48 had the lowest (11.08 t/ha).

Above ground biomass (t/ha) and root dry matter content (%) were also significantly affected by stress (Table 5.11). The mean yields of above ground biomass under no irrigation and irrigation were 11.93 and 15.80 t/ha, respectively. However, genetic differences were observed within each growing environment. Mean root dry matter content was also significantly affected by moisture stress. However, the extent of the effect varied among the genotypes. Mean root dry matter contents were 36.59 and 31.19% under irrigation and no irrigation, respectively. CTSIA 110 had the root highest dry matter content under irrigation (41.43%) and no irrigation (40.23%). MM96/1751 and TME 419 both had the lowest dry matter content (31.20%) under irrigation whilst UCC2001/449 had the lowest root dry matter content (24.23%) under no irrigation.

Genotypes also varied in harvest indices under both conditions (Table 5.10). Genotype 96/1708 had the highest harvest index under irrigation (0.75) whilst CTSIA 230 had the lowest (0.48). Under no irrigation, 96/1708 again had the highest HI of 0.68 with CTSIA 110 having the lowest of 0.44. Apart from CTSIA 230, all the genotypes had lower harvest indices under no irrigation than under irrigation. Significant differences ($P<0.05$) were observed among genotypes for number of roots per plant under both conditions. I91934 had the highest number of roots per plant under irrigation (11.58) with *Pontisange* having the least number of 5.36 roots per plant. Under no irrigation, CTSIA 45 had 9.58 roots per plant with TME 435 having the lowest number of roots per plant (5.08). Overall, average number or roots per plant was higher under irrigation than under no irrigation but was not significantly different ($P>0.05$). Generally moisture stress resulted in decline of 37.9, 40.9, 19.4, 15.9 and 14.2% for root yield, mean root weight, above ground biomass yield, harvest index and dry matter content, respectively (Fig. 5.9).

Table 5.11 Fresh root yield, above ground biomass (AGB), root dry matter, harvest index, number of roots/plant of 20 cassava genotypes at 12 months after planting under irrigation and no irrigation

Genotypes	Root yield (t/ha)		AGB (t/ha)		DM%		HI		No. of roots /plant	
	Irri	**No irri**	**Irri**	**No irri**	**Irri**	**No irri**	**Irri**	**No irri**	**Irri**	**No irri**
00/0203	33.56	16.00	15.08	10.79	35.13	28.17	0.71	0.60	9.42	8.00
96/1708	38.25	20.75	14.17	9.54	34.70	31.70	0.75	0.68	10.50	8.50
96/409	28.42	17.46	18.08	15.00	35.10	26.17	0.63	0.50	8.00	8.08
ATR 002	25.33	16.50	10.29	10.50	40.50	37.03	0.72	0.56	5.58	5.25
ATR 007	23.08	13.38	15.33	12.42	36.17	33.67	0.60	0.49	8.33	6.33
*Biabasse**	23.5	14.33	11.00	9.25	34.93	28.60	0.67	0.52	4.50	6.50
CTSIA 110	21.5	14.72	21.38	14.25	41.43	40.23	0.52	0.44	9.58	6.50
CTSIA 112	26.42	16.17	18.42	11.54	38.97	31.33	0.62	0.57	8.08	7.92
CTSIA 230	21.67	14.58	22.79	12.17	37.63	30.63	0.48	0.49	9.00	8.58
CTSIA 45	25.63	14.58	12.79	11.75	38.10	34.77	0.65	0.52	6.83	9.58
CTSIA 48	18.29	11.08	15.75	11.08	37.23	34.87	0.56	0.46	8.42	6.67
CTSIA 65	20.46	13.42	17.83	10.83	40.70	32.97	0.54	0.45	9.00	6.92
CTSIA 72	20.75	14.96	12.62	10.75	40.17	36.27	0.65	0.53	7.50	6.19
I91934	37.42	21.67	19.29	13.33	34.40	27.03	0.68	0.61	11.58	7.75
MM 96/1751	29.29	19.97	12.17	13.50	31.20	27.00	0.70	0.60	8.17	6.83
NWA 004	21.75	15.96	13.00	12.62	35.40	28.27	0.64	0.49	6.83	7.33
*Pontisange**	25.5	16.83	12.37	12.36	33.37	31.17	0.66	0.46	5.36	5.86
TME 419	33.54	17.50	18.96	12.33	31.20	29.27	0.65	0.56	7.50	6.50
TME 435	29.5	15.75	15.12	11.33	39.10	30.43	0.68	0.53	7.33	5.08
UCC 2001/449	33.38	21.25	19.58	13.17	36.37	24.23	0.62	0.59	8.58	7.00
Mean	**26.58**	**16.34**	**15.80**	**11.93**	**36.59**	**31.19**	**0.64**	**0.53**	**8.00**	**7.07**
SED	**2.98**	**2.11**	**3.29**	**1.94**	**2.67**	**1.58**	**0.05**	**0.03**	**1.46**	**1.03**
t (cal) (means)	7.45		4.48		4.78		4.97		NS	
$t_{0.05(2), 38}$	2.024		2.024		2.024		2.024		2.024	

* Local farmer-–preferred varieties, NS= not significant (P=0.048), Irri = irrigation, No irri = no irrigation

Significant (P<0.05) differences in responses of genotypes were observed under irrigation and no irrigation for mean root weight, root length, root girth and root length/girth ratio (Table 5.12). Mean root weight (MRW) ranged from 229.4 g to 527.3 g with a mean of 364.95 g under irrigation. *Biabasse* had the largest mean root weight and CTSIA 65 had the lowest mean root weight. Under no irrigation, CTSIA 65 again had the lowest mean root weight of 128.5 g while

UCC2001/449 had the highest of 294.5 g. CTSIA 45 had the longest roots (53.54 cm) with MM 96/1751 having the shortest (32.3 cm) under irrigation. Root length ranged from 38.55 cm (I91934) to 60.59 cm (TME 419) under no irrigation. Mean root length was higher under no irrigation (48.0 cm) than irrigation (42.44 cm). Under irrigation, root girth varied from 4.27 cm (CTSIA 45) to 10.79 cm (TME 435) with a mean of 6.26 cm. Under no irrigation, root girth ranged from 2.96 to 5.83 cm for CTSIA 45 and I91934, respectively (Table 5.12). Significant (P<0.05) differences were observed among the genotypes under both growing conditions. CTSIA 110 had the smallest root girth under both conditions. The ratio of root length/girth was also significantly different (P<0.05) among the genotypes under both conditions. Mean root length/girth ratio was higher under no irrigation (11.94 cm) than irrigation (7.22 cm). CTSIA 45 had the highest root length/girth ratio under irrigation (12.61) and no irrigation (18.61). I91934 had the smallest root girth to length ratio under irrigation whilst MM96/1751 had the smallest ratio under no irrigation (Table 5.12).

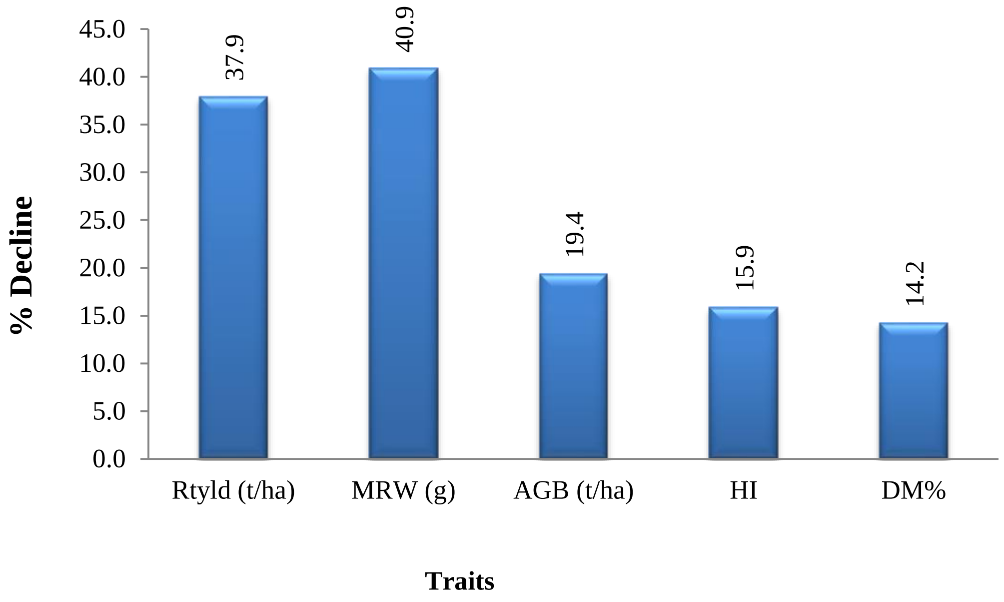


Fig. 5.9 Effect of moisture stress on decline in performance of genotypes

Rtyld (t/ha) = root yield (t/ha), MRW = Mean root weight (g), AGB (t/ha) = Above ground biomass yield (t/ha), HI = Harvest index, DM% = Dry matter content (%).

Table 5.12 Mean storage root weight and dimensions of 20 cassava genotypes at 12 months after planting under irrigation and no irrigation

Genotypes	**MRW (g)**		**Root length (cm) [L]**		**Root girth (cm) [G]**		**L//G**	
	Irri	**No irri**	**Irri**	**No irri**	**Irri**	**No irri**	**Irri**	**No irri**
00/0203	386.80	221.80	41.46	50.38	6.65	4.52	6.26	11.43
96/1708	379.00	248.80	51.88	60.24	6.51	3.83	7.99	15.99
96/409	379.50	183.60	40.95	42.86	6.24	3.93	6.61	10.93
ATR 002	481.80	260.20	45.25	45.07	6.24	4.52	7.32	10.27
ATR 007	281.70	199.30	41.77	47.32	4.88	4.15	8.73	12.14
*Biabasse**	527.30	154.50	41.43	42.61	6.67	4.04	6.36	10.73
CTSIA 110	239.70	173.90	38.64	45.96	4.47	3.48	8.68	13.23
CTSIA 112	375.80	208.20	41.77	51.89	5.86	4.52	7.1	11.65
CTSIA 230	241.50	137.50	40.56	47.99	4.57	3.72	9.22	13.16
CTSIA 45	363.40	138.80	53.54	54.98	4.27	2.96	12.61	18.61
CTSIA 48	265.90	146.50	34.62	42.03	5.25	3.78	6.56	11.29
CTSIA 65	229.40	128.50	38.05	41.70	5.34	3.86	7.22	10.84
CTSIA 72	318.70	208.90	40.53	43.65	5.82	4.04	6.95	10.86
I91934	354.20	279.50	37.85	38.55	8.13	5.83	4.87	6.63
MM 96/1751	350.10	290.60	32.30	46.22	7.52	5.43	4.3	8.51
NWA 004	341.60	165.00	47.27	50.47	5.59	3.92	8.42	12.88
*Pontisange**	466.70	179.00	41.56	42.42	6.01	3.94	6.92	10.86
TME 419	483.10	243.60	53.27	60.59	7.08	4.23	7.54	14.72
TME 435	453.90	248.70	48.48	59.91	10.79	4.37	5.72	14.58
UCC 2001/449	378.90	294.50	37.57	45.23	7.31	4.78	5.11	9.50
Mean	**364.95**	**205.57**	**42.44**	**48.00**	**6.26**	**4.19**	**7.22**	**11.94**
SED	**70.75**	**36.79**	**5.88**	**4.65**	**1.48**	**0.41**	**1.27**	**1.60**
t (cal)(means)	7.01		2.83		5.69		6.53	
$t_{0.05(2), 38}$	2.024		2.024		2.024		2.024	

* Local farmer –preferred varieties, Irri = irrigation, No irri = no irrigation

5.3.7.5 Root yield at different harvest times under irrigation and no irrigation

Significant differences (P<0.05) in root yield were observed for genotypes at the different harvesting times under irrigation and no irrigation (Table 5.13). Mean root yields at six months after planting (MAP) for all genotypes were 10.54 and 10.91 t/ha under irrigation and no irrigation, respectively. Genotype 96/1708 had the highest root yield (19.25 t/ha) under irrigation whilst CTSIA 48 had the lowest (7.0 t/ha). Under no irrigation, root yield ranged between 7.5 and

17.0 t/ha for *Biabasse* and 96/1708 respectively. Mean root yield under irrigation increased to 14.47 t/ha at 8 MAP whilst under no irrigation it only increased to 12.28 t/ha. Root yields varied from 10.17 t/ha for CTSIA 48 to 22.25 t/ha for 96/1708 under irrigation. Under no irrigation, root yields ranged between 9.08 and 18.0 t/ha for CTSIA 48 and 96/1708, respectively. Root yield rankings of genotypes changed at 10 MAP under irrigation and no irrigation. The highest root yield (25.67 t/ha) under irrigation was obtained from 00/0203 with CTSIA 48 giving the lowest root yield (12.08 t/ha). Under no irrigation, 96/1708 had the highest root yield of 19.67 t/ha whilst CTSIA 48 had the lowest (11.42 t/ha) at 10 months after planting.

Table 5.13 Root yield (t/ha) of 20 cassava genotypes at different harvest times under irrigation and no irrigation

Genotypes	**Root yield (t/ha)**					
	6 MAP		**8 MAP**		**10 MAP**	
	Irri	**No irri**	**Irri**	**No irri**	**Irri**	**No irri**
00/0203	9.08	11.67	14.50	12.17	25.67	15.50
96/1708	19.25	17.00	22.25	18.00	24.33	19.67
96/409	10.33	12.75	15.42	13.50	18.67	15.33
ATR 002	9.42	8.67	12.50	11.50	16.92	15.42
ATR 007	9.42	8.42	12.25	10.92	15.58	13.00
*Biabasse**	7.75	7.50	11.42	9.92	17.33	12.92
CTSIA 110	12.17	8.42	13.83	11.17	15.50	14.00
CTSIA 112	10.83	11.25	13.83	13.33	15.75	15.58
CTSIA 230	10.83	10.60	14.83	11.42	15.92	13.50
CTSIA 45	8.83	9.67	13.75	10.60	17.92	12.50
CTSIA 48	7.00	7.67	10.17	9.08	12.08	11.42
CTSIA 65	8.50	9.92	10.92	11.33	14.67	12.42
CTSIA 72	7.67	8.08	11.42	9.34	16.42	12.24
I91934	12.83	11.17	20.83	13.83	25.50	18.83
MM 96/1751	10.75	12.83	14.67	14.75	23.42	16.92
NWA 004	8.75	12.50	12.83	13.27	17.50	15.00
*Ponstisange**	8.58	11.42	12.75	14.02	18.33	15.62
TME 419	11.83	11.42	18.42	13.17	22.08	16.25
TME 435	14.83	12.83	18.00	13.33	20.00	14.67
UCC 2001/449	12.17	13.33	14.83	14.58	24.08	17.50
Mean	**10.54**	**10.91**	**14.47**	**12.28**	**18.88**	**14.91**
SED	**1.07**	**0.88**	**1.09**	**1.07**	**1.66**	**0.85**
t (cal)(means)	NS		2.33		3.9	
$t_{0.05(2), 38}$	2.024		2.024		2.024	

* Local farmer –preferred varieties, NS = not significant (P= 0.706), Irri = irrigation, Non irri = no irrigation

There was an increase in root bulking during the course of the experiment (Fig. 5.10). Storage root bulking rate declined under no irrigation compared with under irrigation. The rate of bulking was slightly higher under the irrigation at eight months after planting but large differences were observed at 10 and 12 months after planting. Root dry matter content (%) generally declined after the first harvest at six months but the decline was greater under no irrigation (Fig. 5.11). Rate of accumulation of dry matter into the roots also varied under irrigation and under no irrigation and also among the genotypes (Table 5.14). At six months after planting, most of the genotypes had accumulated more than 50% of their final root yield expected at 12 MAP under no irrigation but only three genotypes (96/1708, CTSIA 110 and TME 435) had produced over 50% of their final root yield under irrigation. 96/1708 had accumulated 55.8% of its final root yield at 12 MAP under irrigation and 81% of its expected final root yield at 12 MAP under no irrigation.

