UNDERSTANDING THE PRODUCTIVITY OF CASSAVA IN WEST AFRICA

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Thesis

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Pour mon défunt père Vitus!
Pour ma mère Alexine, ma femme Myriam, mes enfants Eyram Aurel et Elom Audrey!

ABSTRACT

Drought stress and sub-optimal soil fertility management are major constraints to crop production in general and to cassava (*Manihot esculenta* Crantz) in particular in the rain-fed cropping systems in West Africa. Cassava is an important source of calories for millions of smallholder households in sub-Sahara Africa. The prime aim of this research was to understand cassava productivity in order to contribute to improving yields, food security and farm incomes in rain-fed cassava production systems in West Africa. A long-term goal was to contribute to a decision support tool for site-specific crop and nutrient management recommendations. Firstly, we studied farmers' perception of cassava production constraints, assessed drivers of diversity among households and analysed the suitability of farmers' resource endowment groups to the intensification of cassava production. The results indicate that farmers perceived erractic rainfall and poor soil fertility to be prime constraints to cassava production. The agricultural potential of the area and the proximity to regional markets were major drivers for the adoption of crop intensification options including the use of mineral and organic fertilizers. While the use of mineral and organic fertilizers was common in the Maritime zone that had a low agricultural potential, storage roots yields were below the national average of 2.2 Mg dry matter per hectare, and average incomes of 0.62, 0.46 and 0.46 US$ per capita per day for the high, medium and low farmer resource groups (REGs – HRE, MRE and LRE, respectively) were below the poverty line requirement of 1.25 US$. In the high agricultural potential Plateaux zone, HRE and MRE households passed this poverty line by earning 2.58 and 2.59 US$ per capita per day, respectively, unlike the LRE households with 0.89 US$ per capita per day. Secondly, we investigated the effects of mineral fertilizer on nutrient uptake, nutrient physiological use efficiency and storage roots yields of cassava since soil fertility was a major issue across the zones. We used an approach based on the model for the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS). This model was successfully adapted for cassava and it appropriately assessed the response of cassava to N, P and K applications, especially in years with good rainfall. Under high drought stress, the model overestimated cassava yields. Thirdly, we investigated the impact of balanced nutrition on nutrient use efficiency, yield and return on investment compared to blanket fertilizer use as commonly practiced in cassava production systems in Southern Togo, and in Southern and Northern Ghana. The balanced nutrition approach of the QUEFTS model aimed to maximize simultanously nutrient use efficiency of N, P and K in accordance with the plant's needs. Larger nutrient use efficiencies of 20.5 to 23.9 kg storage root dry matter (DM) per kilo crop nutrient equivalent (1kCNE of a nutrient is the quantity of that nutrient that has the same effect on yield as 1 kg of N under balanced nutrition conditions) were achieved at balanced nutrition at harvest index (*HI*) of 0.50 compared to 20.0 to 20.5 kg storage root DM per kilo CNE for the blanket rates recommended by national research services for cassava production. Lower benefit:cost ratios of 2.4±0.9 were obtained for the blanket fertilizer rates versus 3.8±1.1 for the balanced fertilizer rates. Our study revealed that potassium (K) was a major yield limiting factor for cassava production, especially on the Ferralsols in Southern Togo. Hence, we fourthly studied the effect of K and its interaction with nitrogen (N), phosphorus (P), and the timing of harvest on the productivity of cassava in relation to the effects of K on radiation use efficiency (RUE), light interception, water use efficiency (WUE) and water transpiration. The results suggest that K plays a leading role in RUE and WUE, while N is the leading nutrient for light interception and water transpiration. Potassium effects on RUE and WUE depended on the availability of N and harvest time. Values of RUE and WUE declined with harvest at 4, 8 and 11 months after planting. Thus, enhanced K management with sufficient supply of N during the early stage of development of cassava is needed to maximize RUE and WUE, and consequently attain larger storage root yields. Given that erratic rainfall was another major constraint to cassava production according to the results of the farm survey, and due to the inability of QUEFTS modelling to assess drought effects on cassava yield successfully, another modelling approach based on light interception and utilization (LINTUL) was used. We quantified drought impacts on yields and explored strategies to improve yields through evaluation of planting dates in Southern Togo. The evaluation of the model indicated good agreement between simulated and observed leaf area index (Normalised Root Mean Square Error - NRMSE - 17% of the average observed LAI), storage roots yields (NRMSE 5.8% of the average observed yield) and total biomass yield (NRMSE 5.8% of the average observed). Simulated yield losses due to drought ranged from 9-60% of the water-limited yields. The evaluation of planting dates from mid-January to mid-July indicated that the best planting window is around mid-February. Higher amount of cropping season rainfall was also achieved with early planting. These results contradict current practices of starting planting around mid-March to mid-April. However, the results indicate the possibility to increase cassava yields with early planting, which led to less yield losses due to drought. By contrast, late planting around June-July gave larger potential yields, and suggested these periods to be the best planting window for cassava under irrigated conditions in Southern Togo. This shows that appropriate water control and planting periods can contribute to attaining larger yields in Southern Togo. Further improvement of the LINTUL model is required towards using it to assess water-limited yield, which can be used as boundary constraint in QUEFTS to derive site-specific fertilizer requirements for enhanced cassava yield and returns on investments in West Africa.