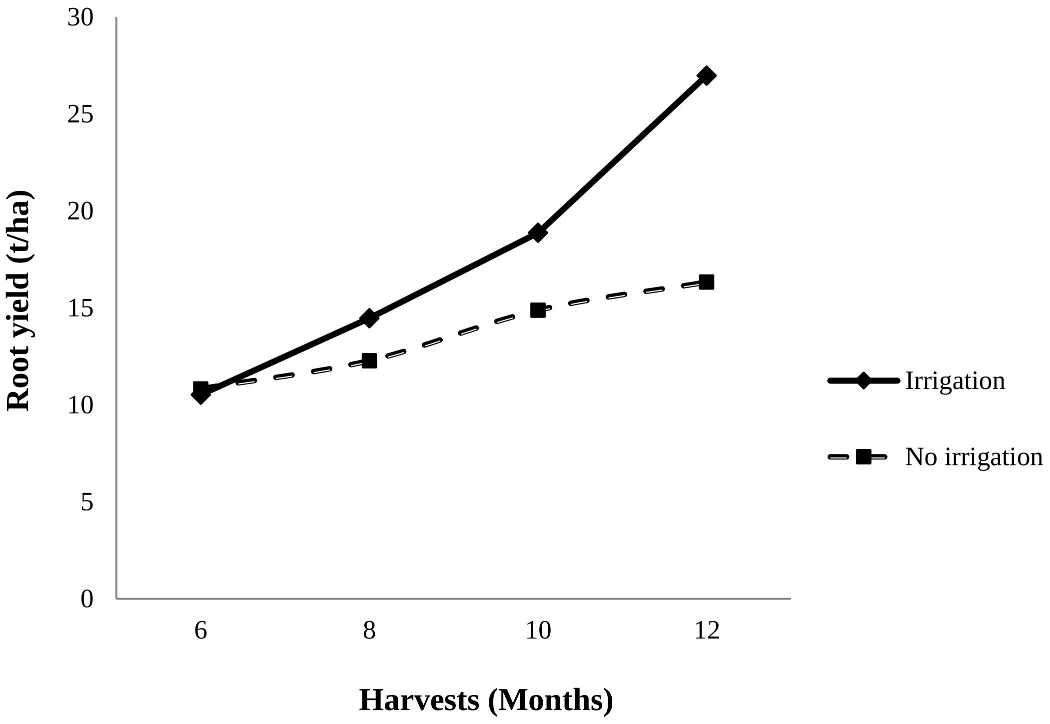
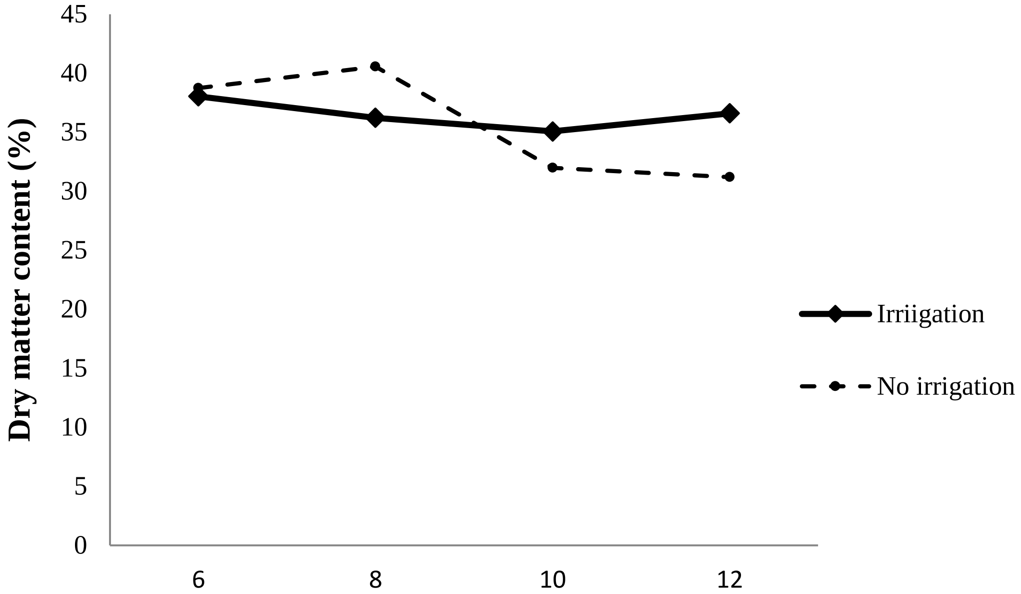


Fig. 5.10 Root bulking trend from 6-12 months after planting under irrigation and no irrigation



Harvests (Months)

Fig. 5.11 Average dry matter content at different harvest times under irrigation and no irrigation

Table 5.14 Root yield as percentage of final root yield at 12 months under irrigation and no irrigation

Genotypes	% of Root yield at 12 MAP					
	6 MAP		8 MAP		10 MAP	
	Irri	No irri	Irri	No irri	Irri	No irri
00/0203	25.7	73.1	42.3	76.2	75.74	95.66
96/1708	55.8	81	64.2	85.9	69.81	95.05
96/409	36.3	72.8	53.7	77.1	64.51	87.47
ATR 002	36.8	52.5	49.1	68.5	65.9	93.09
ATR 007	41.0	64.0	53.4	81.7	67.78	96.95
*Biabasse**	33.5	53.2	49.8	70.2	75.91	90.06
CTSIA 110	54.6	58.4	62.3	77.5	70.27	95.24
CTSIA 112	40.6	69.9	52.6	82.5	60.07	96.31
CTSIA 230	50.0	74.0	70.4	78.9	73.95	92.25
CTSIA 45	37.1	65.8	57.3	72.2	74.81	85.4
CTSIA 48	37.1	65.5	52.9	77.4	63.69	94.24
CTSIA 65	40.2	74.5	52.7	84.8	71.0	92.79
CTSIA 72	34.9	59.9	51.1	63.9	72.65	91.03
I91934	33.1	53.3	54.1	65.5	65.21	87.65
MM 96/1751	39.9	65.2	54.0	75.2	86.25	86.2
NWA 004	38.2	78.4	56.1	83.0	76.72	93.96
*Pontisange**	34.7	68.5	52.4	81.3	72.61	91.64
TME 419	35.4	65.6	55.2	74.9	65.96	92.61
TME 435	51.8	81.7	62.4	84.7	69.0	93.2
UCC 2001/449	34.9	66.6	42.6	72.2	69.62	84.98
Mean	**39.58**	**67.15**	**54.43**	**75.68**	**70.57**	**91.78**
SED	**6.12**	**10.4**	**8.42**	**12.56**	**11.23**	**12.65**
t (cal)(means)	10.56		8.24		13.68	
$t_{0.05(2), 38}$	2.024		2.024		2.024	

* Local farmer –preferred varieties, Irri = irrigation, No irri = no irrigation

5.3.8 Pearson correlation between root yield at different times of harvest and final root yield

High phenotypic correlations were observed between root yields at different harvest times and the final root yields under no irrigation and under irrigation (Table 5.15). The strongest correlation with final root yield under no irrigation was root yield at 10 MAP (Fig. 5.12). A large proportion of the dry matter obtained at the final harvest was dependent on what was accumulated during the first few months before the stress period. However, under irrigation, root yield at final harvest depended on the entire activities by the plants before final the harvest.

Table 5.15 Pearson correlation between root yields at different times under irrigation and no irrigation

	Root yield at 6 MAP	**Root yield at 8 MAP**	**Root yield at 10 MAP**	**Root yield at 12MAP**
Root yield at 6 MAP	-	0.87***	0.62***	0.55***
Root yield at 8 MAP	0.87***	-	0.74***	0.64***
Root yield at 10 MAP	0.38**	0.63***	-	0.96***
Root yield at 12 MAP	0.56***	0.67***	0.71***	-

*** = significant at P<0.001. Values above the diagonal represent root yield under no irrigation. Values below the diagonal represent root yield under irrigation

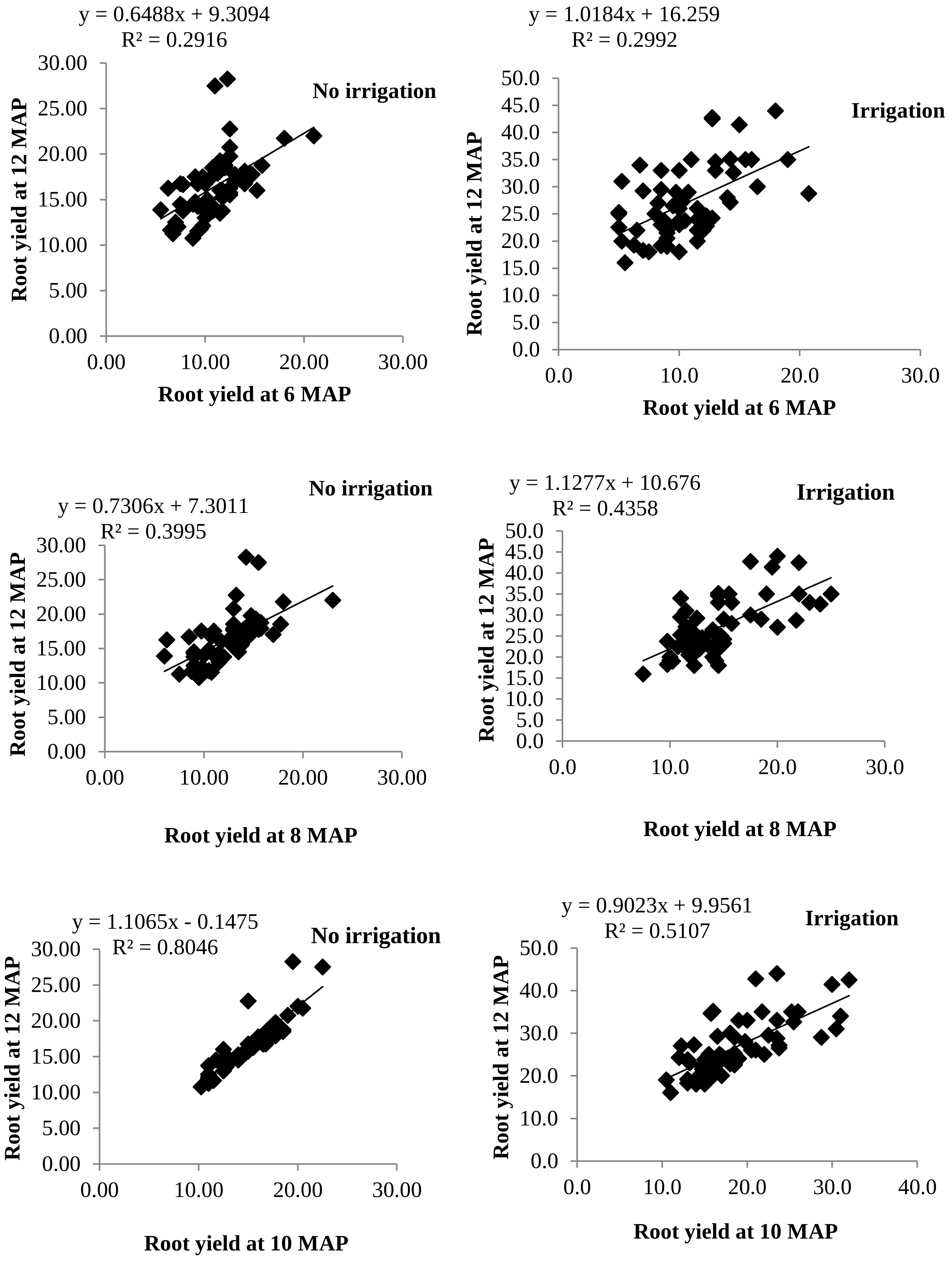


Fig. 5.12 Relationships between root yield at different harvests and root yield at 12 MAP under no irrigation and irrigation

5.4 Discussion

5.4.1 Effect of stress on growth and yield components

Physiological and growth processes were significantly affected by moistures stress. Growth parameters such as plant height and leaf production and abscission were also significantly different among genotypes under irrigation and no irrigation. Previous studies by Okogbenin *et al.* (2003) and Aina *et al.* (2007a) also reported reduced plant growth of cassava under moisture stress. Genetic variations were observed in plant height under irrigation and no irrigation. Other studies on effects of drought in cassava have reported reduced leaf expansion (Alves and Setter, 2004a), reduced vigour (Okogbenin *et al.*, 2003) and reduction in root yield (Turyagyenda *et al.*, 2013) as were found in this study.

The emphasis of this study was to assess genetic variability for ABA content and its relationship with root yield. ABA content was higher under no irrigation. This confirms earlier findings by Duque and Setter (2013) who observed higher ABA content in leaves under moisture stress conditions. Abscisic acid in cassava is a signal for initiation of survival mechanisms under moisture stress conditions (Alves and Setter, 2004b). Abscisic acid has been reported to promote drought tolerance in crops by stimulating root growth (Jacqmard *et al.*, 1995; Sharp and LeNoble, 2001) but that was not seen in this study. Reports suggest that ABA accumulation in plants reduces stomatal aperture and hence limits water loss through transpiration (Zhang and Davies, 1989; Zhang and Davies, 1990). However, it also caused growth retardation, reduced leaf area, stomatal closure and reduced photosynthesis as was observed here. In this study, stomatal conductance decreased under no irrigation probably due to the closure of stomata. Cassava plants rapidly closed their stomata under stress to reduce water loss but this inhibits photosynthetic activity (El-Sharkawy, 2007). Blum (2011) also associated short term growth retardation by ABA accumulation with the inhibition of both cell expansion and cell division thereby increasing root/shoot dry matter ratio under drought stress. ABA content had a negative correlation with root yield but a strong positive correlation with root length/girth ratio. This suggests that the ABA mediated the partitioning of dry matter for root extension instead of expansion. ABA content of leaves also stimulated leaf abscission thereby depriving the plant of its photosynthetic apparatus. However, Lenis *et al.* (2006) reported that leaf retention results in up to 33% increase in root yield. This means that selecting for low ABA genotypes may result in more productivity under mild stress than highly sensitive genotypes.

The proportion of photosynthetically active radiation (%PAR) that was intercepted also varied among the genotypes due to differential leaf retention capacity. Per cent PAR was positively correlated with the amount of leaves that were available for light interception and with root yield. Aspiazu *et al.* (2010) indicated that photosynthetic rate is directly related to the photosynthetically active radiation (composition of light) that is absorbed and has implications for the amount of photoassimilates that will be produced for growth and root yield. Genotypes that maintained their leaves under no irrigation had a better chance of intercepting incoming solar radiation for photosynthesis. This reflected in the positive significant correlation of %PAR with root yield. Okogbenin *et al.* (2011) also indicated that leaf retention in cassava improves light interception and promotes high root yield under stress.

5.4.2 Stomatal conductance, leaf temperature and root yield

Stomatal conductance indicates gas exchange capability by stomata, considered to be the main limitation for photosynthetic CO_2 assimilation (Aspiazu *et al.*, 2010). However cassava responds to mild drought by closing stomata (El-Sharkawy, 2007) which may limit transpiration and photosynthetic activity. Ability to maintain high rates of growth and transpiration under mild drought has been found to be correlated with increased productivity (Fisher and Edmeades, 2010). This was reflected in the positive correlation between stomatal conductance and root yield.

Genotypes with very sensitive stomata often close them in response to mild stress. The closure of cassava stomata under limited moisture often increases the leaf temperature and reduces net photosynthesis (El-Sharkawy and Cock, 1984). In this study, differential responses of genotypes were observed for increases in leaf temperature. Leaf temperature was higher under no irrigation than under irrigation and showed a negative correlation with root yield as has previously been reported in other crops such as potato (Lopes and Reynolds, 2010; Monneveux *et al.*, 2013; Prashar *et al.*, 2013).

5.4.3 Carbon isotope ratio ($\Delta^{13}C$)

Carbon isotope ratio was positively correlated with stomatal conductance in this study and also influenced above ground biomass yield, a trait that was positively correlated with root yield. This provides opportunity for in-depth studies under controlled environments to establish the relationship between carbon isotope ratio and root yield in cassava. Selection of low $\Delta^{13}C$ (more negative) wheat genotypes resulted in increased aboveground biomass and kernel weight with up to about 10% in yield under the dry conditions (Rebetzke *et al.*, 2002).

5.4.4 Accumulation of dry matter

According to Alves (2002), cassava plants begin root bulking at 90 days after planting but roots become a major sink only between 180 to 300 days after planting. Therefore, any factors that adversely affect growth during this time will curtail storage root bulking. Differential response of genotypes in root bulking was observed in this study. At six months after planting, some of the genotypes (96/1708 and TME 435) had accumulated over 80% of their final root yield expected at 12 months after planting. However, there were crossover interactions as some genotypes that had lower yield at six months had higher yield at 12 months than most of the ones showing good yield at six months. This implies that such genotypes continuously accumulated dry matter even during the stress periods. Those that had low root yield at six months might have used the above ground part as the major sink before accumulating some into storage roots. El-Sharkawy (2004) stated that distribution of carbohydrates to the different organs of cassava changes during the growth cycle, with the shoot being the major sink during the first five months while storage roots become the major sink later. Previous studies by Adjebeng-Danquah *et al.* (2012) indicated that genotypes that partitioned earlier dry matter production into storage roots were able to bulk over 60 per cent of their final root yield by six months after planting.

Okogbenin and Fregene (2002) also linked high early root yield to genotypic variability in the rate of root bulking. Fast bulking genotypes develop roots and shoots simultaneously, unlike late or slow bulking genotypes that have to develop sufficient top biomass before storage root bulking. This pattern depends on the growth conditions particularly moisture which may affect the choice of sink (El-Sharkawy, 2004). Different plant organs are affected differentially by such conditions and could show different trends. The pattern of storage root development varied among the genotypes under irrigation and no irrigation as shown by the trend in the root length/girth ratio. The results of this study confirm earlier findings on severe yield losses in cassava due to moisture stress (Serraj *et al.*, 2005; Aina *et al.*, 2007a; Turyagyenda *et al.*, 2013).

5.4.5 Relationship among traits

Strong associations were found among most of the traits and root yield. For instance, root yield was positively associated with harvest index, mean root weight, above ground biomass, root girth, stomatal conductance, number of leaves per plant and dry matter content. Traits that showed strong positive correlations can be improved simultaneously or used as indirect selection criteria (Akinwale *et al.*, 2010). On the other hand, ABA content and root length/girth ratio were negatively correlated with root yield indicating that they may be survival traits that will enable cassava plants to survive harsh moisture stress conditions without necessarily producing high root yields in future programmes. Selection for such traits alone may be counter productive as they may not necessarily translate into improved root yield. Several studies have reported that sustained stomatal conductance and transpiration under stress will support yield (Araus *et al.*, 2002; Blum, 2009; Munns and Richards, 2007). Therefore, genotypes that are less sensitive to ABA and other regulatory hormones will specifically promote high yield under drought stress (Blum, 2011). Selection of genotypes that combine high root yield with higher ABA content and low root length/root girth ratio will be productive in developing cassava varieties with improved yield under stress conditions.

5.5 Conclusion

Genetic variation was observed for ABA accumulation under irrigation and no irrigation but was generally higher under no irrigation than under irrigation. ABA accumulation had negative effect on root yield. Two genotypes, UCC2001/449 and I91934 combined relatively high root yields despite having higher ABA content making them good candidates for survival (tolerance) and productivity.

Narrow genetic variation was observed in this experiment for carbon isotope ratio ($\Delta^{13}C$). Positive correlation was found between $\Delta^{13}C$ and yield related traits such as root girth and above ground biomass but not directly with root yield. Carbon isotope ratio was positively correlated with stomatal conductance and above ground biomass yield, both of which were correlated with root yield. This provides an opportunity for in-depth studies under controlled environments to establish the relationship between carbon isotope ratio and root yield in cassava. Above ground biomass and percentage of intercepted photosynthetically active radiation (%PAR) were influenced by leaf production and size of central leaf lobe which had positive association with root yield under stress conditions. Root length/girth ratio was negatively correlated with root yield but stomatal conductance was positively correlated with root yield. Correlation between leaf chlorophyll and root yield was not significant. Genotypes exhibited different root bulking patterns under irrigation and no irrigation. Root bulking continuously increased more under irrigation than no irrigation.

Genotype 96/1708 can be classified as early bulking since it had bulked 81% of its final root yield at 12 MAP and was also the highest yielding genotype from six months up to 12 MAP. Early harvesting may provide an escape from drought but there could be a yield penalty.

According to the findings of this study, genotypes that utilized photosynthates for root extension instead of expansion in girth can survive under the drought conditions but the root yield may be compromised. Six genotypes (96/1708, 96/409, I91934, MM96/1751 and TME 419) gave root yields that were higher than the two local widely cultivated farmer preferred varieties (*Biabasse and Pontisange*). These can be further tested to determine their broad adaptability and yield stability.

CHAPTER SIX

6.0 STABILITY AND BROAD SENSE HERITABILITY OF MORPHO-PHYSIOLOGICAL TRAITS ASSOCIATED WITH HIGH YIELD POTENTIAL IN CASSAVA IN DIFFERENT ENVIRONMENTS

6.1 Introduction

Cassava is capable of growing in a wide range of environments but severe yield losses occur in poor farmers' cultivars (El-Sharkawy, 2004; Aina *et al.*, 2007a; El-Sharkawy, 2007). Root yield losses in poor environments depending on the cultivar can be as high as 80% when compared with root yield in optimum environments (Turyagyenda *et al.*, 2013). This arises due to the inability of the genotypes to exhibit the same level of phenotypic expression under all environmental conditions (Haldavankar *et al.*, 2009). Phenotypic expression of genes of an organism is influenced by the environment as well as its interaction leading to crossover performance in different environments (Kang, 1998).

The environment refers to a set of non genetic factors that affect the phenotypic value associated with a genotype (Falconer and Mackay, 1996; Bernardo, 2010). The phenomenon of crossover performances in different environments results from differential responses of crops under varying environmental conditions (Crossa and Cornelius, 1997; Mkumbira *et al.*, 2003). Dixon and Nukenine (2000) defined it as genotype x environmental (GxE) interaction. GxE effect results from inconsistent performances of genotypes across environments and limits the efficiency of selection of superior genotypes by breeders (Ssemakula and Dixon, 2007). Differences in the sensitivities of different genotypes to the conditions in the target environment can also give rise to GxE (Falconer and Mackay, 1996). In GxE interaction, the magnitude of the genetic variances as observed within individual environments changes from one environment to the next and tends to be larger in better environments than poorer environments (Przystalski *et al.*, 2008).

Breeding for yield involves different attributes of genotypes that are subject to variation in environmental conditions (Ntawuruhunga and Dixon, 2010). Progress in direct selection for yield under moisture-stressed environments has been slow due to its low heritability, polygenic control, epistasis and significant GxE (Piepho, 2000). The objective of most cassava yield improvement programmes is to obtain the high stable yield across several environments and seasons (Egesi *et al.*, 2007b). The efficiency and success of any selection scheme depends on the consistency in varying environments (Otoo *et al.*, 2006). For this reason, genotypes are tested in diverse environments to assess their adaptability and stability (Haldavankar *et al.*, 2009). Genotypes whose GxE effects are not significant are said to be stable (Ssemakula and Dixon, 2007). Stability analysis provides information on the performance of genotypes as linear function of the level of productivity in each environment (Bernardo, 2010). Studies on cassava's performance in different environments have indicated significant GxE effect for root yield and yield components (Okogbenin *et al.*, 2003; Aina *et al.*, 2007c; Egesi *et al.*, 2007b; Aina *et al.*, 2009). However, there is limited information on the effect of genotype x environment interaction on secondary traits such as stomatal conductance, leaf temperature, chlorophyll content as well as their relationships with root yield in cassava under moisture stress.

Several methods have been used to assess the GxE effect and stability in crop performances. Eberhart and Russell (1966) proposed joint regression analysis to estimate the average performance of a genotype in different environments relative to the mean performance of all genotypes in the same environment. Multiplicative models which include the Additive Main effect and Multiplicative Interaction (AMMI) model have also been used (Gauch, 1988; van Eeuwijk, 1995). The AMMI model allows fitting of the sum of several multiplicative terms rather than only one multiplicative term in dissecting the performance of genotypes in different environments (Bernardo, 2010). AMMI analysis can also be used to determine stability of the genotypes across locations using the PCA (principal component axis) scores and AMMI stability value (ASV) (Hagos and Abay, 2013). The ASV is based on the AMMI model's IPCA1 and IPCA2 (interaction principal components axes 1 and 2, respectively) scores for each genotype (Purchase *et al.*, 2000). Genotypes having the least ASV are considered as widely adapted genotype. Similarly, IPCA2 score near zero indicates more stable genotypes whilst, large values represent more responsive and less stable genotypes. IPCA2 score near zero reveals more stable, while large values indicated more responsive and less stable genotypes. Yan (2001) and Yan *et al.* (2000) also suggested the use of the genotype and genotype x environment interaction (GGE) biplot to graphically visualise genotypic performance across several environments.

In order to develop improved high yielding stable cassava genotypes for drought prone areas, there is the need to get a better understanding of the effect of different environments on the physiological traits underlying mechanism of cassava's improved yield under moisture stress conditions.

The objectives of this study were to:

1. Determine the genotype x environment effect and stability of physiological traits associated with high yield under different growing environments,
2. Estimate broad sense heritability and associations of these traits with root yield, and
3. Assess stability genotypic responses in terms of yield under the different growing environments.

6.2 Materials and Methods

6.2.1 The study site

The experiments were conducted during the 2012/2013 and 2013/2014 growing seasons. The trials were conducted at the research fields of the Savanna Agricultural Research Institute located at Nyankpala (9^{o}25'N, 0^{o}58'W) in the Guinea Savannah Agroecological zone and the Crops Research Institute located at Fumesua (6^{o}41N 1^{o}28W) in the Forest Agroecololgical Zone of Ghana (Fig. 6.1). The Guinea Savannah Zone covers over one third of the entire land area of Ghana. The site characteristics in Nyankpala have been previously described in Section 4.2.1 of Chapter four of this Thesis.

The site at the CSIR-Crops Research Institute (CSIR-CRI) was located at Fumesua within the Forest Agroecology. The Forest Agroecology is characterised by a bimodal rainfall pattern; major and minor rainy seasons. The major rainy season begins in February and ends in August and then followed by the minor season which begins in September and ends in November. In each of the two seasons, two trials were conducted at Nyankpala; one under irrigation and another under no irrigation. One trial was conducted in each of the two years at CSIR-CRI, Fumesua in the humid ecology to serve as the optimum environment for the assessment of high yield potential. The combination of the sites, irrigation and years gave six environments vis No irrigation-2013 (NIR13), No-irrigation-2014 (NIR14), Irrigation-2013 (IRR13), Irrigation-2014 (IRR14), Fumesua-2013 (FUM13) and Fumesua-2014 (FUM14)

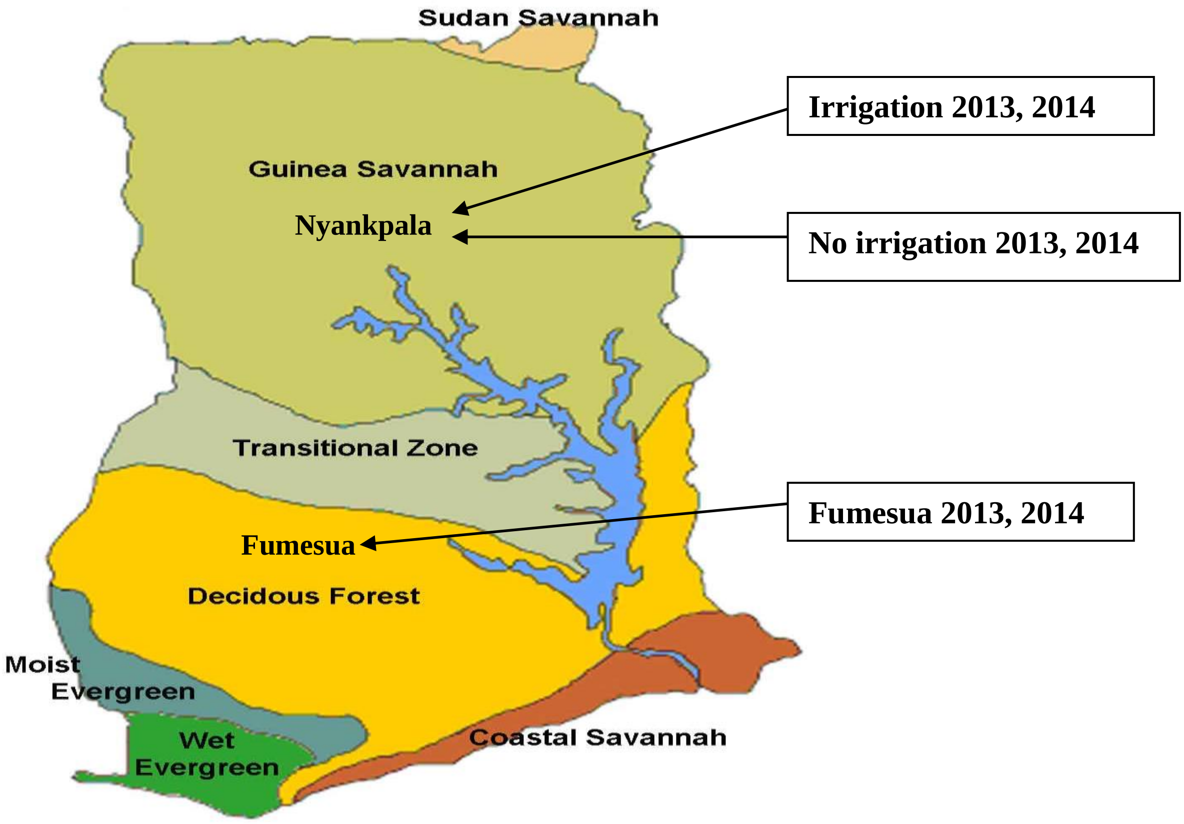


Fig.6.1 Map of Ghana indicating the agroecological zones

6.2.2 Genotypes and experimental design

Twenty cassava genotypes selected from the preliminary evaluation were used in the trials (Table 6.1). These genotypes were made up of six local landraces collected from farmers' fields, seven drought tolerant genotypes collected from the International Institute of Tropical Agriculture (IITA) and seven from the International Center for Tropical Agriculture (CIAT), Columbia. The genotypes were arranged in a randomised complete block design with three replications under each growing condition. A plot consisted of four rows with ten plants in a row giving a population of 40 plants in each plot.

Table 6.1 List of cassava genotypes used in the study

Genotype	Source	Genotype	Source
ATR 002	Local	00/0203	IITA
ATR 007	Local	96/1708	IITA
NWA 004	Local	I91934	IITA
*Pontisange**	Local	CTSIA 45	CIAT
*Biabasse**	Local	CTSIA 48	CIAT
UCC2001/449	Local	CTSIA 65	CIAT
TME 419	IITA	CTSIA 72	CIAT
TME 435	IITA	CTSIA 112	CIAT
96/409	IITA	CTSIA 230	CIAT
MM96/1751	IITA	CTSIA 110	CIAT

* Checks (local farmer preferred varieties)

6.2.3 Land preparation and planting

At each site the land was ploughed and harrowed before planting. In the case of the trials at CSIR-SARI Nyankpala, the cuttings were planted on ridges spaced at one metre apart and one metre between rows to facilitate the laying of drip irrigation lines. The trials at CSIR-CRI, Fumesua were planted on the flat with no ridging. Mature cassava cuttings measuring 25-30 cm were planted on the top of ridge or flat as the case may be at an angle of 45^{o} to the ground surface (Ekanayake, 1996). No fertilizer was applied to the trials but weeds were controlled as and when necessary. Reshaping of ridges was done to prevent exposure of the roots.

6.2.4 Irrigation regime at Nyankpala

As previously described in Section 5.2.4 of Chapter five of this Thesis.

6.2.5 Data collection

6.2.5.1 Growth parameters

Monthly data were recorded on growth parameters beginning at three months after planting. These included plant height (cm), stem girth (cm), number of leaves/plant and number of branches per plant.

6.2.5.2 Stomatal conductance and leaf temperature

Stomatal conductance ($mmol/m^2s^{-1}$) and leaf temperature (°C) were simultaneously measured using a leaf porometer (Decagon services, USA). Monthly data collection commenced in September in 2012 at all sites and October in 2013 when the plants were four months old. The readings were taken on two plants from each plot between the hours of 10:00 – 13:00 each day.

6.2.5.3 Fresh root yield (t/ha) and yield components:

Harvesting was done at 12 months after planting. Eight plants from the two inner rows were sampled for yield determination. For root dimensions measurements, 10 roots were selected, measured from one tip to the other using a tape measure to determine root length (cm). Root girth (cm) was also determined by measuring the widest portion of the same roots using vernier callipers. The ratio of root length to girth was then estimated. Number of storage roots per plant was also recorded. Mean root weight (g) was estimated from the weight of roots divided by the total number of roots harvested from each plot.

6.2.5.4 Root dry matter content

As previously described in Section 4.2.4.2 of Chapter four of this Thesis.

6.2.5.5 Cassava mosaic isease severity score

This was determined as described in Section 4.2.4.3 of Chapter four of this Thesis.

6.2.6 Data analysis

The data were subjected to analysis of variance using the PROC GLM of the Statistical Analysis System (SAS, 2009) to determine the significance of the main effects and interactions. Combined analysis of all physiological, growth parameters as well as root yield and yield components from the different growing environments was done. In this case, a combination of three growing environments (irrigation, no irrigation and Fumesua, humid ecology) and two growing seasons (2013 and 2014) were used giving a total of six environments. The main environment and genotype x environment sources of variation were further partitioned into informative and orthogonal sources of variation using SAS (2009). Significant differences between genotypes under each growing environment were compared using the standard errors of their differences (5%). Pearson's correlation was used to determine association between traits. Genotypic (σ^2_g) and phenotypic (σ^2_p) variances were computed using the expected mean squares from the analysis of variance table according to Ntawuruhunga and Dixon (2010).

Broad heritability (H) and phenotypic coefficient of variation (PCV) and genotypic coefficient of variation (GCV) were estimated according to Padi (2007) as follows:

$H^2 = \sigma^2_g/\sigma^2_p$

Where: σ^2_g = genotypic variance

σ^2_p = phenotypic variance

$\sigma^2_p = (\sigma^2_g) + (\sigma^2_{ge}/E) + (\sigma^2_e/ER)$

Where:

σ^2_g = Genotypic variance

σ^2_{ge} = Genotype * environment variance

σ^2_{ge} = Pooled error

E = number of environments

R = number of replications

Genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) were estimated according to Singh and Chaudhary (1979) as follows:

$$\text{GCV (\%)} = \frac{\sqrt{\sigma_g^2}}{\overline{X}} \text{ x } 100$$

$$\text{PCV (\%)} = \frac{\sqrt{\sigma_p^2}}{\overline{X}} \text{ x } 100$$

Where: $\overline{X}$ =grand mean

Expected genetic advance, GA was calculated as:

$$\text{GA} = (\text{K})\sigma_A H^2$$

Where GA = expected genetic advance

K = Selection differential (2.06 at 5% selection intensity)

σ_A = Phenotypic standard deviation

Genetic advance as a percentage of mean (GAM) was also estimated using the formula:

$$\text{GAM} = (\text{GA}/\overline{X})* 100$$

6.2.7.1 Stability analysis

Additive Main Effect and Multiplicative Interaction (AMMI) model in Genstat 12.1 (Payne *et al.*, 2009) was used to determine the stability of the genotypes across environments. AMMI stability value (ASV) was calculated for each genotype according to the relative contributions of the principal component axis scores (IPCA1 and IPCA2) to the interaction sum of squares.

The AMMI stability value (ASV) as described by Purchase *et al.* (2000) was calculated as follows:

$$ASV = \sqrt{\left[\frac{IPCA1_{\text{Sum of squares}}}{IPCA2_{\text{Sum of squares}}}\left(IPCA1_{score}\right)\right]^2 + \left(IPCA2_{score}\right)^2}$$

Where: $\dfrac{IPCA1_{\text{Sum of squares}}}{IPCA2_{\text{Sum of squares}}} = Ko$

Ko = the weight given to the IPCA1-value by dividing the IPCA1 sum of squares (from the AMMI analysis of variance table) by the IPCA2 sum of squares.

The larger the IPCA score, either negative or positive, the more specifically adapted a genotype is to certain environments. Smaller ASV scores indicate a more stable genotype across environments (Farshadfar *et al.*, 2011). GGE biplot (Yan, 2001) analysis was performed to visualise stability of genotypes in different environments and identify mega environments using the GGE biplot in the meta analysis of GenStat 12.1 (Payne *et al.*, 2009).

6.3 Results

6.3.1 Weather conditions in the different environments

The environments differed in monthly rainfall amounts, mean temperature and relative humidity (Table 6.2). In addition to the monthly rainfall, a monthly average of 162.53 mm of irrigation water was supplied to the irrigated plots in 2013 whereas a monthly amount of 170.66 mm was applied in 2014. The monthly rainfall for Fumesua in 2014 (135.00 mm/month) was higher than in 2013 (95.59 mm/month). Mean monthly temperature recordings at Nyankpala were higher than at Fumesua in both years. The environments at Fumesua (FUM13 and FUM14) were more humid than at Nyankpala in both years.

Table 6.2 Mean monthly rainfall, irrigation water supplied, temperature and relative humidity

Environment	Mean monthly rainfall (mm)	Irrigation water/month	Mean temperature (°C)	Relative humidity (%)
NIR13	82.64	-	28.29	68.68
NIR14	98.42	-	28.71	68.5
IRR13	82.64	162.53	28.29	68.68
IRR14	98.42	170.66	28.71	68.5
FUM13	95.59	-	27.3	75.4
FUM14	135.00	-	25.8	81.3

6.3.2 Mean squares for physiological, growth and yield traits

Mean squares from the combined analysis of variance across environments indicated that environment had very highly significant ($P<0.001$) effect on all traits (Tables 6.3 and 6.4). The environments were further partitioned into five contrasts namely forest ecology vs savannah ecology (E1), Fumesua 2013 vs Fumesua 2014 (E2), irrigation vs no irrigation (E3), no irrigation 2013 vs no irrigation 2014 (E4) and irrigation 2013 vs irrigation 2014 (E5). Variations within environments were not significantly different for most of the traits. Genotype effects were significant for all the traits except leaf temperature ($P>0.05$). Genotype x environment (GxE) interactions were also significant for all traits except leaf temperature. The G x E interaction was further partitioned into the interaction of genotypes with the contrasted environments. This also indicated that genotypes reacted differently in Fumesua and Nyankpala (GxE1) for all traits except stomatal conductance, leaf temperature, harvest index, root girth and root length ($P>0.05$). Performance of genotypes in Fumesua in 2013 and 2014 (GxE2) were significant ($P<0.05$) for stomatal conductance, stem diameter and root number per plant as well as highly significant ($P<0.01$) for harvest index, root yield and storage root length. It was however insignificant ($P>0.05$) for all the other traits. Genotype x environment interaction effect under irrigation and no irrigation (GxE3) was not significant ($P>0.05$) for all the other traits except mean root weight. The interaction of genotypes with the two non-irrigated trials in 2013 and 2014 (GxE4) was not significant for most of the other traits except stomatal conductance, number of branches per plant, stem diameter, height at branching ($P<0.001$) and storage root length: girth ratio. Apart from number of branches per plant ($P<0.001$), height at branching ($P<0.05$) and cassava mosaic disease severity score ($P<0.001$), the interaction of genotypes with the two irrigated trials in 2013 and 2014 (GxE5) were not significant ($P>0.05$) for most of the traits.