Keywords: *Rain-fed, drought stress, water-limited yield, potential yield, QUEFTS, LINTUL, light interception, transpiration, radiation use efficiency, water use efficiency, cassava,* Manihot esculenta*, fertilizer requirement, potassium, resource endowment, Togo, Ghana.*

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CHAPTER ONE

1.0. General Introduction

1.1. Background

Traditionally considered a subsistence crop, cassava (*Manihot esculenta* Crantz), is increasingly a commercial crop in sub-Saharan Africa (SSA) (Nweke 1996). It has become a potential substitute for many imported cereals including wheat for bread and other foodstuff (FAO and IFAD 2005). This interest for cassava is motivated by its capacity to produce even under hostile environmental conditions where other crops fail (Howeler 2002). Environmental conditions for crop production in SSA are increasingly degraded due to the galloping demographic growth that induces high pressure on farmers' land and reduces farm sizes. Unsustainable intensification of crop production leads to nutrient mining and soil fertility decline, especially in cassava production systems with little nutrient input. Sub-optimal management of land, labour, nutrients and water and reducing factors such as pests and diseases contribute to widening cassava yield gaps, as was found in East Africa (Fermont 2009; Tittonell 2009). Addressing these constraints requires the prior understanding of the productivity of cassava under optimal management compared to farmer's conditions in various agro-ecological conditions. Given the diversity of agro-ecological zones, soils and crop management practices across SSA, the use of blanket or "passe-partout" solutions will not suit all farmers' needs. The use of computer models to analyse holistically the cropping systems to have a better understanding of their functioning and to formulate site-specific recommendations has been reported for many crops including maize, rice, potatoes, etc. (Janssen et al. 1990; Jones et al. 2003; Spitters 1990; Witt et al. 1999). Computer models have been developed for cassava (Boerboom 1978; Fukai and Hammer 1987; Gijzen et al. 1990; Matthews and Hunt 1994), but none has been adapted to unveil the productivity and derive site-specific crop and nutrients management recommendations for rain-fed cassava production under West African conditions. Developing a decision support system to assess water-limited yields and site-specific nutrient needs may be useful for improving cassava productivity and reducing environmental pollution. However, farmers' ability to invest in nutrient applications depends on resource endowment (Fermont 2009). Hence, in order to meet the high food demand of the growing population, it is crucial to understand farmers' production constraints as well as their perceptions. Further, we need to explore management strategies that minimise drought effects and improve cassava yield, profitability and food security in West Africa.

1.2. The cassava crop

Native to South America, cassava was introduced in Africa in the 16^{th} century (Jones 1959), but did not spread widely until the 20^{th} century (Hillocks et al. 2002). Cassava is a perennial shrub with alternating periods of vegetative growth, storage of carbohydrates in the storage roots, and periods of dormancy when environmental conditions are adverse. It produces storage roots that are harvestable from 6 to 24 months after planting, depending on the cultivar and growing conditions (El-Sharkawy 1993). The vegetative stage of the crop is characterised by stem, leaf and adventitious and fibrous root growths and occurs within the first 180 days of the crop's life cycle. The fastest vegetative growth occurs between 90 and 180 days after planting (Alves 2002). The reproductive phase is characterised by the occurrence of the first sympodial branch. The storage of carbohydrate in the roots starts around 60 to 90 days after planting and is marked by the development of 3 to 14 fibrous roots into storage roots. The translocation of carbohydrate from leaves to storage roots is accelerated from 180 to 300 days after planting. Within this period, leaf senescence increases and stem lignification occurs. This latter phase is followed by a dormancy phase from 300 to 360 days after planting if environmental conditions are adverse. According to Alves (2002), this period is characterised by a decreased leaf production, shedding of most leaves, cessation of vegetative shoot growth and maximum dry matter partitioning to roots, and can be caused by long periods of drought and or low temperatures. Hence, this period can be avoided in the tropics if sufficient water is supplied. At the end of the first 12-month cycle, another cycle can follow with the beginning of a new rainy season.

1.3. Importance of cassava

A major staple food for the growing population in many tropical regions, cassava provides food to about 800 million people across the world. It can be grown in a wide range of rainfall zones from 400 to 1700 mm (FAO, 2013) with a high tolerance of drought, low soil fertility (Howeler 2002), acidity and aluminium toxicity (Howeler 1991). Cassava is considered a crop with a high water use efficiency (El-Sharkawy 2007) and a high productivity per unit of land and per unit labour (Fermont 2009). It is a secure source of calories for smallholder farmers, especially at the beginning of the growing season when the food reserves of other crops are exhausted. Cassava storage roots constitute an important source of raw material for the starch industry and are a potential substitute to cereals in food and feed industries.

Global production has increased tremendously during the last decade. The world production of fresh cassava storage roots increased from 176 to 277 million Mg between 2000 and 2013. About 57% of this production is in Africa (FAOSTAT 2014).

West Africa contributes half of Africa's production. Nigeria, which is the first cassava producer in the world, produced 54 million Mg of fresh storage roots in 2013 (FAOSTAT 2014). However, cassava yields are still poor in West Africa, and its production cannot meet the increasing local demand. Despite the rise in average storage roots yields from 9.7 to 13 Mg ha^{-1} of fresh storage roots between 2000 and 2013 (FAOSTAT 2014), the yield gap is still large given that storage roots yields of 60 Mg ha^{-1} have been recorded in field experiments in the region (Odedina et al. 2009). Understanding the productivity of cassava under the current practices relatively to optimal management practices may improve our understanding of this yield gap, and contribute to reducing it.