Table 6.3 Mean squares for physiological and growth parameters of 20 cassava genotypes in six environments

Source of variation	**Df**	**St_cond (mmol/m^{2}s^{-1})**	**L_temp (°C)**	**Levs/plt**	**Brnchno**	**St_diam (cm)**	**Plt_ht (cm)**	**Ht_brnch (cm)**	**CMD (1-5)**
Environment (E)	5	284443.82***	93.84***	388753.78***	1984.39***	2.03***	209255.66***	24425.24***	14.55***
E1‡	1	34168.0NS	0.65NS	1056514.0**	193.72NS	2.42**	996235.0***	143882.7*	71.57**
E2	1	16652.8**	81.08NS	26182.0NS	407.32*	5.84NS	5044.0NS	896.0NS	0.28NS
E3	1	1166299.0**	305.02**	720638.0*	91.03NS	0.08NS	17791.8NS	867.2*	0.05NS
E4	1	337282.0**	119.49*	573.1NS	4298.69**	0.24*	22177.1*	4927.3NS	0.41NS
E5	1	1249.0NS	3.96NS	139861.0*	4931.21*	1.58NS	5030.1NS	1665.9NS	0.47NS
Rep(Env)	12	10666.25***	11.41***	9711.18NS	77.69*	0.38***	2479.11**	1080.11**	0.58**
Genotype (G)	19	2334.88***	1.46NS	44420.61***	388.37***	0.54***	15303.01***	10549.46***	6.13***
GxE	95	1725.02**	0.85NS	13113.46**	66.50***	0.15**	1281.88**	742.27***	1.08***
GxE1	19	1459.0NS	0.59NS	40639.0***	124.51*	0.23**	2212.0**	1741.1***	3.92***
GxE2	19	1309.1*	0.85NS	17956.0NS	39.40NS	0.19*	1595.0NS	1293.1NS	0.32NS
GxE3	19	2459.0NS	0.99NS	3531.0NS	20.48NS	0.09NS	715.9NS	207.6NS	0.22NS
GxE4	19	1928.3*	0.77NS	546.8NS	73.94***	0.12*	630.6NS	672.3***	0.30NS
GxE5	19	2202.0NS	1.40NS	2893.0NS	74.18**	0.10NS	1255.4NS	427.6*	0.65***
Error	228	1051.04	0.93	7377.27	34.85	0.08	775.71	357.06	0.19
Total	359								

*, **, *** = significant at $P<0.05$, $P<0.01$, and $P<0.001$ respectively. NS = Not significant ($P>0.05$). St_cond =Stomatal conductance (mmol/m^{2}s^{-1}), L_temp = leaf temperature (°C), Levs/plt = Number of leaves per plant, Brnchno = Number of branches per plant, St_diam =Stem diameter (cm), Plt_ht = Plant height (cm), Ht_brnch = height at branching (cm), CMD = cassava mosaic disease severity score

‡= Contrasts between environments: E1 = Fumesua vs Nyankpala, E2 = Fumesua 13 vs Fumesua 14, E3 = Irrigation vs No irrigation, E4 = No irrigation 13 vs No irrigation 14 and E5 = Irrigation 2013 vs Irrigation 14

Table 6.4 Mean squares for root yield and yield components of 20 cassava genotypes in six environments

Source	DF	AGBio (t/ha)	HI	Rt_yld (t/ha)	Rtno/plt	MRW (g)	Rt_girth (cm)	Rt_len (cm)	L/G	DM%
Environment (E)	5	2999.32***	0.43***	3114.57***	38.15***	618381.22***	92.41***	2051.68***	333.84***	299.21***
E1‡	1	14135.2**	0.91*	8618.93*	18.11NS	1599794.0**	287.19**	73.31NS	474.09**	16.09NS
E2	1	37.6NS	0.14NS	738.20NS	102.16**	85668.00NS	0.01NS	3340.22**	58.44**	11.92NS
E3	1	830.4*	0.89***	6551.28*	0.19NS	1401588.00*	168.49*	1098.98*	793.22**	1330.10**
E4	1	153.4NS	0.04*	44.20NS	1.45NS	53118.00NS	0.73NS	3675.84*	315.76NS	124.64*
E5	1	198.6NS	0.17*	19.66NS	71.05*	23687.00NS	11.80NS	2164.88***	35.21*	12.87NS
Rep(Env)	12	87.96*	0.01***	95.86*	5.46*	19121.65NS	2.09NS	40.16NS	8.19***	28.86**
Genotype (G)	19	270.17***	0.06***	715.89***	14.96***	103773.41***	12.11***	348.85***	34.96***	117.28***
GxE	95	104.54***	0.01***	136.35***	4.81**	20202.78*	1.78*	46.07*	2.95**	17.78**
GxE1	19	303.4***	0.01NS	330.67***	8.50***	40933.0**	2.76NS	63.75NS	2.76NS	31.78**
GxE2	19	185.0*	0.01**	263.90**	5.14*	36493.00NS	2.24NS	75.8**	1.11NS	11.94NS
GxE3	19	16.2NS	0.08NS	29.33NS	3.92NS	13203.00*	1.10NS	30.11NS	3.25NS	17.69NS
GxE4	19	4.3NS	0.03NS	19.54NS	3.94NS	4092.00NS	0.27NS	43.76NS	5.67*	12.25NS
GxE5	19	27.2NS	0.03NS	56.59*	2.83NS	7358.00NS	2.57NS	18.87NS	1.92NS	15.26NS
Error	228	41.18	0.02	52.18	2.76	14700.17	1.31	31.61	1.84	11.44
Total	359									

*, **, *** = significant at P<0.05, P<0.01, and P<0.001 respectively. NS = Not significant (P>0.05). AGBio = Above ground biomass yield (t/ha), HI = Harvest index, Rt_yld = Root yield (t/ha), Rtno/plt = Storage root number per plant, MRW = Mean root weight (g), Rt_girth = Storage root girth (cm), Rt_length = Storage root length (cm), L/G = Storage root length: girth ratio, DM% = Dry matter content (%)

‡ = Contrasts between environments: E1 = Fumesua vs Nyankpala, E2 = Fumesua 13 vs Fumesua 14, E3 = Irrigation vs No irrigation, E4 = No irrigation 13 vs No irrigation 14 and E5 = Irrigation 2013 vs Irrigation 14

6.3.3 Variance components, broad sense heritability, phenotypic and genotypic coefficient of variation and genetic advance for root yield and other traits

A large part of the phenotypic variance (σ^2_p) of stomatal conductance was accounted for by the genetic variance (σ^2_g) (Table 6.5). However the error variance (σ^2_e) was higher than all the other variance components. The genetic variance for leaf temperature was also higher than the interaction variance. Genetic variances (σ^2_g) for plant height, number of branches and height at branching were higher than the σ^2_{ge}. Root yield and yield components such as dry matter, root girth, root length, root length/girth ratio and number of roots per plant were mostly influenced by the genetic variances more than the interactions. However σ^2_{ge} for above ground biomass was higher than the genetic variance. Error variances (σ^2_e) for all traits were higher than their phenotypic variances except plant height, height at branching, root yield and harvest index.

The broad-sense heritability values varied for all the traits and were especially low for stomatal conductance (24.36%), above ground biomass (24.96%), stem diameter (43.08%) and root number per plant (46.48%) (Table 6.5). Broad sense heritability values were intermediate for number of leaves per plant (52.09%), root yield (52.15%), number of branches per plant (60.95%) and leaf temperature (67.67%). Relatively high broad sense heritability estimates were observed for plant height (82.84%), root length (77.31%), root girth (75.03% and storage root length/girth ratio (84.63%). The PCV values of all traits were lower than their corresponding GCV values. Wide differences between PCV and GCV were observed for number of leaves per plant and above ground biomass yield (t/ha). PCV ranged from 1.01% for leaf temperature to 38.89% for height at branching. GCV on the hand varied from 0.83% (leaf temperature) to 36.19% (height at branching). Stomatal conductance, leaf temperature, stem diameter, dry matter content and root length had low PCV values (<10) whereas moderate PCV’s (10-20) were observed for plant height, harvest index, root girth, root length/ girth ratio and root number per plant. High PCV’s (>20) were recorded for above ground biomass, root yield, leaves per plant, number of branches and height at branching. GCV estimates for traits such as leaves per plant and above ground biomass were very different from their corresponding PCV compared with leaf temperature, height at branching and root girth to length ratio. The analysis of the expected genetic advance as percentage of the mean (GAM) indicated that height at branching could be improved by 65.9% whilst only 1.40% reduction could be made in leaf temperature if plants are selected from this population. Root yield can also be improved by 32.77% whilst progress of 17.06 and 31.95% could be made in harvest index and root length/girth ratio respectively.

Table 6.5 Estimates of variance components, broad sense heritability, phenotypic coefficient of variation and genotypic coefficient of variation for 16 traits in 20 cassava genotypes in six environments

Trait	σ^2_g	σ^2_{ge}	σ^2_e	σ^2_p	H^2	GCV	PCV	GA	GAM
ST_cond	59.17	-7.00	1537.00	242.89	24.36	4.26	7.34	7.82	4.33
L_temp	0.08	-0.07	1.19	0.12	67.67	0.83	1.01	0.49	1.40
Plt_ht	746.98	72.47	843.90	901.67	82.84	14.75	15.70	51.25	27.66
Brnchno	15.32	3.90	36.32	25.13	60.95	32.29	37.63	6.29	51.93
Levs/plt	1169.50	2563.50	7506.00	2245.06	52.09	25.13	35.81	50.85	37.36
Ht_brnch	630.94	111.68	387.10	805.59	78.32	36.19	38.89	45.79	65.98
St_diam	0.013	0.012	0.091	0.031	43.08	5.14	7.06	0.16	6.94
AGBio	5.33	13.89	44.33	21.37	24.96	13.54	23.01	2.38	13.93
Rt_yld	29.82	7.28	54.10	57.19	52.15	22.03	26.32	8.12	32.77
DM%	4.90	2.38	13.27	6.30	77.70	6.53	7.46	4.02	11.86
HI	0.0030	0.0006	0.0037	0.0042	71.66	9.79	10.81	0.10	17.06
Rt_girth	0.54	0.06	1.36	0.73	75.03	12.86	14.25	1.32	22.94
Rt_length	13.03	4.30	31.92	16.85	77.31	8.89	9.99	6.54	16.11
L/G	1.68	0.14	2.15	1.98	84.63	16.86	17.89	2.46	31.95
Rt_no	0.47	0.43	2.84	1.01	46.48	9.98	13.43	0.96	14.01
MRW	4361.39	1604.50	14254.00	6179.78	70.58	19.71	23.47	114.29	29.94

σ^2_g = genotypic variance, σ^2_{ge} = genotype x environment variance, σ^2_e = error variance, σ^2_p = phenotypic variance, H^2= broad sense heritability, PCV = Phenotypic coefficient of variation, GCV = Genotypic coefficient of variation, GA = genetic advance, GAM = genetic advance as percentage of the mean, ST_cond =stomatal conductance (mmol/m^2s^{-1}), L_temp = leaf temperature (°C), Plt_ht = Plant height (cm), Brnchno = Number of branches per plant, Levs/plt = Number of leaves per plant, Ht_brnch = height at branching (cm), St_diam =Stem diameter (cm), AGBio = Above ground biomass yield (t/ha), Rt_yld = Root yield (t/ha), DM% = Dry matter content (%), HI = Harvest index, Rt_girth = Storage root girth (cm), Rt_length = Storage root length (cm), L/G = Storage root length : girth ratio, Rt_no = Storage root number per plant, MRW = Mean root weight (g).

6.3.4 Pearson's correlation among traits across environments

Pearson correlation analysis performed for traits across all environments indicated highly significant correlations were observed between root yield and all the traits except root dry matter content (Table 6.6). Strong positive correlation was found between root yield and mean root weight (r = 0.72), root girth (r = 0.58) and above ground biomass (0.61). There were weak correlations between root yield and root length (r = 0.34), plant height (r = 0.21), number of leaves/plant (r=0.32) and stomatal conductance (0.33). Root yield was negatively correlated with cassava mosaic disease severity score (r = -0.23), root length/girth ratio (r = -0.31) and leaf temperature (r = -0.24). Root length/girth ratio was negatively correlated with root girth (r = -64), stomatal conductance (r = -0.19), plant height (r = -34), number of leaves per plant (r = -0.34), mean root weight (r = -0.40) and harvest index, all of which are positively correlated with root yield. Negative correlation was observed between harvest index and above ground biomass (r = -0.40), plant height, (r = -0.49), leaf temperature (r = -0.26), root length/girth ratio (r = -0.13) and number of leaves per plant (r = -0.15). Above ground biomass yield (t/ha) was positively correlated with plant height (r = 0.56), mean root weight (r = 0.47), number of leaves per plant (r = 0.41), root girth (r = 0.38) and stomatal conductance (r = 0.37). Leaf temperature was significantly negatively correlated with all traits except storage root length/ girth ratio. The correlation between leaf temperature and above ground biomass, CMD severity score and root dry matter content were not significant (P>0.05).

Table 6.6 Pearson phenotypic correlations between traits for 20 cassava genotypes in six environments

AGbio	1	-											
CMD	2	0.03NS	-										
HI	3	-0.40***	-0.37***	-									
L/G	4	-0.15**	-0.11*	-0.13*	-								
L_temp	5	0.04NS	-0.01NS	-0.26***	0.14**	-							
MRW	6	0.47***	-0.07NS	0.29***	-0.40***	-0.14**	-						
Rt_girth	7	0.38***	-0.03NS	0.16**	-0.64***	-0.26***	0.60***	-					
Rt_length	8	0.31***	-0.12*	0.06NS	0.57***	-0.19***	0.19***	0.12*	-				
Rt_yld	9	0.61***	-0.23***	0.37***	-0.31***	-0.24***	0.72***	0.58***	0.34***	-			
ST_cond	10	0.37***	0.32***	0.34***	-0.44***	-0.64***	0.42***	0.46 ***	0.05NS	0.33***	-		
Levs_plt	11	0.41***	0.18**	-0.15**	-0.34***	-0.13*	0.29***	0.27***	-0.08NS	0.32***	0.16**	-	
Plt_ht	12	0.56***	0.40***	-0.49***	-0.34***	0.08NS	0.30***	0.33***	-0.03NS	0.21***	-0.13*	0.32***	-
DM%	13	-0.16*	-0.09NS	0.16**	0.09NS	-0.21***	-0.08NS	-0.05NS	0.07NS	0.04NS	0.27***	0.01NS	-0.05NS
		1	2	3	4	5	6	7	8	9	10	11	12

*, **, *** = significant at P<0.05, P<0.01, and P<0.001 respectively. NS = Not significant (P>0.05). AGbio = Above ground biomass yield (t/ha), CMD = cassava mosaic virus disease score, HI = Harvest index, L/G = Storage root length : girth ratio, L_temp = leaf temperature (°C), MRW = Mean root weight (g), Rt_girth = Storage root girth (cm), Plt_ht = Plant height (cm), Levs/plt = Number of leaves per plant, Rt_yld = Root yield (t/ha), ST_cond =stomatal conductance (mmol/m^2s^{-1}), DM% = Dry matter content (%), Rt_length = Storage root length (cm)

6.3.5 Physiological traits

6.3.5.1 Stomatal conductance

Stomatal conductance varied significantly across environments and among genotypes (Table 6.7). Fumesua (FUM13 and FUM14) favoured high stomatal conductance for all the genotypes with average stomatal conductance of 252.42 and 249.44 mmol/m^{2}s^{-1} in 2013 and 2014, respectively. Average stomatal conductance under irrigation for all genotypes was 191.84 mmol/m^{2}s for 2013 and 178.98 mmol/m^{2}s^{-1} in 2014. In the non-irrigated environments, average stomatal conductance was 114.01 mmol/m^{2}s^{-1} in 2013 and 122.12 mmol/m^{2}s in 2014. The highest average stomatal conductance across all environments was from the local genotype *Pontisange* (203.78 mmol/m^{2}s^{-1}). *Biabasse* had the lowest average stomatal conductance (171.0 mmol/m^{2}s^{-1}) across all environments.

Table 6.7 Stomatal conductance (mmol/m^{2}s^{-1}) of 20 cassava genotypes in six environments

Genotypes	**FUM13**	**FUM14**	**IRR13**	**IRR14**	**NIR13**	**NIR14**	**Mean**
Biabasse	251.90	177.20	218.90	165.00	96.30	116.70	171.00
CTSIA 230	195.20	230.10	198.80	181.20	121.00	104.00	171.72
96/409	231.50	190.20	217.00	178.40	93.10	127.00	172.87
TME 419	268.40	221.80	164.10	157.00	95.00	133.60	173.32
ATR 007	233.60	224.00	184.70	174.90	111.00	114.50	173.78
00/0203	249.30	247.10	170.10	181.10	113.40	120.70	180.28
CTSIA 110	250.80	205.30	193.00	180.70	122.80	130.20	180.47
I91934	245.90	248.00	172.50	164.10	121.90	140.00	182.07
NWA 004	251.60	256.70	182.80	168.40	122.50	112.30	182.38
ATR 002	242.30	239.40	191.30	182.50	133.70	113.00	183.70
UCC 2001/449	261.40	226.70	223.00	161.40	118.20	141.50	188.70
CTSIA 45	260.00	287.10	184.60	182.10	106.90	111.50	188.70
CTSIA 65	283.20	276.20	178.10	176.90	96.10	124.40	189.15
96/1708	245.30	278.80	193.50	185.70	119.20	117.80	190.05
MM 96/1751	244.10	295.80	198.70	193.70	89.60	118.50	190.07
CTSIA 112	275.70	278.00	182.80	208.90	95.40	104.00	190.80
CTSIA 48	292.20	249.80	172.70	195.50	126.40	114.00	191.77
CTSIA 72	245.50	254.90	199.20	183.20	150.20	119.40	192.07
TME 435	274.60	307.70	201.60	173.70	103.20	135.50	199.38
Pontisange	245.80	293.90	209.30	185.10	144.30	143.80	203.70
Mean	**252.42**	**249.44**	**191.84**	**178.98**	**114.01**	**122.12**	**184.80**
SED	**21.73**	**40.29**	**24.64**	**16.34**	**24.5**	**24.42**	**13.14**

FUM13 = Fumesua 2013, FUM14 = Fumesua 2014, IRR13 =Irrigation 2013, IRR14 = Irrigation 2014, NIR13 = No irrigation 2013, NIR14 = No irrigation 2014

6.3.5.2 Leaf temperature

Leaf temperature varied significantly among the genotypes in the different environments (Table 6.8). Leaf temperatures were generally higher in the non-irrigated environments (NIR13 and NIR14) than the irrigated environments and at Fumesua in both years. The highest average leaf temperature across all environments was recorded from CTSIA 65 (35.41^{o}C) with TME 435 having the least average leaf temperature (34.0^{o}C) across all environments.