1.4. Factors determining cassava productivity in West Africa

Numerous factors determine cassava productivity, and contribute to the gap between potential and actual yields achieved in farmers' fields. The potential yield is the maximum attainable yield achieved for a given cultivar under non-limiting conditions of water and nutrient supply, with effective control of biotic stress (van Ittersum and Rabbinge 1997). It is determined by defining factors such as temperature, light or solar radiation, carbon dioxide and crop or variety characteristics such as canopy architecture, and assumes optimal planting density and other management. The water-limited yield is the maximum attainable yield under rain-fed conditions when nutrients are sufficiently supplied for crop growth (van Wart et al. 2013), and is determined by rainfall, soil texture, topography, soil surface cover and the plant rooting pattern, in addition to the factors determining potential yield. Water-limited yield is relevant to crop production systems in SSA, where agriculture highly depends on rainfall that is variable in distribution. When nutrients become limiting, crop yield is defined as nutrient-limited yield. The actual yield is the average yield obtained on farmers' fields in a given location under water and nutrient-limited conditions with the prevalence of reducing factors such as weed, pests and diseases.

The analysis of cassava yield gaps in East Africa by Fermont (2009) revealed that cassava yields can be seriously undermined by pests and diseases, and sub-optimal crop and nutrient management practices (Fig. 1.1). The poorest yield was obtained under high pest or disease pressure, which however can be controlled through the use of resistant cultivars. Yield was improved through enhanced crop management practices including improved crop establishment, weed control and drought avoidance.

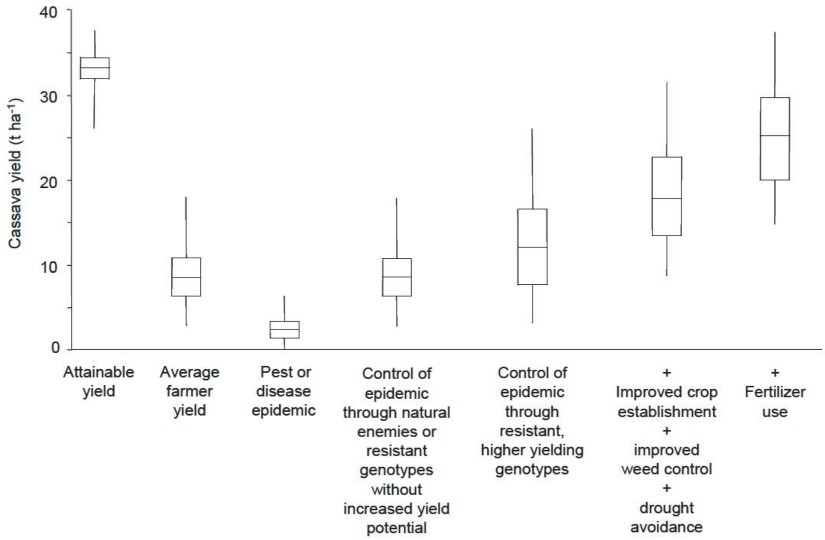

Fig. 1.1. Attainable yield, average farmer yield and other cassava yields as affected by different levels of agronomic interventions in East Africa. Source: Fermont et al. (2009).

The application of mineral fertilizer further increased yield. Poor soil fertility is also likely an important biophysical constraint to cassava production in West Africa where nutrient amendments significantly increase cassava yield (Adekayode and Adeola 2009; Sogbedji et al. 2015).

The importance of nutrient constraints is supported by the fact that most African soils are inherently poor in fertility (Smaling et al. 1997), and by the nutrient mining agricultural practices of most smallholder farming systems. The large amounts of nutrients removed in cassava biomass, especially of K and N (Howeler 2002), together with the limited external fertilizer use deplete the soil. Moreover, cassava residues as well as the residues of intercropped cereals and legumes are rarely recycled in the field. This contributes to soil nutrient mining, given that residues of grain crops (cereals and legumes) can recycle back to the soil up to 90% of K, 50-70% of N and 40% of P removed, assuming complete residue return (Sanchez et al. 1997).

Nutrient depletion generates unbalanced soil nutrient stocks, which can negatively affect nutrient use efficiency of cassava. A poor supply of nutrients, particularly of N, can reduce light interception with a reduced cassava canopy development. Likewise, a poor supply of K can reduce water use efficiency of cassava (El-Sharkawy 2007). In turn, a low light, water and nutrient use efficiency may lead to poor crop growth and consequently expose the crop to the damaging effects of drought, pests and diseases. Although cassava is drought tolerant, exposure to drought can cause 32 to 60% storage root losses (Alves 2002). Likewise, pest and diseases may cause yield losses up to 50% (Gutierrez et al. 1988b). Timely planting of healthy cuttings from disease resistant cultivars may reduce drought and pest and disease damage, and improve cassava yields.