Table 6.8 Average leaf temperature (°C) of 20 cassava genotypes in six environments

Genotypes	FUM13	FUM14	IRR13	IRR14	NIR13	NIR14	Mean
CTSIA 65	34.45	34.92	35.97	34.59	37.33	35.20	35.41
ATR 007	32.98	34.72	37.52	33.95	36.58	35.88	35.27
CTSIA 112	34.27	35.05	37.13	34.03	37.07	33.93	35.24
96/1708	34.47	34.47	35.92	34.29	36.92	34.91	35.16
MM 96/1751	33.97	33.67	35.95	34.19	37.83	35.05	35.11
UCC 2001/449	34.28	34.03	35.67	34.08	37.35	35.18	35.10
NWA 004	34.02	33.22	35.73	34.73	36.83	36.03	35.09
CTSIA 110	34.47	34.22	35.70	34.00	36.67	35.42	35.08
I91934	33.45	34.38	36.15	34.33	37.05	35.02	35.06
CTSIA 45	34.30	32.97	35.93	34.45	37.12	35.13	34.98
CTSIA 48	34.28	32.85	36.40	34.21	36.45	35.32	34.92
CTSIA 72	34.38	35.18	34.62	34.37	36.97	33.87	34.90
Pontisange	33.92	32.92	35.75	34.16	37.10	35.46	34.88
CTSIA 230	33.83	33.63	35.23	33.93	36.95	35.35	34.82
Biabasse	34.00	33.05	35.37	33.78	37.25	35.18	34.77
00/0203	33.92	34.00	35.73	33.97	36.92	34.02	34.76
TME 419	34.05	33.25	35.87	33.89	36.77	34.38	34.70
ATR 002	34.35	32.40	35.50	34.20	36.98	34.28	34.62
96/409	33.77	32.55	35.77	34.24	37.40	33.48	34.53
TME 435	33.63	32.05	34.25	33.90	36.12	34.05	34.00
Mean	**34.04**	**33.68**	**35.81**	**34.16**	**36.98**	**34.86**	**34.92**
SED	**0.99**	**0.29**	**0.60**	**2.40**	**0.60**	**0.72**	**0.29**

FUM13 = Fumesua 2013, FUM14 = Fumesua 2014, IRR13 =Irrigation 2013, IRR14 = Irrigation 2014, NIR13 = No irrigation 2013, NIR14 = No irrigation 2014

6.3.6 Growth parameters and cassava mosaic disease severity

Combined analysis of variance for all genotypes across the six environments showed significant ($P<0.05$) genetic variability for plant height, number of leaves per plant, number of branches per plant, height at branching, stem girth and cassava mosaic disease severity score (Table 6.9). CTSIA 65 had the highest plant height (249.67 cm) with genotype 00/0203 having the shortest average plant height across all environments. CTSIA 110 produced both the highest average number of leaves (233.45) and branches (19.71) per plant whilst MM96/1751 had the least average number of leaves (63.42) and branches (3.47) per plant. The lowest branching genotype was I91934 (36.38 cm) whilst CTSIA 65 had the highest height at first branching (136.65 cm). Average stem diameter ranged between 1.84 cm (CTSIA 72) and 2.61 cm (96/409). Cassava mosaic disease score also varied significantly among the different genotypes (Table 6.9). MM96/1751 had the lowest overall mean CMD score (1.00) with CTSIA 230 having the highest CMD score (2.53).

Table 6.9 Mean performance of 20 cassava genotypes evaluated in six environments

Genotypes	**Plant height (cm)**	**No. leaves/ plants**	**No. of branches/ plant**	**Height at branching (cm)**	**Stem girth (cm)**	**CMD score (1-5)**
00/0203	137.73	205.23	18.63	35.38	2.33	1.06
96/1708	142.52	117.38	10.67	75.27	2.22	1.06
96/409	180.88	143.55	11.84	58.58	2.61	1.11
ATR 002	160.53	99.90	9.55	62.17	2.36	1.21
ATR 007	221.98	103.42	11.37	77.95	2.16	1.54
Biabasse	158.42	128.72	12.92	69.87	2.14	2.44
CTSIA 110	214.08	233.45	19.71	46.58	2.39	2.03
CTSIA 112	203.43	173.32	16.45	55.30	2.40	2.19
CTSIA 230	191.73	182.37	16.13	45.72	2.14	2.53
CTSIA 45	174.40	156.45	14.05	48.95	2.30	1.94
CTSIA 48	157.05	134.78	13.39	57.93	2.21	2.31
CTSIA 65	249.67	96.95	7.85	136.65	2.01	2.33
CTSIA 72	211.65	69.83	6.23	110.83	1.84	2.31
I91934	146.37	187.27	18.58	36.38	2.13	1.17
MM 96/1751	190.92	63.42	3.47	75.80	2.32	1.00
NWA 004	200.22	140.12	12.52	69.47	2.15	1.32
Pontisange	202.22	83.37	7.39	115.20	2.19	2.28
TME 419	199.12	96.82	8.27	89.42	2.34	1.07
TME 435	188.97	93.45	6.60	79.95	2.33	1.07
UCC 2001/449	173.37	212.68	16.84	41.03	2.52	1.22
Mean	**185.26**	**136.12**	**12.12**	**69.42**	**2.25**	**1.66**
SED	**9.68**	**28.88**	**2.01**	**6.56**	**0.10**	**0.15**

6.3.7 Root yield in different environments

Genotypes differed in root yields in the different environments in the different years (Table 6.10). The highest root yield at Fumesua in 2013 (FUM13) was obtained from MM96/1751 (45.9 t/ha) with the lowest yield coming from CTSIA 110 (9.46 t/ha). Average root yield for all genotypes across environments was 24.79 t/ha (Table 6.10). UCC2001/449 had the highest overall root yield of 34.09 t/ha with CTSIA 65 having the lowest root yield (14.24 t/ha). Six genotypes (UCC2001/449, MM96/1751, I91934, 96/1708, 96/409 and 00/0203) had significantly higher root yields than the average of all genotypes.

Table 6.10 Root yield (t/ha) of 20 cassava genotypes evaluated in six environments

Genotypes	FUM13	FUM14	IRR13	IRR14	NIR13	NIR14	Mean
00/0203	36.04	48.88	27.25	32.56	24.25	16.00	30.83
96/1708	24.65	61.61	31.75	38.25	24.79	20.75	33.63
96/409	27.53	45.92	33.93	28.42	19.83	17.46	28.85
ATR 002	18.92	36.56	32.33	25.33	17.46	16.50	24.52
ATR 007	34.00	33.93	22.75	20.08	15.83	13.38	23.33
Biabasse	36.03	33.07	21.50	23.50	13.86	14.33	23.72
CTSIA 110	9.46	25.01	20.79	21.50	16.44	14.72	17.99
CTSIA 112	28.08	20.06	28.88	26.42	20.67	16.17	23.38
CTSIA 230	12.34	12.64	25.71	21.67	14.51	14.58	16.91
CTSIA 45	30.50	20.22	23.83	25.63	19.29	14.58	22.34
CTSIA 48	14.19	10.37	26.63	18.29	11.83	11.08	15.40
CTSIA 65	13.31	15.01	15.46	20.46	7.79	13.42	14.24
CTSIA 72	17.26	13.05	23.46	20.75	11.42	14.96	16.82
I91934	19.61	49.51	44.13	37.42	20.96	21.67	32.22
MM 96/1751	45.90	40.88	40.50	29.29	22.96	19.97	33.25
NWA 004	24.89	38.98	20.00	21.75	12.04	15.96	22.27
Pontisange	34.02	38.96	23.83	26.08	13.25	16.83	25.50
TME 419	18.99	51.04	34.92	31.33	18.58	17.50	28.73
TME 435	23.10	44.81	31.21	29.50	22.75	15.75	27.85
UCC 2001/449	44.03	56.00	27.25	33.38	22.61	21.25	34.09
Mean	**25.64**	**34.82**	**27.81**	**26.58**	**17.56**	**16.34**	**24.79**
SED	**9.30**	**8.19**	**5.432**	**2.943**	**3.613**	**2.081**	**2.45**

FUM13 = Fumesua 2013, FUM14 = Fumesua 2014, IRR13 =Irrigation 2013, IRR14 = Irrigation 2014, NIR13 = No irrigation 2013, NIR14 = No irrigation 2014

6.3.8 Root yield components analyzed from six environments

Combined analysis of variance for all genotypes across the three environments over the two years indicated significant genetic variability for root yield components at 12 months after planting (Table 6.11). Above ground biomass yield (t/ha) ranged between 9.82 and 26.06 t/ha for CTSIA 72 and 96/409 respectively with a mean of 17.06 t/ha. Mean root weight varied from 180.47 to 463.40 g for CTSIA 65 and MM96/1751, respectively. Significant differences (P<0.05) were also observed for number of roots per plant. The highest average number of roots was produced by 96/409 (8.86) with *Pontisange* having the least (5.72). Harvest index also varied among the genotypes from a low of 0.43 (CTSIA 110) to a relatively high of 0.63 (00/0203). Average root girth across environments ranged from 4.33 to 7.21 cm for CTSIA 45 and MM96/1751, respectively. The longest roots were produced by 96/1708 (48.19 cm) with CTSIA 65 having the shortest root length (32.78 cm). Root length/girth ratio, which indicates the extension of roots relative to expansion in girth, also varied from 5.06 (I91934) to 11.68 (CTSIA 45), with a mean of 7.68 for all genotypes.

Table 6.11 Mean performance of 20 cassava genotypes evaluated in six environments

Genotypes	AGB (t/ha)	MRW (g)	Rtno/plt	HI	Rtgirth (cm)	Rt_lent (cm)	L/G
00/0203	15.42	372.62	8.18	0.66	6.35	42.53	7.00
96/1708	19.44	379.27	8.29	0.65	5.58	48.19	9.25
96/409	26.06	318.78	8.86	0.53	5.52	40.01	7.66
ATR 002	13.72	375.92	5.96	0.61	6.64	41.48	7.04
ATR 007	19.87	338.85	6.77	0.53	5.41	43.17	8.49
Biabasse	13.90	360.03	5.78	0.59	5.95	38.74	6.89
CTSIA 110	19.45	222.55	6.95	0.43	4.66	37.35	8.48
CTSIA 112	18.23	323.00	7.17	0.54	5.46	38.79	7.42
CTSIA 230	14.99	270.37	5.97	0.47	4.79	39.52	8.76
CTSIA 45	16.77	286.40	7.43	0.55	4.33	47.70	11.68
CTSIA 48	11.64	232.22	5.95	0.52	4.95	36.86	7.87
CTSIA 65	13.05	180.47	6.49	0.47	4.85	32.78	7.07
CTSIA 72	9.82	244.65	6.18	0.59	5.20	36.24	7.26
I91934	19.34	375.05	7.98	0.60	7.19	35.14	5.08
MM 96/1751	15.57	463.40	7.19	0.66	7.21	37.30	5.52
NWA 004	17.85	327.82	6.18	0.54	5.73	42.86	7.97
Pontisange	15.41	393.13	5.72	0.57	5.96	38.66	7.00
TME 419	19.52	400.28	6.76	0.56	6.00	47.45	8.44
TME 435	17.77	409.58	6.38	0.59	6.57	47.31	8.24
UCC 2001/449	23.38	426.28	7.41	0.59	6.40	39.66	6.54
Mean	**17.06**	**335.03**	**6.88**	**0.56**	**5.74**	**40.59**	**7.68**
SED	**2.22**	**39.80**	**0.56**	**0.02**	**0.39**	**1.88**	**0.49**

AGB = Above ground biomass yield (t/ha), MRW = Mean root weight (g), Rtno = Root number per plant, HI = harvest index, Rtgirth = Root girth (cm), Rt_lent = Storage root length (cm), L/G = Root length/girth ratio

6.3.9 Additive Main effect Multiplicative Interaction (AMMI) analysis

6.3.9.1 AMMI analysis of variance

The analysis of variance for the AMMI (Tables 6.12) for plant height and cassava mosaic disease severity score indicated very highly significant (P<0.001) effects of genotype, environment and the interactions. Genotype accounted for 17.46% of the total sum of squares (SS) of the phenotypic variation whilst environment accounted for 62.82% of the total variation for plant height. Interaction accounted for 7.31%. The first two interaction principal component axes (IPCA1 and IPCA2) accounted for 62.94% of the interaction sum of squares. Genotype accounted for 33.98% of the total sum of squares for cassava mosaic disease severity score whilst environment and interaction accounted for 21.24% and 30.2% respectively. The IPCA1 accounted for 84.94% of the interaction sum of squares.

Table 6.12 AMMI analysis of variance for plant height and cassava mosaic disease scores of 20 cassava genotypes evaluated in six environments

Source	df	SS	MS	% of total SS	% of GxE
Plant height					
Total	359	1665426	4639***		
Treatments	119	1458814	12259***		
Genotypes	19	290757	15303***	17.46	
Environments	5	1046278	209256***	62.82	
Block	12	29749	2479***		
Interactions	95	121779	1282**	7.31	
IPCA1	23	44470	1933**		36.52
IPCA2	21	32173	1532**		26.42
Residuals	51	45135	885NS	2.71	
Error	228	176862	776		
CMD (1-5)					
Total	359	342.80	0.95		
Treatments	119	292.20	2.46***		
Genotypes	19	116.50	6.13***	33.98	
Environments	5	72.80	14.55***	21.24	
Block	12	7.00	0.58***		
Interactions	95	102.90	1.08***	30.02	
IPCA1	23	87.40	3.79***		84.94
IPCA2	21	8.50	0.41***		9.73
Residuals	51	7.00	0.14NS	2.04	
Error	228	43.7	0.192		

The AMMI analyses for root yield, root length/girth ratio and above ground biomass are presented in Tables 6.13. Genotype effect accounted for 25.23% of the total sum of squares for root yield whilst environment and interaction accounted for 26.47% and 24.32% of the total sum of squares respectively. The first two interaction principal component axes (IPCA1 and IPCA2) accounted for 56.16 and 32.16% of the interaction sum of squares respectively. For root length/girth ratio, genotype accounted for 21.21% of the total sum of squares whilst environment accounted for 53.52% of the total sum of squares. Interaction accounted for

8.96% of the total sum of squares. IPCA1 and IPCA2 accounted for 51.98% and 22.47% respectively.

Table 6.13 AMMI analysis of variance for root yield and root length/girth ratio of 20 cassava genotypes evaluated in six environments

Source	Df	SS	MS	% of total SS	% of GxE
Root yield (t/ha)					
Total	359	53800.00	149.90		
Treatments	119	40898.00	343.70***		
Genotypes	19	13575.00	714.50***	25.23	
Environments	5	14240.00	2848.00***	26.47	
Block	12	1248.00	104.00*		
Interactions	95	13083.00	137.70***	24.32	
IPCA1	23	7216.00	313.70***		55.16
IPCA2	21	4207.00	200.30***		32.16
Residuals	51	1660.00	32.60NS	3.09	
Error	226	11653.00	51.60		
Root length/ girth ratio					
Total	359	3148.70	8.77		
Treatments	119	2635.30	22.15***		
Genotypes	19	667.80	35.15***	21.21	
Environments	5	1685.30	337.06***	53.52	
Block	12	98.40	8.20***		
Interactions	95	282.20	2.97***	8.96	
IPCA1	23	146.70	6.38***		51.98
IPCA2	21	63.40	3.02*		22.47
Residuals	51	72.10	1.41	2.29	
Error	226	415.00	1.84		

Both environment (37.14%) and interaction (24.46%) accounted for a greater proportion of the total sum of squares than genotype (12.63%) for above ground biomass. IPCA1 and IPCA2 accounted for 56.43 and 35.50% of the interaction sum of squares respectively. Greater part of the total sum of squares for harvest index was accounted for by environment (42.55%) followed by genotype (25.26%) and interaction (14.16%). Both IPCA1 and IPCA2 accounted for 81.97% of the interaction sum of squares (Table 6.14).

Table 6.14 AMMI analysis of variance for above ground biomass and harvest index of 20 cassava genotypes evaluated in six environments

Source	Df	SS	MS	% of total SS	% of GxE
Above ground biomass (t/ha)					
Total	359	40708	113.4***		
Treatments	119	30219	253.9***		
Genotypes	19	5143	270.7***	12.63	
Environments	5	15118	3023.7***	37.14	
Block	12	1132	94.3**		
Interactions	95	9958	104.8***	24.46	
IPCA1	23	5619	244.3***		56.43
IPCA2	21	3535	168.3***		35.50
Residuals	51	803	15.8	1.97	
Error	226	9356	41.4		
Harvest index					
Total	359	5.170	0.014		
Treatments	119	4.239	0.036***		
Genotypes	19	1.306	0.069***	25.26	
Environments	5	2.200	0.440***	42.55	
Block	12	0.146	0.012***		
Interactions	95	0.732	0.008***	14.16	
IPCA1	23	0.429	0.019***		58.61
IPCA2	21	0.171	0.008***		23.36
Residuals	51	0.133	0.003	2.57	
Error	226	0.785	0.003		

6.3.9.2 Stability analysis for root yield and related traits

Additive Main effect and Multiplicative Interaction (AMMI) stability value (ASV) ranked the genotypes based on the least score (Table 6.15). Low scores represent the most stable genotypes. Based on the ASV, the most stable genotype in terms of stomatal conductance across environments was I91934 (0.35). *Biabasse*, with the highest ASV score (10.78), was the most unstable across environments. The most stable genotype in terms of root yield was ATR 002 with a score of 1.24 (Table 6.15). The least stable genotype was 96/1708 which had an ASV score of 5.0. In the case of harvest index, TME 435 with a score of 0.04 was the most stable genotype with *Pontisange* being the most unstable genotype with a score of 0.66. CTSIA 65 had the lowest ASV score (0.44) for root length/girth ratio (L/G) making it the most stable genotype whereas CTSIA 48 had the highest ASV (2.98) making it the most unstable genotype.

Table 6.15 Genotypic performance and AMMI stability values of 20 cassava genotypes evaluated in three environments in two years

Genotype	St_cond	ASV	Rtyld (t/ha)	ASV	HI	ASV	L/G	ASV
I91934	184.80	0.35	30.51	3.04	0.60	0.53	5.08	2.63
00/0203	183.70	0.94	30.83	2.65	0.66	0.05	7.00	0.94
ATR 002	185.10	2.51	24.52	1.24	0.61	0.12	7.04	0.61
CTSIA 72	192.10	2.78	16.82	3.83	0.59	0.32	7.26	0.58
NWA 004	178.30	2.82	22.15	1.84	0.54	0.24	7.95	1.09
CTSIA 48	193.10	3.11	15.40	4.29	0.52	0.38	7.87	1.16
ATR 007	177.90	3.25	23.33	1.87	0.53	0.21	8.49	0.49
96/1708	197.50	3.68	33.66	5.00	0.65	0.43	9.23	2.20
TME 419	172.80	3.85	28.73	3.58	0.56	0.49	8.44	2.03
Pontisange	207.50	4.34	25.50	1.86	0.57	0.66	7.00	0.59
CTSIA 112	194.20	5.58	23.38	3.54	0.54	0.10	7.42	0.24
UCC 2001/449	188.70	5.59	34.09	4.04	0.59	0.19	6.54	1.53
CTSIA 45	193.80	5.74	22.34	3.27	0.55	0.22	11.68	2.98
CTSIA 65	190.90	5.93	14.24	2.56	0.47	0.18	7.07	0.44
CTSIA 230	172.50	6.05	16.91	4.26	0.47	0.11	8.76	1.11
MM 96/1751	192.80	6.97	33.25	1.98	0.66	0.47	5.52	1.55
TME 435	200.80	7.60	27.85	1.99	0.59	0.04	8.24	1.90
CTSIA 110	190.70	8.08	17.99	1.96	0.43	0.35	8.48	0.95
96/409	177.00	9.76	30.55	1.51	0.53	0.47	7.66	1.25
Biabasse	171.00	10.78	23.72	2.12	0.59	0.64	6.89	0.54

St_cond = Stomatal conductance (mmol/m^{2}s^{-1}), Rtyld = root yield (t/ha), ASV = AMMI stability value, HI = harvest index, L/G = storage root length/girth ratio

6.3.9.3 Cultivar superiority for root yield

Additive main effect and multiplicative interaction analysis identified four highest yielding genotypes in each of the six environments. 96/1708, UCC2001/449, TME 419 and I91934 were selected in the high potential environment, FUM14. The next favourable environment (IRR14) had genotypes 96/1708, I91934, 96/409 and MM96/1751. In environment FUM13, MM96/1751, UCC2001/449, 00/0203 and *Biabasse* were selected as the top genotypes. The top four genotypes in environment NIR13 were 96/1708, 00/0203, MM96/1751, and TME 435. In environment IRR13, genotypes I91934, MM96/1751, TME 419 and 96/409 were identified in order of performance. In the least favourable environment (NIR14), genotypes I91934, UCC2001/449, 96/1708 and MM96/1751 were selected.

Table 6.16 First four AMMI selections based on best root yielding genotype in each environment

Environment	Mean	Effect	1	2	3	4
FUM14	34.82	6.283	96/1708	UCC2001/449	TME419	I91934
IRR14	26.58	-0.444	96/1708	I91934	96/409	MM 96/1751
FUM13	25.62	-0.732	MM 96/1751	UCC2001/449	00/0203	*Biabasse*
NIR13	17.56	-1.481	96/1708	00/0203	MM96/1751	TME 435
IRR13	27.81	-1.637	I91934	MM 96/1751	TME419	96/409
NIR14	16.34	-1.989	I91934	UCC2001/449	96/1708	MM 96/1751

6.3.10 GGE biplot analysis for ideal genotype

6.3.10.1 Stomatal conductance

The comparison biplot graphic analysis for stomatal conductance over the six environments indicated that the first two principal components (PC1 and PC2) explained 87.48% of the total variation (Fig. 6.2). PC1 is plotted against PC2. Positive PC1 scores represent positive performance whilst negative or low PC2 scores indicate stability. Statistically stable genotypes and environments are located near to the origin of the biplot. The genotypes near the origin are I91934, 00/0203 and NWA 004 which also had low ASV estimates. The centre of the concentric circles represents the position of the ideal genotype that combined high performance with stability across environments. In this case TME 435 combined high performance with stability across all environments. Genotypes *Biabasse*, CTSIA 110, TME 419 were unresponsive to the environmental conditions and showed low but stable conductance across environnments. On the other hand, CTSIA 48, CTSIA 65, CTSIA 112, TME 435 had positive interaction with the enviroments and combined high stomatal conductance with high stability.

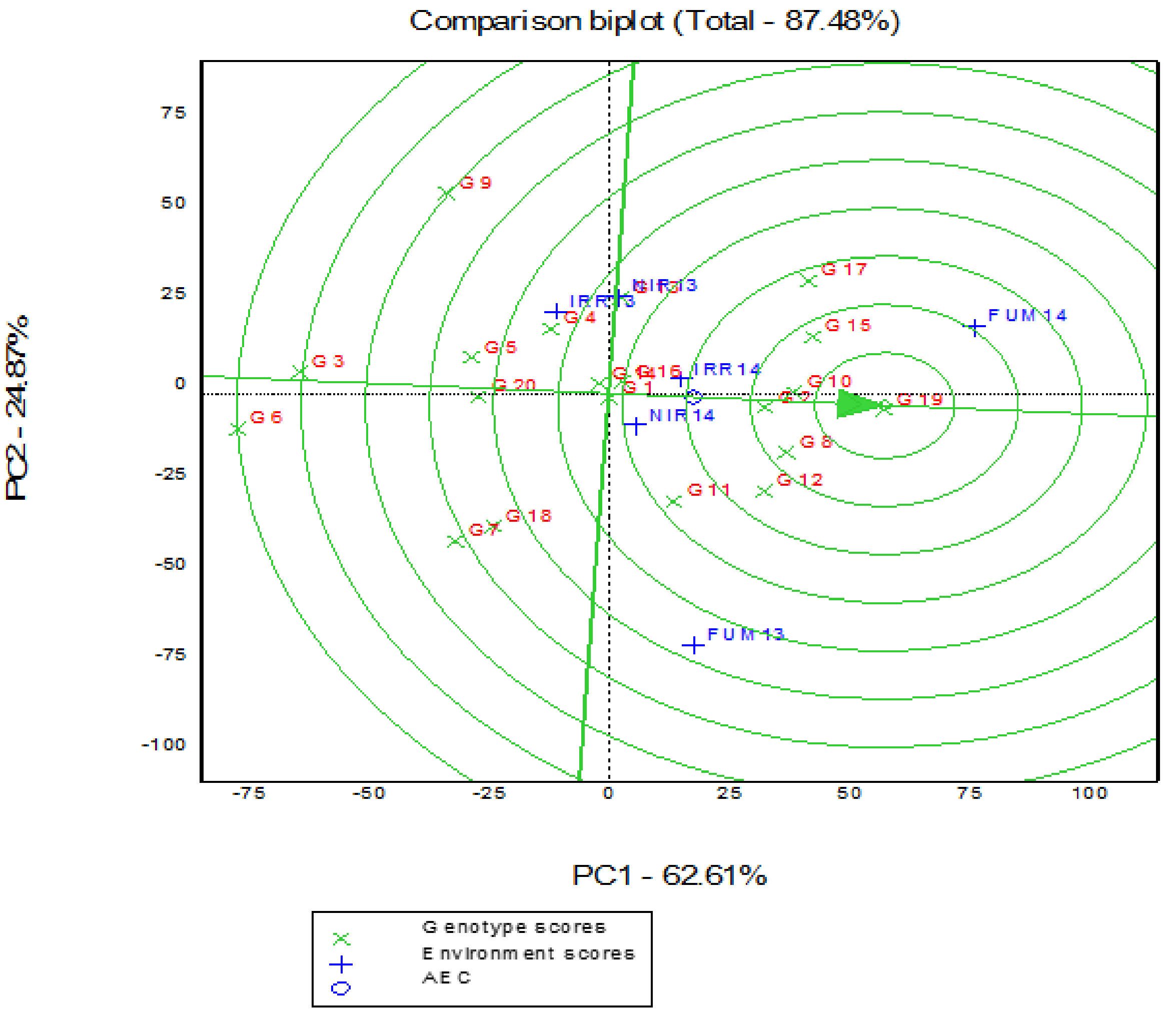


Fig.6.2 Comparison biplot of stomatal conductance of 20 cassava genotypes in six environments

G1=00/0203, G2=96/1708, G3= 96/409, G4=ATR 002, G5=ATR 007, G6=*Biabasse*, G7=CTSIA 110, G8=CTSIA 112, G9=CTSIA 230, G10=CTSIA 45, G11=CTSIA 48, G12=CTSIA 65, G13=CTSIA 72, G14=I91934, G15=MM96/1751, G16= NWA 004, G17=*Pontisange*, G18=TME 419, G19=TME 435, G20=UCC2001/449

6.3.10.2 Storage root yield

The comparison biplot showed that the first two principal component axes accounted for 93.45% of the variation due to GxE on root yield (Fig. 6.3). Three genotypes, (00/0203, MM96/1751 and UCC2001/449) were identified as both high yielding and stable as they were close to the centre of the concentric circles where as ideal genotype should be. Genotypes 96/1708, 96/409, I91934, TME 419 and TME 435 were high yielding but unstable. The most stable genotype is CTSIA 112 which appeared close to the origin of the biplot. Genotypes CTSIA 65, CTSIA 48, CTSIA 72, CTSIA 110 and CTSIA 230 were low yielding and unstable given their negative PC1 scores and high PC2 scores.

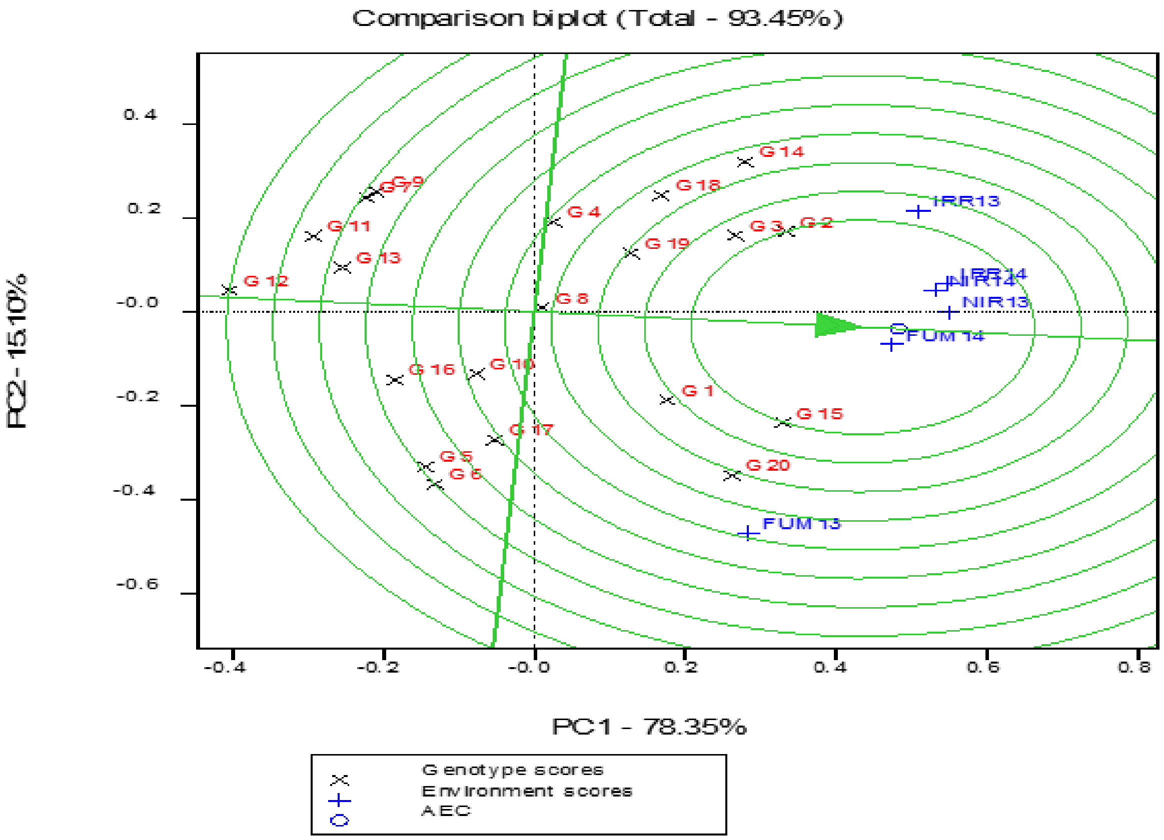


Fig. 6.3 Comparison biplot for storage root yield of 20 cassava genotypes in six environments

G1=00/0203, G2=96/1708, G3= 96/409, G4=ATR 002, G5=ATR 007, G6=*Biabasse*, G7=CTSIA 110, G8=CTSIA 112, G9=CTSIA 230, G10=CTSIA 45, G11=CTSIA 48, G12=CTSIA 65, G13=CTSIA 72, G14=I91934, G15=MM96/1751, G16= NWA 004, G17=*Pontisange*, G18=TME 419, G19=TME 435, G20=UCC2001/449

6.3.10.3 GGE biplot of best root yielding genotypes in different environments

The GGE biplot for the best performing genotypes in each environment indicated the similar genotypes as the AMMI selections (Fig.6.4). The two principal axes used to plot the biplot explained 93.45% of the yield variation due to GGE. The convex-hull drawn on genotypes from the biplot origin identified seven sectors with UCC2001/449, MM96/1751, 96/1708, I91934, CTSIA 110, CTSIA 65 and *Biabasse* as the vertex genotypes. The vertex genotype of a sector is the best performing genotype in all the environments that fell in such a sector. Environments IRR14, NIR14 and NIR13 all fell within the sector with 96/1708 as the wining vertex. No environments fell in sectors with CTSIA 65, CTSIA 110 and *Biabasse* indicating that these genotypes were unresponsive and were the poorest genotypes in some or all of the environments because they were located far from the origin of the biplot. The biplot also suggested the existence of mega environments among the sites used. The groupings indicated that environments IRR13, FUM14 AND FUM13 were distinct and grouped into mega environments. Environments IRR14, NIR14 and NIR13 were grouped in the same mega environment.

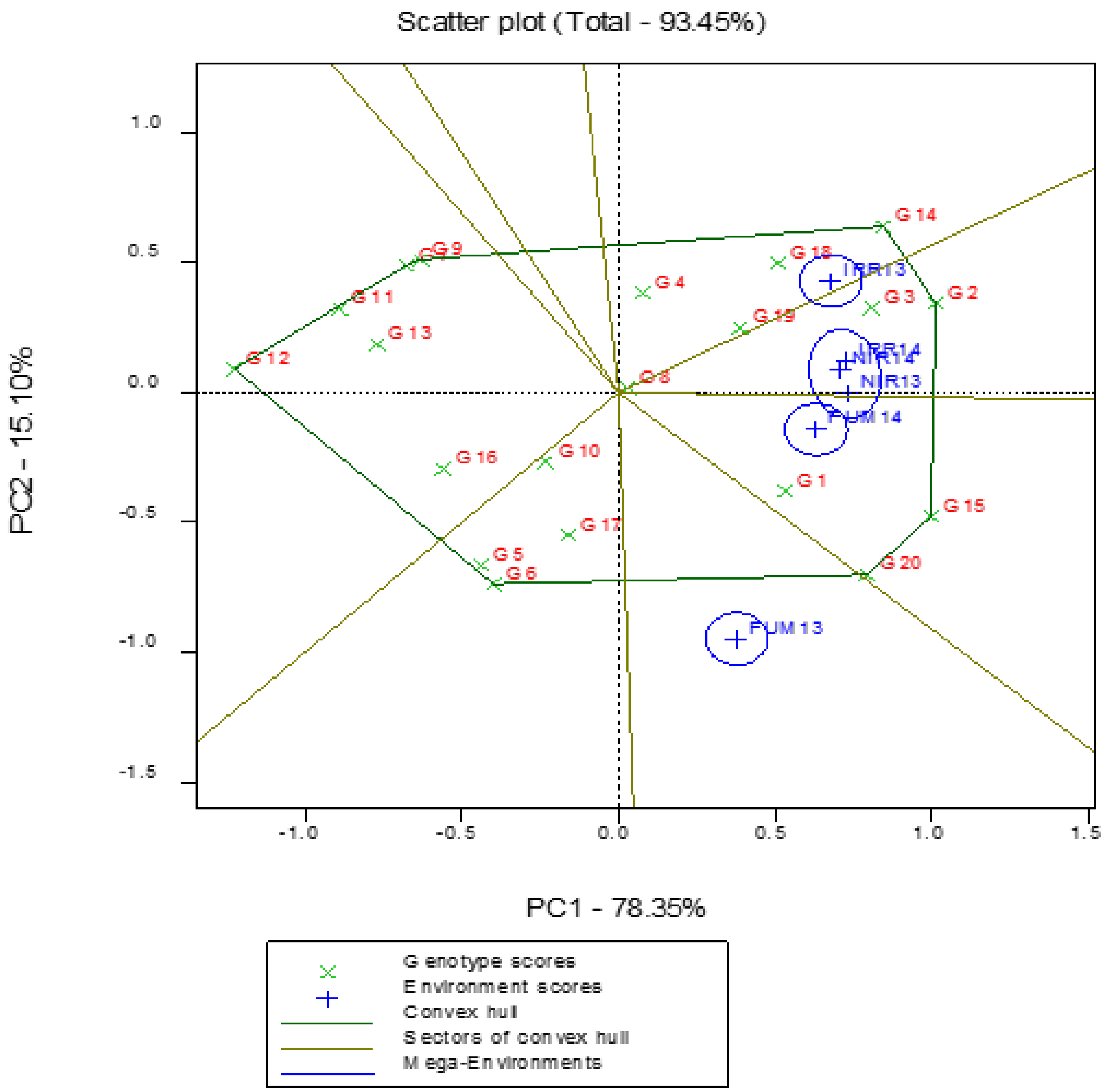


Fig.6.4 GGE biplot showing best genotypes for fresh root yield (t/ha) of 20 cassava genotypes in six environments

G1=00/0203, G2=96/1708, G3= 96/409, G4=ATR 002, G5=ATR 007, G6=*Biabasse*, G7=CTSIA 110, G8=CTSIA 112, G9=CTSIA 230, G10=CTSIA 45, G11=CTSIA 48, G12=CTSIA 65, G13=CTSIA 72, G14=I91934, G15=MM96/1751, G16= NWA 004, G17=*Pontisange*, G18=TME 419, G19=TME 435, G20=UCC2001/449

6.4 Discussion

Cassava responds to varying environmental conditions through a series of physiological processes (Alves, 2002; Okogbenin *et al.,* 2003; El-Sharkawy, 2007) which include stomatal closure that decrease stomatal conductance and increase in leaf temperature.