Other production constraints that lead to poor crop management include farmers' resource endowment and management skills. Resource endowment determines farmers' capacity to access arable lands, labour, livestock, and external inputs. A study carried out in East Africa showed that wealthier households had the highest resource use efficiency for labour, mineral fertilizer and manure compared to poorer households (Fermont 2009; Tittonell 2009). In this region, wealthier households tended to invest more in improved soil fertility management (mineral fertilizer and or organic resources application) than poor household. Giller et al. (2006) reported that the same pattern in soil fertility management in relation to resource endowment can be found across Africa. However, the significance of this pattern for cassava based farming systems of West Africa requires further investigation because of the common generalisation that farmers hardly use any fertilizers for cassava production.

Access to market and micro-credits can also limit cassava production. The availability of markets and the distance to market determine farmers' access to inputs such as seeds, mineral fertilizers, chemicals, etc. Market demand stimulates cassava production as a cash crop. The access of farmers to micro-credit facilitates their investments in farming activities. These community scale constraints apply to all farming activities, and are not specific to cassava cultivation.

1.5. Cassava based cropping systems in West Africa

In the past, when the availability of arable land was less limiting, cassava was cultivated as the last crop at the end of crop rotations (IITA 1990). Nowadays, due to land pressure caused by the demographic growth, cassava is increasingly cultivated as an intercrop, particularly with cereals and or legumes. This intercropping system is possible due to the long life cycle of cassava and its slow early growth and low leaf area for much of its growth cycle (Norman et al. 1995). After the harvest of cereals and legume intercrops, cassava plants remain alone in the field until harvest. Cassava productivity increases with the duration of the crop from planting to harvest (FAO 2013). Some local cultivars attain their maximum yields only around 18 months after planting, compared with 12-15 months for some improved cultivars (Hillocks et al. 2002). However, in case of land scarcity, cassava cultivation does not exceed one 12-month cycle, since the land is needed for another crop in the subsequent growing season. This practice is common in southern Togo, Benin, Ghana and Nigeria. The cultivation of cultivars that can attain their maximum yields by 12 MAP is also preferred by commercial farmers in West Africa (Nigeria, Ghana) for the continuous cultivation of cassava (FAO and IFAD 2005). Cassava is produced by these commercial farmers either as a sole crop or as an intercrop. These farms are generally linked to industries that secure the market for them and are owned by individual farmers or farmers' associations.

1.6. Fertilizer recommendations for cassava production in West Africa

In the past, farmers overcame or avoided soil fertility problems through long fallow periods and crop rotations. Nowadays, crop rotations and long fallow periods are diminished in favour of intercropping and short or no fallow periods, which are insufficient to sustain soil fertility. The application of external fertilizers is necessary to replenish the soil with nutrients removed through harvested products and exported crop residues. The application of the right nutrient at the right rate and at the right time in synchrony with the plant needs is recommended (Zingore and Johnston 2013). However, only blanket recommendations are found in most countries in sub-Saharan Africa. In Ghana, a blanket rate of 68 kg N, 20 kg P and 57 kg K ha^{-1} is used for cassava production. In Nigeria, 400 kg of NPK 15-15-15, equivalent of 60 kg N, 26 kg P and 50 kg K ha^{-1} is recommended (Fondufe et al. 2001). In Togo, a blanket rate of 76 kg N, 13 kg P and 25 kg K ha^{-1}, applied in the form of 200 kg ha^{-1} NPK 15-15-15 and 100 kg ha^{-1} of urea, is used for cassava as well as maize production in southern Togo. However, in case of maize-cassava intercropping system, the national research institute of agronomy in Togo recommends the addition of 100 kg NPK to the blanket rate of 200 kg ha^{-1} NPK 15-15-15 and 100 kg ha^{-1} of urea (Somana and Nkpenu 2008). These blanket recommendations derived many years ago are not suitable to account for agro-ecological diversity. Given the large heterogeneity of soils, even within small geographic areas (Adjei-Nsiah et al. 2007), the use of blanket fertilizer recommendations for cassava production is likely to generate unbalanced crop nutrition. This situation can cause nutrient losses, generating environmental pollution, and put the productivity and profitability of the farm at stake. A major consequence of the inappropriate use of blanket rates is the reinforcement of farmers' unwillingness to invest in fertilizer.

The improvement of soil N, P and K through mineral fertilizers should go along with maintaining or building up soil organic carbon (SOC) to ensure long term productivity (Sanchez et al. 1997). This can be achieved through the Integrated Soil Fertility Management (ISFM) approach aiming at sustainably increasing crop productivity through the use of improved germplasm and the combined application of mineral fertilizers and organic resources (Vanlauwe et al. 2002). However, organic fertilizers are hardly used for cassava production in West Africa (Hillocks et al. 2002). Nevertheless, the use of manure, livestock grazing and other agricultural land-use intensification are expected to increase in cassava production zones when fallow periods decline as population density increases according to Hillocks (2002).

1.7. Modelling cassava cropping systems

Several computer models have been developed to assess cassava growth, development and yield. Those models can be grouped based on the pattern of dry matter partitioning. A fixed dry matter partitioning pattern is considered in the models by Boerboom (1978), Gutierrez et al. (1988b), Gijzen et al. (1990), whereas a "spill-over" pattern for dry matter partitioning was used in the models of Cock et al. (1979), Fukai and Hammer (1987) and Matthews and Hunt (1994). The latter pattern used in the process-oriented GUMCAS model of Matthews and Hunt (1994), assumes independent leaf and stem growth that has priority for new assimilates before allocating the remainder of the assimilates to storage roots. This pattern is seen as the most realistic approach by Gabriel et al. (2014). The GUMCAS model is referred to as CROPSIM-Cassava in the framework of the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al. 2003). None of these models has been adapted to West African conditions, where cassava is produced under rain-fed conditions. Furthermore, they are generally restricted to the simulation of potential and water-limited yields, and particularly to the simulation of nitrogen-limited yields, whereas potassium nutrition is crucial for the productivity of cassava. Thus, these models cannot be used to assess the effect of N, P and K and their interactions on cassava yield and to formulate site-specific fertilizer recommendations.