Genetic variations were observed for stomatal conductance and leaf temperature in the different environments but genotype x environment interaction was not significant. Stomatal conductance and leaf temperature were influenced more by the growing environments, being especially high in the optimum environments compared with the dry environments, though genotypic variations were significant. El-Sharkawy (2007) indicated that under optimum conditions, cassava plants generally maintain high stomatal conductance for optimum growth. However, this did not translate into high root yield for some of the genotypes. Leaf temperature was negatively correlated with stomatal conductance and storage root yield and varied among the genotypes and the environments. Mason and Singh (2014) also found strong negative correlation between canopy temperature and yield in wheat. Partial closure of the stomata reduced stomatal conductance leading to build up of heat from the metabolic processes. Aspiazu *et al.* (2010) reported that closure of stomata by cassava plants prevent the dissipation of heat from metabolic processes resulting in increase in leaf temperature. Leaf temperature drops below air temperature when water evaporates making temperature an indirect measure of the instantaneous transpiration at the whole-crop level (Reynolds, 2002) and plant water status (Araus *et al.,* 2002). This was reflected in the findings of this study in the relationship between stomatal conductance and leaf temperature. Measurement of canopy and leaf temperatures can be used to evaluate the transpiration rate and activities of cassava plants under stress as have been done for crops like potato (Monneveux *et al.,* 2013) and wheat (Araus *et al.,* 2002; Condon *et al.,* 2002; Olivares-Villegas *et al.,* 2007). Yield improvement was observed in wheat plants that maintained low leaf temperature under low moisture conditions (Mohammandi *et al.*, 2012).

Growth parameters such as plant height, number of leaves, stem diameter and height at branching were significantly influenced by the genotypes and the growing environments. Similar variations in response of cassava in different environments have been reported (Okogbenin *et al.,* 2003; Aina *et al.,* 2009; Mutegi, 2009). The variation in the number of leaves per plant can also be attributed to the effect of environment and genotypic variability. Leaf abscission is a key mechanism employed by plants to minimise water loss through transpiration. However, this has implications for photosynthesis and dry matter production as has been observed by Lenis *et al.* (2006). Rivero *et al.* (2007) reported that moisture stress conditions accelerate leaf senescence, leading to a decrease in canopy size, loss in photosynthesis and reduced yields. Differential accumulation of abscisic acid in leaves by different genotypes also account genetic variability in leaf abscission (Duque and Setter, 2013) as has been reported in chapter five of this Thesis. Lenis *et al.* (2006) reported that cassava genotypes with greater leaf longevity produced higher total fresh biomass and a 33% higher root dry matter compared to drought susceptible genotypes. This was observed in this study as more leaves were retained in the humid ecology at Fumesua and under irrigation. The genotypic variability and the relationship observed between leaf retention and root yield provides an opportunity for selecting genotypes with leaf retention ability for maximum root yield.

Fresh root yield was significantly affected by genotype and the growing environments. Higher root yields were obtained at Fumesua and under irrigation than under stress conditions. This confirms findings by Okogbenin *et al.* (2003) and Turyagyenda *et al.* (2013) who observed higher yields under optimum condition than under limited moisture. Genotypic variation was observed for the different environments as there were crossover performances for some of the genotypes. The crossing over was as a result of genotype x environment interaction which led to variations in the mean ranks of cultivar performance in different environments (Dixon and Nukenine, 2000; Marlosetti *et al.*, 2013). Yield stability analysis was therefore, necessary to identify genotypes that would remain consistent in their root yield across optimum and under water stress conditions (Mutegi, 2009). In this study, genotypes responded more favourably in the optimum environments than under stress conditions. The genotypes that performed relatively better indicated their tolerance to the stress conditions and can therefore be selected and used as parents in future breeding programmes.

Root size which was assessed as mean root weight and root girth was strongly influenced by the environments. This indicates that more environments are needed to establish the true potential of the genotypes. Similar findings were obtained by Aina *et al.* (2007c) and Ntawuruhunga and Dixon (2010) who observed reduced root sizes across environments. Harvest index was higher in the stress environments than in the humid environments (FUM13 and FUM14). Okogbenin *et al.* (2003) reported higher harvest index under limited moisture conditions than under optimum conditions. This was probably because cassava has the tendency to grow vigorously and produce more above ground biomass relative to their root growth in such environments than under stress environments (Alves, 2002; El-Sharkawy, 2007).

One of the mechanisms cassava uses to combat moisture stress is the extension of roots into deep soil layers for moisture absorption (El-Sharkawy *et al.*, 1992; Pardales and Yamauchi, 2003). This is aided by accumulation of dry matter for root extension rather than expansion in girth for survival. In this study, extension in root length compromised expansion in root girth. The ratio of root length/girth was higher in the stress environments than in the favourable environments indicating that genotypes tend to extend their roots to deeper soil layers for moisture in stress environments (El-Sharkawy *et al.*, 1992) instead of expansion in root girth. This resulted in reduction in storage root girth and hence bulking. Alves (2002) indicated that cassava roots extend into the soil at the initial stages of growth before dry matter accumulation commences. It has been assumed that cassava genotypes will develop root lengths equally but the final root yield will depend on the source-sink relationship and the amount of dry matter that is partitioned for root expansion (El-Sharkawy, 2004). However, genotype 96/1708 combined high root yield as well as high root length/girth ratio indicating possible simultaneous partitioning of dry matter into roots for expansion and extension.

Root yield was positively influenced by above ground biomass, plant height, mean root weight, root girth, harvest index and stomatal conductance. Some of the genotypes that had vigorous growth eventually had higher root yield. However, there were exceptions where plants with the highest plant height had low root yields. This response could be attributed to differential partitioning of dry matter into the above ground parts and storage roots (Alves, 2002; El-Sharkawy, 2004). CTSIA 65 had the highest plant height but also had the lowest root yield, mean root weight as well as root length. This indicates that dry matter partitioning was directed for top growth instead of storage roots. Okogbenin and Fregene (2002) stated that certain cassava genotypes allocate initial dry matter production for shoot growth before storage root development commences. Genotypes that are able to balance initial dry matter accumulation between shoot and root will be ideal for moisture limited environments.

Though above ground biomass yield was positively correlated with root yield, it was also negatively correlated with harvest index, the proportion of the total dry matter partitioned to the economic part. This implies that not all the genotypes with vigorous growth translated it into root yield. Selection for productive genotypes should therefore, focus on high absolute root yield and harvest index (Aina *et al.*, 2007c).

A greater proportion of the observed phenotypic variance for HI, plant height, number of roots per plant, and number of leaves per plant was accounted for by the genetic components giving an indication of the inherent genetic variation for these traits (Tsegaye *et al.* 2007). On the contrary, Tewodros *et al.* (2013) found lower genetic variances for these traits indicating strong environmental influences. Though estimates of genetic components indicated large genetic variance (σ^2_g) for a number of traits, their error variances were higher than the phenotypic variances in most cases. This implies that these traits were strongly influenced by the environment. Progress in their improvement requires careful selection. Root yield and yield components such as dry matter, root girth, root length, length to girth ratio and root number were influenced by the genetic variances more than the interactions indicating that genetic improvement can be made with selection. Similar observations were made by Ntawuruhunga and Dixon (2010) who observed large environmental variance for fresh root yield in cassava. Broad sense heritability estimates recorded for root number, dry matter content and plant height were similar to the findings of Ntawuruhunga and Dixon (2010) who recorded 39.9, 56.1, 53.8 and 41.9% for root number, dry matter content. Heritability estimates indicate the amount of progress that can be made in future performance for a trait (Sabesan *et al.*, 2009). However, broad sense heritability alone does not give a full indication of genetic gain that can be made through selection (Pradeepkumar *et al.*, 2001; Singh *et al.*, 2013). It is necessary to estimate the genetic advance as a percentage of the mean to determine the actual progress.

Stability analysis methods are used by breeders to identify genotypes that have predictable performance and respond positively to improvements in environmental conditions (Farshadfar *et al.*, 2012). AMMI stability value indicates the stability of genotypes. Genotypes having low ASV are considered as widely adapted genotypes while those with high values indicate more responsive and less stable genotypes (Hagos and Abay, 2013). From the results, CTSIA 110, MM96/1751 and TME 435 were the most stable for root yield. Stability *per se* for a performance does not warrant selection since a consistently poor genotype can still be considered stable (Yan and Tinker, 2006). Therefore, high root yield is considered alongside stability. This revealed that MM96/1751, 00/0203 and UCC2001/449 were the most stable and high yielding genotypes according to the GGE biplot. The range of variation in the more favourable environments (Fumesua, irrigated conditions) was larger than in the poor environments indicating that genotypes were able to exploit their full potential yield in the good environments (Przystalski *et al.*, 2008).

6.6 Conclusions

The study sought to determine the effect of genotype x environment interaction and stability of physiological and morphological traits associated with yield in cassava under different growing environments. Genotype had a strong effect on all traits except leaf temperature. Genotype by environment interaction was significant for all traits except stomatal conductance and leaf temperature. Stomatal conductance was positively correlated with root yield. Leaf temperature was negatively correlated with root yield, stomatal conductance and dry matter content. This implies that genotypes that maintain low leaf temperature could be productive under stress conditions.

High broad sense heritability was found for plant height, root length/girth ratio, mean root weight and height at branching. Heritability for stomatal conductance was low. Both stomatal conductance and leaf temperature varied among genotypes and across environments. This makes these traits difficult to use for screening genotypes for drought tolerance.

Root yield was positively correlated with a number of traits such as above ground biomass yield and number of leaves per plant. Root yield was influenced by environmental conditions and genotypes as shown by the strong genotype x environment interaction. Certain genotypes were found to have high and stable root yield across environments. It can be concluded that the significant GEI in root yield and yield components makes it difficult to select one genotype for all environments.

The AMMI analysis and the use of GGE biplot helped to identify three genotypes, MM96/1751, 00/0203 and UCC2001/449, as high yielding and stable. Based on the overall mean root yield from the multi-environment analysis, six genotypes (UCC2001/449, 96/1708, MM96/1751, 00/0203, 96/409 and I91934) had significantly higher root yield than the best local farmer preferred genotype, *Pontisange*. Genotypes 96/1708, 00/0203, I91934 and 96/409, though high yielding, were unstable according to the GGE biplot but they can be recommended for specific environments where they performed well.

CHAPTER SEVEN

7.0 GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1 Discussion

Drought is a major abiotic constraint to crop production in the Guinea Savannah ecology of West and Central Africa particularly high in areas of unpredictable rainfall (Subbarao *et al.*, 2005). Drought limits cassava production thereby necessitating the identification of morphological traits that may be used is selecting drought tolerant cultivars (Nasser, 2007; Nassar *et al.*, 2008). The Participatory Rural Appraisal carried out to assess farmers' constraints in cassava production in the Northern part of Ghana indicated that majority of the farmers cultivate local unimproved cassava varieties. This is possibly due to the poor dissemination of the three improved cassava varieties that have been released for the Guinea Savannah ecology since 2003 (Sam and Dapaah, 2009). More so, poor dissemination and differences in varietal preferences by farmers might have accounted for the rejection of the improved varieties. Lack of credit was ranked as the number one constraint facing cassava production. Drought was ranked as the second most constraining factor facing cassava production among majority of the farmers in the districts which is typical of the savannah zones of the world that experience terminal and intermittent drought during most parts of the year (Okogbenin *et al.*, 2003). Over seventy per cent of the farmers agreed that drought has been major challenge in cassava cultivation. The perception of the negative effect of drought was found to vary with districts. Some common mitigation strategies employed by the farmers include early planting and the cultivation of improved varieties.

The farmers also ranked their preferences in the order of high yield, early maturity, plant type and marketability. This agrees with earlier findings that farmers rank yield and earliness ahead of all other preferences based on their ecology (Annor-Frempong, 1994; Nweke *et al.*, 1994). Farmers in areas with uncertain rainfall pattern prefer early maturing varieties (Okogbenin *et al.*, 2003). Manu-Aduening *et al.* (2005) also reported adaptability to harsh environments as one of their criteria for adoption of cassava varieties by farmers. Plant type has been a very important consideration in farming systems as early branching genotypes are preferred for weed control in sole-cropping whilst late or non-branching cultivars are preferred in intercropping systems (Njukwe *et al.*, 2013).

The morphological traits were effective in characterising the genotypes as have been reported for several crop genotypes, particularly in stressful environments (Asare *et al.*, 2011; Sathyanarayana *et al.*, 2012; Tewodros, 2013; Onaga *et al.*, 2013). Principal component analysis of the qualitative traits indicated that genotypes were diverse for traits such as distance between leaf scars, colour of stem exterior, colour of end branches, shape of plant, growth habit and habit of branching. In the case of the quantitative traits, plant height, petiole length, height at branching, number of leaf lobes, root yield and harvest index were the important characteristics that distinguished among the genotypes. These traits are very important characteristics to consider in breeding for drought tolerance in cassava since they are found to contribute to its survival mechanisms. Nasser *et al.* (2010) working on diverse cassava genotypes in Brazil found that brown stem colour was associated with drought tolerance in cassava. The height that cassava plants attain at maturity reflects its growth habit during the season (Okogbenin *et al.*, 2013). Early branching promotes dense canopy development, prevents soil heating and water loss through evaporation. The morphological variability observed corroborate earlier studies by Raghu *et al.* (2007) and Asare *et al.* (2011).

The simple sequence repeat markers generated high allelic polymorphism (100%) among the cassava genotypes. The high number of polymorphic markers is an indication of the level of genetic variability within *Manihot esculenta* Crantz (Kawano *et al.*, 1978). Huff *et al.* (1993)

stated that the average number of primers required to adequately assess genetic diversity in crops differ and depends on the level of out-crossing within the species. An average of 4.77 alleles per locus was detected by these SSR primers. High level of heterozygosity observed within the genotypes studied can be attributed to the diverse origins of these genotypes and hybridization of the exotic accessions from IITA and CIAT.

The estimates of the variance components in this study indicated significant genetic effects. This implies that there is the possibility of making progress through selection from the population since genetic variability within a germplasm is a prerequisite for selection for the relevant traits (Aina *et al.*, 2007b; Tsegaye *et al.*, 2007; Singh *et al.*, 2013). The ranking of genotypes varied with the different traits as some produced high root yield with some having better dry matter, harvest index and plant height. This indicates a rich source of variability for these traits and for possible genetic combination for improvement.

A large proportion of the phenotypic variance of HI, plant height, height at branching, number of roots per plant and number of leaves per plant was accounted for by the genetic components. However, root yield, mean root weight and severity of cassava mosaic disease (CMD) were more influenced by the environmental factors as their observed genetic variances were lower than the error variances. Growth parameters and physiological traits were significantly different under stress and irrigation as have been reported in previous studies (Okogbenin *et al.*, 2003; Aina *et al.*, 2007c). Genetic variations were observed for plant height under both stress and irrigation. Other studies on effects of drought on crops have reported reduced leaf expansion (Alves and Setter, 2004a), reduced vigour (Okogbenin *et al.*, 2003) and reduction in root yield (Turyagyenda *et al.*, 2013) which were also confirmed by this study. Reduction in growth and yield parameter under stress conditions could be attributed to accumulation of abscisic acid which was higher under no irrigation than under irrigation as reported in other studies (Alves and Setter, 2004b; Blum, 2011; Duque and Setter, 2013).

The proportion of intercepted photosynthetically active radiation (%PAR) also varied among the genotypes due to differential leaf retention capacity. Aspiazu *et al.* (2010) indicated that photosynthetic rate is directly related to the photosynthetically active radiation (composition of light) and is proportional to the amount of photoassimilates that will be produced for growth and root yield.

Significant effect of genotype and irrigation effect was observed for stomatal conductance and leaf temperature. Stomatal conductance was positively correlated with yield as a result of increased transpiration rate and photosynthetic activity which translated into carbon dioxide assimilation (Aspiazu *et al.*, 2010). Ability to maintain high rates of growth and transpiration under mild drought has been found to be correlated with increased productivity (Fisher and Edmeades, 2010). Genotypes with very sensitive stomata closed them in response to moisture deficit leading to increase in leaf temperature (El-Sharkawy and Cock, 1984; Aspiazu *et al.*, 2010). This resulted in higher leaf temperature under no irrigation than under irrigation.

Carbon isotope ratio was positively correlated with stomatal conductance in this study and it also influenced above ground biomass yield but not root yield. This provides opportunity for in-depth studies under controlled environments to establish the relationship between carbon isotope ratio and root yield in cassava. Selection of low $\Delta^{13}C$ (more negative) wheat genotypes resulted in increased aboveground biomass and kernel weight with up to about 10% in yield under the dry conditions (Rebetzke *et al.*, 2002). Though these crops vary in physiology and phenology, $\Delta^{13}C$ was positively correlated with above ground biomass as occurs in cereals. Carbon isotope ratio can further be exploited in cassava for yield improvement under drought conditions.

The pattern of dry matter accumulation also varied with genotypes and stress. Differential responses of genotypes were observed in storage root bulking as some genotypes (96/1708 and TME 435) accumulated over 80% of their final root yield at six months after planting. In cassava shoot growth and root growth occur simultaneously therefore an ideal genotype should be able to balance the partition of dry matter into shoots and roots (El-Sharkawy (2004). The ratio of root length to the girth indicates the direction of partition into roots; whether for expansion in size or for extension in root length.

Significant correlations were found between most of the traits and root yield. Root yield was positively correlated with harvest index, mean root weight, above ground biomass, root girth, stomatal conductance, number of leaves per plant and dry matter content. Traits that showed strong positive correlations can be improved simultaneously and or used as indirect selection criteria (Akinwale *et al.,* 2010). Abscisic acid content and root length/girth ratio were negatively correlated with root yield indicating that they may be survival traits that will enable cassava plants to survive harsh moisture stress conditions but not produce high root yields.

High broad sense heritability was found for plant height, root length/girth ratio, mean root weight and height at branching. Heritability for stomatal conductance and leaf temperature were low. Both stomatal conductance and leaf temperature varied among genotypes and across environments. This makes these traits difficult to use for screening genotypes for drought tolerance. Fresh root yield and yield components were significantly affected by genotype and the growing environments as well as their interactions as observed in other studies (Aina *et al.*, 2007c; Ntawuruhunga and Dixon, 2010). The use of stability analysis methods helped to identify genotypes with predictable performance across environments (Farshadfar *et al.*, 2012). Results from this study identified genotypes MM96/1751, 00/0203 and UCC2001/449 as the most stable and high yielding genotypes according to the GGE biplot. The range of variation in the more favourable environments (Fumesua, under irrigation) was larger than in the poor environments indicating that genotypes were able to exploit their full potential yield in the good environments (Przystalski *et al.*, 2008).

7.2 Conclusions

Drought is a major challenge in cassava cultivation and its severity was observed to be increasing in the Northern region of Ghana. Farmers adopt early planting as a mitigation strategy. Most farmers lack access to improved cassava varieties in the region. Farmers' choices of improved varieties were influenced by high yield, early maturity, easy marketability and good plant type. Farmers mostly processed their cassava into *kokonte*, gari, cassava dough and flour.

The morphological traits and simple sequence repeat markers revealed significant genetic diversity among the genotypes. Significant genetic variability, high broad sense heritability and significant phenotypic associations were observed between the traits studied. Growth rate, branching habit and yield traits of the genotypes accounted for a large proportion of the genetic variability observed among the genotypes used for the study.

Abscisic acid content in the leaves was significantly different among the genotypes and negatively correlated with root yield, stomatal conductance, above ground biomass yield, harvest index, root girth, dry matter content and mean root weight. However there were few exceptions as two genotypes, UCC2001/449 and I91934 had relatively high root yields despite having higher ABA content than other genotypes. These genotypes possibility combine tolerance with productivity and thus good candidates for improvement in drought tolerance and productivity. Narrow genetic variation was observed for carbon isotope discrimination ($\Delta^{13}C$) in this study. There was no direct correlation between $\Delta^{13}C$ and root yield but it was positively correlated with above ground biomass yield, which also positively correlated with root yield. Significant genetic variation was observed for leaf chlorophyll content and was higher under stress than irrigation. Its correlation with root yield was not significant.

Stomatal conductance and leaf temperature were influenced by genotype and environment effects but their interaction was not significant. Root yield was positively correlated stomatal conductance, above ground biomass yield and leaf production across environments. Leaf temperature was negatively correlated with root yield, stomatal conductance and dry matter content.

High broad sense heritability was found for plant height, root length/girth ratio, mean root weight and height at branching. Heritability for stomatal conductance was low. Differential accumulation of dry matter in roots was observed among the genotypes under irrigation and no irrigation. Genotypes varied in their accumulation pattern as some genotypes initiated root bulking earlier than others. Final root yield under irrigation was independent of initial root yield at six months. Root yield was influenced by environmental conditions and genotypes as shown by the strong genotype x environment interaction.

Based on the overall mean root yield from the multi-environment analysis, six genotypes (UCC2001/449, 96/1708, MM96/1751, 00/0203, 96/409 and I91934) had significantly higher root yield than the best local farmer preferred genotype, *Pontisange*. Genotypes 96/1708, 00/0203, I91934 and 96/409, though high yielding, were unstable according to the GGE biplot analysis.

7.3 Recommendations

1. Breeding efforts should focus on developing new farmer preferred cassava varieties that are high yielding and drought tolerant.

2. Genotypes should be further screened at varying moisture levels and different planting dates to determine the critical stage of drought susceptibility.

3. Further studies should investigate the concentration of carbon isotope in roots since they influenced above ground biomass yield in this study and not root yield.

4. Two genotypes that combined relatively high root yield and high abscisic acid content under no irrigation should be investigated further.

5. Efficiency of root length/girth ratio should be tested to assess its relationship with dry matter accumulation in storage roots.

6. Six genotypes, UCC2001/449, MM96/1751, 96/1708, 00/0203, I91934 and 96/409 were high yielding under no irrigation and can be used as donor parents to introgress genes for drought tolerance into farmer preferred varieties

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APPENDICES

Appendix 3.1 Questionnaire for farmers' survey

A. GENERAL INFORMATION

1.Name of Respondent		12. Marital Status **Code** 1. Married 2. Single 3. Widowed 4. Divorced	[ ]
2.Gender of Respondent (**Code:** 1 = Male 0 = Female)			
3.Age (Years)		13.Level of Education **Codes** 1. None 2. Primary 3. JHS 4. SHS 5. Certificate Diploma 6. Degree 7. Master's degree	[ ]
4.Cell Phone Number			
5.Total Household size (No.)			
6. No. of HH members that assist on the farm			
7.Years of farming experience		14.Nativity Status (1=native 0=non-native)	
8. Principal Activity **Codes** 0=none, 1=Agriculture, 2=Rearing 3=Fishing/hunting, 4=Commerce, 5=Handicraft,6=Labourer, 7=Employee, 8=House chores , 9=Driver/motor taxi , 10= Pupil teacher 11= Other(specify)		15.Off-farm income source **Codes** 0=Petty trading 1=Teaching 2=Masonry /carpentry 3=Nursing 4=Art and craft 5=Driving 6=Fitting mechanic 7=Farm labor 8=Other 9=N/A	[ ]
9. Membership of Farmer Organization (**Code:** 1 = Yes and 0 = No)			
10.Total landholding (Acres) (Cassava+Groundnut+Maize+Soybean+Rice)			
11.Area under cassava cultivation (Acres)		16.Type of religion **Codes:** 1=Islamic 2=Christian 3=Traditional religions 4=Other	
17. Do you have access to mobile phone?	1-Yes [ ] 0-No [ ]	18. Did you participate in any agricultural development project in 2012?	1-Yes [ ] 0-No [ ]
19. Did the project have any benefit on your farming?	1-Yes [ ] 0-No [ ]	20. Mention one main benefit from the project?	

B. FARM CHARACTERISTICS

21a. Do you cultivate local or improved cassava variety?	1-Yes [ ] 0-No [ ]	21b.What are the 3 most preferred cassava variety (Rank- a to c)	a………………………………………………… b………………………………………………… c…………………………………………………
21c.Reason (s) for the Ranking	a………………………………………………… b………………………………………………… c…………………………………………………	21d.Which of these varieties do you mostly cultivate?	
21e. Give 2 reason (s)	a………………………………………………… b…………………………………………………	2 1f. What is the total area under the most preferred variety (Acres) *(NB: Must be a proportion of the total land under cassava cultivation Q_11)*	
22.How influential were the ff. in the selection of cassava variety ❖ Plant type ❖ Earliness (6 months) ❖ High yielding after 12 months ❖ Resistance to pests and diseases ❖ Easy access to planting material ❖ Easily marketable	**Ranks** *(NB: Use 1,2,3……,N)* ……………………………….. ………………………………... ………………………………... ……………………………… ……………………………… ………………………………	23. Area under the following crops (2012): Maize Soybean Groundnut Rice Cowpea **TOTAL**	……………………………… Acres ……………………………… Acres ……………………………… Acres ……………………………… Acres ……………………………… Acres ……………………………… Acres

24. Where do you normally obtain planting material from? **Codes:** 1-Own farm 2-Male neighbour 3-Female neighbour 4-Relatives 5-Farmer group 6-Research 7-NGO 8-MoFA 9-Other (specify)________________	[ ]	25.Cassava Ownership and Decision Making 25a. Who mainly owns? 25b. Who decides the amount of cassava to grow? 25c. Who decides on the variety to grow? 25d. To sell or not? 25e. How much cassava to sell? 25f. How to use the proceeds from cassava sales? 25g. Revenue sharing?	**Who decides** **(Codes: 0**=Man **1**=Woman **2**= Children) ………………………………………………. ………………………………………………. ………………………………………………. ………………………………………………. ………………………………………………. ……………………………………………….. ………………………………………………..
26. Are the planting material readily available when needed?	1-Yes [ ] 0-No [ ]		
27. If you want a new variety (improved) where do you go to get it?	**1**-Local farmers **2**-Farmers far away **3**-Specialized multipliers **4**-Extension agents **5**-Research stations **6**-Markets 7-MoFA **8**-Other (specify) _______________	28. Are you satisfied with the quality of planting material usually available at planting time?	**1**-Satisfied [ ] **2**-Somewhatsatisfied [ ] **3**-Notsatisfied [ ]
29. Do you know of a specialized multiplier (that is, someone who has been trained in cassava multiplication for quality)?	1-Yes [ ] 0-No [ ]	30. How long can the planting material last (year)?	

C. PERCEPTION ON DROUGHT AND PESTS & DISEASES

31. Which month of the year do you plant your cassava?		33. Drought is a major challenge in cassava cultivation	1 = Strongly agree 2 = Agree 3 = Do not know or do not have an opinion 4= Disagree 5 = Strongly disagree
32. Which month of the year do you harvest your cassava?			
34. Do you apply fertilizer on cassava	1-Yes [ ] 0-No [ ]	35. If yes which type of fertilizer (Specify)?	
36. Do you use irrigation?	1-Yes [ ] 0-No [ ]	37. Which ecology do you mostly cultivate cassava?	1-Upland[ ] 0-Lowland [ ]
38. Has there been a change in the pattern of rainfall for the past ten years?	1-Yes [ ] 0-No [ ]	39. Have you experienced drought on your field for the past ten years?	1-Yes [ ] 0-No [ ]
40. If yes, has it affected cassava production on your farm?	1-Yes [ ] 0-No [ ]	41. What is the severity of drought you have observed for the past ten years?	1 = Increasing [ ] 2 = Decreasing [ ] 3. Unchanged [ ]
42. Have you observed pest and disease infestation on your cassava farm	1-Yes [ ] 0-No [ ]	43. If yes, what is the pattern of disease infestation on your cassava farm	1 = Increasing [ ] 2 = Decreasing [ ] 3. Unchanged [ ]

44. Information on Pest and Diseases	Stage of attack (Code 1)	Mode of Attack (Code 2)	Effect on Plant (Code 3)	Control Strategy (Code 4)
Pests				
44a.				
44b.				
Diseases				
44c				
44d				

Code 1: 1=immediately after emergence 2=Vegetative stage 3=Flowering stage. 4=Matured stage Code 2: 1= Chew the leaves 2= Lay eggs on the plant 3=Other(specify)…………..

Code 3: 1=stunted growth 2=yellowing of leaves 3=defoliation 4=die back 5=wilting 6=leaf curl 7= mouldy leaves 9=other (specify) …………..

Code 4: 1=Neem extract 2=Insecticide 3= Cultural practice 4=pest resistant varieties 5=chemical application 6=other(specify)……………………………………………..

45. Where do you receive information on control of pests and diseases?	**1**-Local farmers **2**-Farmers far away **3**-Specialized multipliers **4**-Extension agents **5**-Research stations **6**-Markets **7**-Other (specify) ________________	46. What strategies do you often put in place to overcome the issue of drought?	a…………………………………………………… b…………………………………………………… c…………………………………………………… d……………………………………………………

D. CASSAVA MARKETING DECISION

47. What is the area (acres) under cassava production (2012)?		48. What is the quantity (Bag) of cassava harvested in 2012?	Amount	Unit **Codes:** 1=Maxi Bag 2=Mini Bag 3=No 5 fertilizer bag 4=Kilogram

49.Disposal of Harvested crops (2012)	Quantity (Bag) **Note**: consumed + sold + gift + stored + loss=harvest					
	Harvest	Consumed	Sold	Given out as gift	Stored	Loss in store
Cassava						
Maize						
Groundnut						
Rice						
Soybean						

50. Where do you normally sell most of your produce? **Codes:** 0=N/A 1=At home 2=In a neighbouring market 3=Big markets in city/town	[ ]	51. Which of the marketing outlet do you prefer mostly for disposal of cassava? Codes: 0=N/A 1=At home 2=In a neighbouring market 3=Big markets in city/town	[ ]

52. What is the unit price of cassava	Price/Kg	Price/Bag	53. Who is the main buyer of your produce? Codes 2: 1- Trader 2- Established agent 3- Marketing co-ops 4- Company 5- Government 6 Other………………	[ ]

54. What is the main information source for market price? **Codes:** 1-Radio 2-TV 3-Other farmer 4-Local market	[ ]	55. How do you make market contacts? **Codes:** 1-By myself 2-From neighbour 3-Other farmer 4-Extension	[ ]

5-Extension agents 6-Other		professional 5-Other	
56. What is the distance from homestead to nearest market?	[ ]km	57. What is the main transport mode to the nearest market? **Codes:** 1-Walking 2-Bicycle 3-Motorbike 4-Bus/small van 5-Car/truck 6-Motor tricycle	[ ]
58. What is the transportation cost incurred per a bag of cassava to the market?		59. Which month of the year do you sell majority of your produce	[……………………….., 2012]
60. How far is the AEA from your homestead?	[ ]km	61. How many contacts have you had with the AEA over the last year (2012)?	[ ]

E. PROCESSING OF CASSAVA

62. Do you normally process cassava?	1-Yes [ ] 0-No [ ]	63. If yes, did you process in 2012?	1-Yes [ ] 0-No [ ]
64. If yes which processed form do you mostly prefer?	**Rank** *(Use 1,2,3,......,N)* a. Chips [ ] ***b.*** *Kokonte* [ ] **c.** Cassava dough [ ] **d.** Flour [ ] *e.* Gari [ ]	65. Which of these characteristics will you prefer in the selection of a variety?	1-Poundable[ ] 0-Unpoundable [ ]

F. CREDIT ACCESS AND UTILIZATION

66. Have you ever applied for credit in the last cropping season (2012)?	1-Yes [ ] 0-No [ ]	67. If yes, did you receive the credit?	1-Yes [ ] 0-No [ ]
68. If yes, what was the source of the credit? **Codes:** 1-Friend 2-Relative 3-Saving and credit group 4-Microfinance organization 5-Commercial bank 6-Other (specify) __________ 9-N/A		69. If yes, how much credit was received?	[ ]GH₵
70. What was the credit used for? Codes: 1=Purchase fertilizer2=Purchase seed3=Purchase tractor4=Purchase of other farm equipment5=Pay for tractor services7=Other (specify) ________6=Payment for labour	[ ]	71. Was **collateralrequired** to obtain this loan/credit? **Codes:** 1=Yes 2=No 3=Group security	[ ]

G.CONSTRAINTS TO CASSAVA PRODUCTION AND MITIGATION MEASURES

72. Kindly rank the severity of the following constraints in cassava production. ❖ Lack of credit ❖ Drought/inadequate rainfall ❖ Flood ❖ Lack of improved varieties ❖ Difficulty in obtaining planting materials ❖ Diseases and pests ❖ High labour cost ❖ Weed Infestation ❖ Low soil fertility ❖ Low market price ❖ Access to land	Rank *(NB: Use 1, 2, 3,.......n)* ……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ………………………………………	73. What are the key mitigation measures put in place to overcome these constraints? (NB: List five main measures)	a.…………………………………………………………… b.…………………………………………………………… c.…………………………………………………………… d.…………………………………………………………… e.……………………………………………………………

Appendix 4.1 Morphological and agronomic descriptors for the characterization of the cassava germplasm

Descriptors to be scored at three months after planting		**Procedure**
1. Apical leaf colour	3-Light green; 5-Dark green; 7-Purplish green; 9-	Top three leaves considered
2. Pubescence on apical leaves	0-Absent; 1-Present	Top three leaves considered
Descriptors to be scored at six months after planting		
3. Leaf retention (number of leaves/plant)		Total number of leaves for three plants counted and the average obtained
4. Shape of central leaflet	1-Ovoid; 2-Elliptic-lanceolate; 3-Obovate-lanceolate; 4-Oblong-lanceolate; 5-Lanceolate; 6-Strait or linear; 7-Pandurate; 8-Linear-pyramidal; 9-Linear-pandurate; 10-Linear-hostatilobalate	Leaf taken from a mid-height position. The most frequent occurrence was recorded.
5. Petiole colour	3-Light green; 5-Dark green; 7-Purplish green; 9-Purple	A leaf from middle of the plant was observed
6. Number of leaf lobes	3-Three lobes; 5-Five lobes; 7-Seven lobes; 9-Nine lobes; 11-Eleven lobes	Leaf taken from a mid-height position
7. Length of petiole	Measured on two leaves/plant. Expressed in cm	Observed from the middle third of the plant.
Descriptors to be scored at nine months after planting		
8. Colour of stem exterior	3-Orange; 4-Greenish-yellowish; 5-Golden; 6-Light brown; 7-Silver; 8-Grey; 9-Dark brown	A leaf from the middle third of the plant observed
9. Distance between leaf scars	3 Short = (8 cm) 5 Medium (8–15 cm) 7 Long = (15 cm)	Measure from the middle of stem on the middle third of the plant. Make a measurement along the stem then divide the distance by the number of nodes in the measured part.
10. Growth habit of stem	1-Straight; 2-Zigzag	
11. Colour of end branches of adult plant	3 Green 5 Green-purple 7 Purple	Observation to be taken on top 20 cm of plant. Intermediates allowed. The most frequent occurrence is recorded

Descriptors to be scored at harvest 12 Months		
12. Plant height		Vertical height from the ground to the top of the canopy. Expressed in cm. Measurements recorded from three plants.
13. Height to first branching	Zero = no branching. Side branching was ignored	Vertical height from ground to first primary branch measured. Expressed in cm. Measurements recorded from three plants.
14. Levels of branching	Zero (0) for no branching Side branching was ignored	Number of divisions of branching recorded. The most frequent occurrence recorded
15. Habit branching	-Erect; 2-Dichotomous; 3-Trichotomous; 4-Tetrachotomous	Observed at the lowest or first branching. The most frequent occurrence on the plot recorded
16. Angle of branching		Measured at first primary branching (not side branches). The angle was measured and later the angle was divided by two. Measurements recorded from three plants.
17. Shape of plant	1-Compact; 2-Open; 3-Umbrella; 4-Cylindrical	The most frequent occurrence on the plot recorded.
18. Number of storage roots/plant		The number of roots on each plant counted and the average found. Recorded from each of three plants
19. Extent of root peduncle	0-Sessile; 3-Pendunculate, 5-mixed	
20. Root constrictions	-Few to none; 2-Some; 3-Many Measured on mature roots	The most frequent occurrence was recorded
21. Root shape	1-Conical; 2-Conical-cylindrical; 3-Cylindrical; 4-Irregular	The most frequent occurrence was recorded.
22. External colour of storage root		
23. Colour of root pulp	1- White, 2- Cream, 3-Yellow, 4- Orange, 5- Pink,	The most frequent occurrence was recorded
24. Colour of root cortex	1-White or cream; 2-Yellow; 3-Pink; 4-Purple	The most frequent occurrence was recorded.

25. Cortex: ease of peeling	1- Easy, 2- Difficult	
26. Texture of root epidermis	3- Smooth, 5- Intermediate 7- Rough	The roots were touched to feel the texture. The most common root type was recorded.
27. Dry matter content		
28. Root yield		Three plants from each plot were uprooted. The storage roots were detached and weighed. Root yield was expressed in tons per hectare