The model for the model for the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) by Janssen et al. (1990) has been frequently used to assess the effects of N, P and K fertilizers on crop yields and to formulate site-specific fertilizer recommendations. It has been adapted for cassava production under Asian agro-ecological conditions by Byju et al. (2012). The QUEFTS model is not yet calibrated for cassava production in West Africa. This model assumes that the maximum climate-limited yield that can be achieved by the crop in the location of interest is known. Unfortunately, this yield is hardly known, and varies depending on seasonal weather variability. However, this can be captured by adequate process-oriented models.

1.8. Problem statement

Cassava yields gaps in West Africa are huge. However, the key factors explaining these yield gaps are not well documented. Cassava is mainly produced under rain-fed conditions, with erratic and frequently failing rains leading to low yields. Knowledge of the best planting periods to minimize risks of drought and increase yield potentials is still not well documented in cassava production systems in West Africa. Soil fertility decline also appears to be a major constraint. However, the fertility status of soils is highly variable across agro-ecological zones, even within a small area due to the diversity in management practices. The variability in soil fertility and rainfall distribution and amount calls for the promotion of site-specific crop and nutrient management recommendations. Existing recommendations are uniform for regions or entire countries. Nutrient use efficiency of blanket fertilizer rates compared to balanced fertilizer rates have not been widely quantified in cassava production systems in West Africa. Assessing these nutrient use efficiencies will help to appreciate the relevance of a balanced nutrition in increasing cassava productivity and profitability. No decision support tool to assess this balanced nutrition, to formulate site-specific fertilizer recommendations and to assess best planting periods, has been developed or adapted for cassava production systems in West Africa. Developing such a tool may contribute to enhancing cassava productivity, profitability and food security in smallholder farming systems in West Africa.

1.9. Goal and research questions

This thesis focuses on understanding cassava productivity in order to contribute to improving yields, food security and farm incomes in rain-fed cassava production systems in West Africa, with a long-term goal of contributing to a decision support tool for site-specific crop and nutrient management recommendations. It addresses the following research questions:

1. What are the effects of resource endowment on the perception of farmers of the key constraints to cassava production and on crop yield, profitability and food security in cassava-based farming systems in West Africa?
2. What are the effects of fertilizer application on nutrient uptake, physiological use efficiency and yield of cassava in West Africa?
3. What are the effects of balanced nutrition on cassava yield and benefit-cost ratio of fertilizer use?
4. How do the effects of potassium on water and radiation use efficiencies contribute to explaining the impact of potassium on cassava productivity?
5. What are the potential and water-limited yields of cassava in Southern Togo?
6. What are the impacts of drought on cassava yields in Southern Togo?
7. What is the best planting window for cassava production in Southern Togo?

Farm surveys and field experiments have been conducted and a crop model has been designed to address these questions. The spatial distribution of the survey and field trials across Togo and Ghana, and rainfall zones is shown on Fig. 1.2.

1.10. Thesis outline

In Chapter 2 of this thesis, farm surveys were conducted in contrasting cassava production zones in southern Togo to understand the diversity among households, and assess the effects of this diversity on the perception of cassava production constraints, and on crop yield, profitability and food security. With this baseline understanding of the system, we focused in Chapter 3 on assessing the effects of external mineral fertilizer application on nutrient uptake, physiological use efficiency and yield of cassava using multi-locational field experiments across Togo and Ghana. Data collected in the latter experiments were also used in Chapter 4 to study how the use efficiency of N, P and K of cassava can be simultaneously enhanced through balanced nutrition approach of QUEFTS model, and how this balanced nutrition affects yield and profitability of fertilizer use for cassava production compared with blanket fertilizer rates. In Chapter 5, we conducted an in-depth study to improve our understanding of the effects of K on the productivity in relation to radiation (light) interception and radiation use efficiency, and to transpiration and water use efficiency of cassava. Data collected during this latter study were used in Chapter 6 to develop a process-based cassava model, which was used to enhance our understanding of water-limited yields of cassava and to identify best planting periods of cassava in Southern Togo. Chapter 7 discusses the implications of the findings of the above chapters on the development of a decision support system for assessing water-limited yields, site-specific fertilizer recommendation and planting dates in West Africa, and for enhancing farmers' livelihoods in cassava production zones in West Africa.

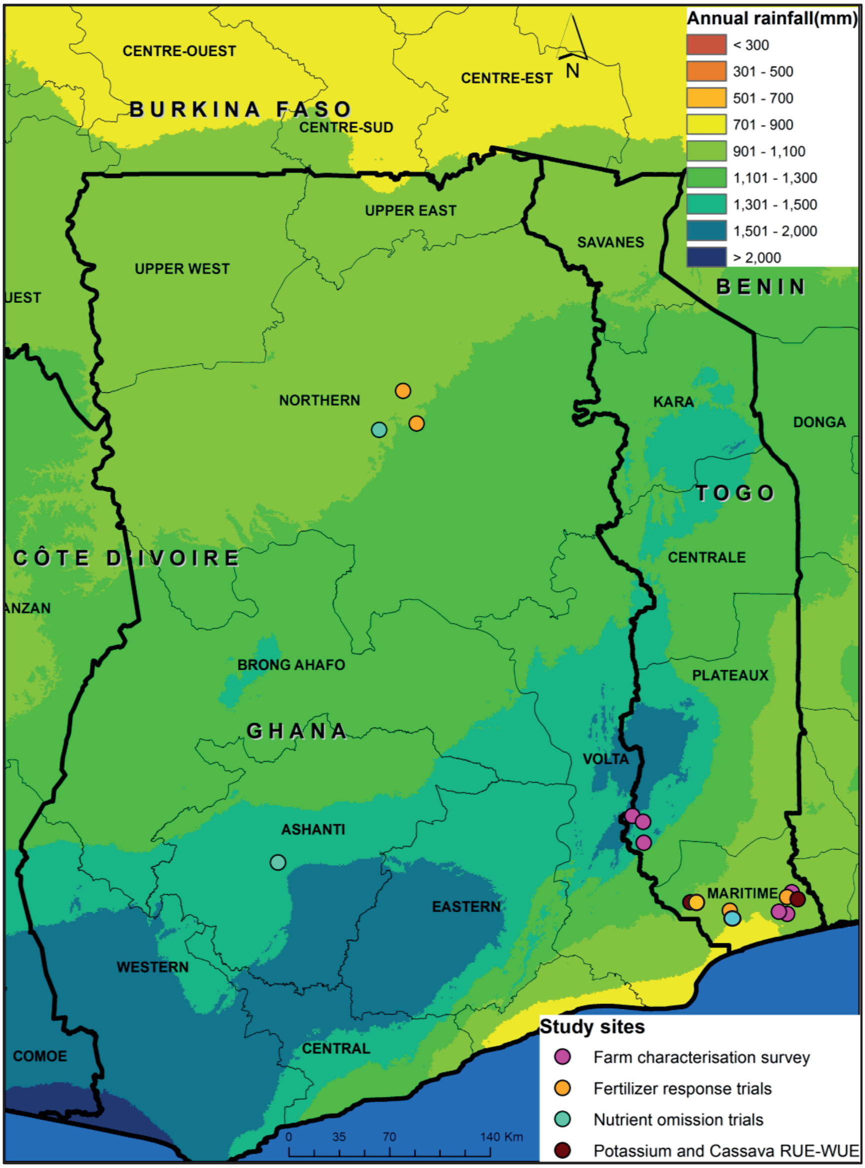

Fig. 1.2. Sites of the survey and field experiments described in this thesis in Ghana and Togo and rainfall zones. Rainfall data adapted from Hijmans et al. (2005). Farm characterisation survey are described in Chapter 2, fertilizer response trials and nutrient omission trials in Chapters 3 & 4, potassium and cassava RUE-WUE trial in Chapters 5 & 6.

CHAPTER TWO

2.0. Drivers of diversity among farmers, constraints and opportunities for intensified cassava production in Togo

Abstract

We studied the effects of the agricultural potential of two contrasting zones and the effects of the diversity among farmers on their perceptions of cassava production constraints, and on crop yields, farm profitability, household incomes and food security in Southern Togo. A rapid rural appraisal and a subsequent detailed farm characterisation were conducted in the Maritime and the Plateaux zones. The total land size, the proportion of time devoted to off-farm activities and the degree of orientation of cassava production to market were the main indicators of diversity, and explained all together 58% and 60% of the variation among households in the Plateaux and in the Maritime zones, respectively. Households in the Maritime had lower agricultural potential for cassava production compared to those in the Plateaux. Households in the Maritime were more land-constrained with land labour ratios of 0.27 – 0.68 compared to 0.60 – 2.14 ha per adult equivalent in the Plateaux. They also had poorer soils and were located in a low rainfall zone, which was reflected in their perception of cassava production constraints. Thus, crop diversification and intensification options with mineral and organic fertilizers use were more commonly practiced in this zone. Nevertheless, cassava yields were low in the Maritime with 1.2 – 1.6 Mg dry matter per ha, compared with 4.4 – 9.8 Mg per ha in the Plateaux. Yields were not affected by resource endowment groups (REGs) per zone since similar soil fertility management practices were used across REGs. Low yields in the Maritime were likely due to the use of blanket fertilizer rates and sub-optimal crop management practices. The average rate of fertilizer used was 53.7 kg N, 8.8 kg P and 16.9 kg K ha^{-1}, which is about 70% of the recommended blanket rate. Average energy and protein production per capita per day ranged from 3827 to 5114 kcal and 77 to 115 g of protein in the Maritime, and 9948 to 29030 kcal and 56 to 121 g of protein in the Plateaux, which were higher than the needs of 2500 kcal and 48 g of protein per capita per day. However, average incomes per capita per day of 0.62, 046 and 0.46 US$ for the high, medium and low REGs (HRE, MRE and LRE, respectively) in the Maritime were below the poverty line requirement of 1.25 US$. This poverty line was passed by HRE and MRE households with 2.58 and 2.59 US$ per capita per day in the Plateaux, unlike the LRE households 0.89 US$ per capita per day. Soils in the Plateaux appeared to be acidic, which likely resulted from erosion. Site-specific soil fertility management should be promoted in the Maritime zone, which has higher need for cassava production intensification, compared to the Plateaux zone, where soil and water conservation should be improved to achieve higher yields, especially among the LRE households.

Keywords: *Farm characterisation, resource endowment, yield, income, food security.*

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2.1. Introduction

Poor soil fertility is perceived as one of the major constraints to crop production in sub-Saharan Africa (SSA) (Smaling et al. 1997). Several studies have shown that soil fertility management can increase cassava yields in West Africa (Adekayode and Adeola 2009; Sogbedji et al. 2015). Local practices to replenish soil fertility in West Africa include manure, household waste, mineral fertilizer applications and legume cultivation as intercrops or in rotation with other crops. The traditional land cultivation with long fallow periods is increasingly being replaced by continuous cultivation with short fallow periods (Hillocks 2002). Given the declining availability of arable land due to population growth, sustainable crop production intensification is required. An integrated soil fertility management (ISFM) approach is recommended, which promotes the judicious use of organic and mineral fertilizers together, the use of improved genotypes and the diversification of crop rotations (Vanlauwe et al. 2010; Vanlauwe et al. 2002).

Soil fertility management is often affected by resource endowment. Resource endowment determines the capacity of a farmer to access agricultural resources, especially land and labour. Households can be classified based on resource endowment within a geographical setting (village, district, country and region). Fermont (2009) and Tittonell (2009) showed that high resource endowed households in East Africa are more likely to adopt intensification options for crop production than farmers who are more resource-constrained with low social and financial capital. This diverging behaviour of households of different resource endowment concerning the intensification of crop production had consequences for crop productivity, profitability and food security with the wealthier households outperforming the poorer households. The relevance of these findings for cassava production systems in West Africa is yet to be confirmed.

The agricultural potential of the area (high rainfall amount and distribution, and inherently fertile soils) and the proximity to urban market can also affect soil fertility management. Households from areas with relatively good agricultural potentials and relatively good access to urban markets proved to be more market oriented with the production of cash crops than households in relatively poor agricultural potential in East Africa (Tittonell 2009). Households from these high agricultural potential areas are thus likely to adopt more ISFM options than those in low agricultural potential areas. Manure and mineral fertilizers use was relatively higher in these high agricultural potential areas than in the low agricultural potential areas in East Africa (Tittonell 2009). However, it is important to assess the applicability of these findings for cassava production areas in West Africa conditions.

The objectives of this explorative study were to understand the diversity among farmers in cassava production systems of West Africa, and to assess the effects of this diversity on farmers' perception of cassava production constraints, and on crop yield, farm profitability, household incomes and food security.

2.2. Material and methods

2.2.1. Location

The study was carried out in Southern Togo in two contrasting rainfall zones: the Maritime region with 700 – 1300 mm per year and the Plateaux region with 1300 – 2000 mm (Hijmans et al. 2005) (Fig. 2.1). The rainfall regime is bimodal in the two zones, allowing two rainy seasons from March to July and September to November. In each zone, three villages were randomly selected: Sekponakondji, Vokoutime and Afowuime in the Maritime, and Kuma Adamé, Tomé and Yokélé in the Plateaux. Sekponakondji village was located within 9 km of Afagnan market; Vokoutime and Afowuime were of the same distance from the Vogan market in the Maritime. Kuma Adamé, Tomé and Yokélé villages of the Plateaux region were located within 22 km away from the Kpalime market. The major soil types were tropical ferruginous soils in the Plateaux, and ferrallitic soils (CPCS 1967) called "terres de barre" in Maritime zones. The tropical ferruginous soils are also highly represented in the Maritime, especially in south west. Average temperature varies between 24-33^{o}C in the Maritime, and between 20-33^{o}C in the Plateaux. The Maritime is the largest cassava production zone in Togo, followed by the Plateaux.

The Maritime hosts 42% of the Togolese population on about one tenth of Togo's total land area size (DGSCN 2011). It is followed by the Plateaux hosting 22% of the population estimated at about 6.2 million inhabitants. The population density is 280 inhabitants per km^2 in the Maritime (excluding Lomé, the capital), and 81 inhabitants per km^2 in the Plateaux zone (DGSCN 2011).

2.2.2. Farm surveys

Farm surveys were carried out in two consecutive steps: i) a rapid rural appraisal using a questionnaire administered to 50 households randomly selected per village from cassava producers lists made with the assistance of agricultural extension agents. In total, 300 households were interviewed (semi-structured interview): 150 households in the Maritime and 150 households in the Plateaux. This rapid rural appraisal helped classify cassava producing households in resource endowment groups (REG); ii) a detailed farm characterization of each REG to assess opportunities for cassava production intensification. Ten households were selected per REG per zone (30 households per zone) for the detailed farm characterization survey. Detailed data were collected regarding farm size, crop yields, cropping systems, soil fertility management, soil properties, farm profitability, etc. Composite soil samples were taken in each field at 0-20 cm depth. These samples were analysed by ICRISAT laboratory in Niamey. Particle size was determined using the hydrometer method, pH (H_2O, 1:2.5) with a glass electrode pH meter, organic carbon by the Walkley-Black method, total N by Kjeldahl digestion method, and available P by Olsen method. Extraction of exchangeable cations (K^+, Na^+, Ca^{2+} and Mg^{2+}) was performed using a single extraction with dilute Silver-Thiourea (AgTU) solution (0.01 M Ag^+), followed by their measurement using an atomic absorption spectrophotometer for Ca^{2+} and Mg^{2+}, and a flame spectrophotometer for Na^+ and K^+.

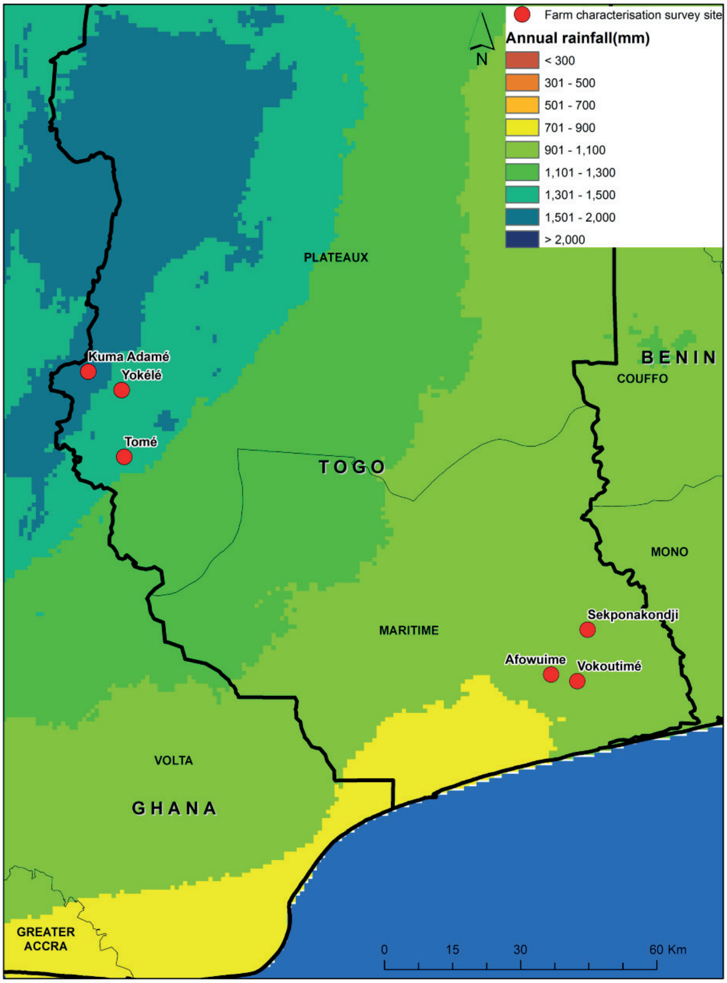

Fig. 2.1. Localisation of the farm survey villages across rainfall zones.

2.2.3. Data analysis

Descriptive statistics of the data provided an overview of the mean and spread of different variables. A principal component analysis (PCA) was conducted to identify variables that explained most of the variation between households. Eight variables generally reported as potential indicators of diversity among farmers (Fermont 2009; Tittonell 2009) were involved in this analysis: age of the household head, total size of the household, the economic value of goods and equipment owned by each household, the number of livestock owned, total land size, the proportion of land allocated for cassava production, the proportion of time devoted to off-farm activities and the proportion of cassava production oriented to market.

Monetary values of household assets including goods, equipment, livestock and land owned by the household, were estimated and considered as total assets value of each household. Land values were 1700 US\$ ha^{-1} in the Maritime and 350 US\$ ha^{-1} in the Plateaux during the period of the survey. Based on these assets and the quality of the house of the household head, TwoStep cluster analysis (Rundle-Thiele et al. 2015) was used to classify households into resource endowment groups (REG). TwoStep cluster analysis is the cluster analysis procedure in SPSS that can form clusters based on both continuous and categorical data (SPSS 2001). It permits to reveal natural groupings within the dataset following two steps: i) a first step of pre-clustering of the original cases to reduce the size of the matrix that contains distances between all possible pairs of cases, ii) the second step consisting of applying the standard hierarchical clustering algorithm on the pre-clusters. The hierarchical clustering algorithm allows exploring a range of solutions with different numbers of clusters before arriving at a final clusters number. We had three clusters in total, representing the three REGs: high (HRE), medium (MRE) and low resource endowed (LRE) households. Since the distribution of the data was often skewed, asset values were log-transformed and standardized before the cluster analysis. Unbalanced ANOVA was performed to compare the resulting REGs. A probability threshold P value of 0.10 was used to assess differences between REGs. All statistical analyses were conducted using SPSS v 19.

To assess the key constraints explaining poor yields of cassava, farmers' perceptions of constraints were assessed and biophysical characteristics and farmers' current management of cassava production systems were evaluated. Variables measured during the detailed characterisation were soil fertility status (physical and chemical characteristics), farmers' management practices (planting periods, mineral fertilizer use, organic fertilizer use or organic resource management, pest and disease management, etc.) and yields. Food security was also assessed. The food security analysis involved counting months of food self-sufficiency, as well as comparing the production and needs of energy and protein per capita per day. The energy and protein productions per capita per day were determined by dividing the household annual productions of energy and protein by the number of adult equivalents and by 365 days. A household was considered food secured only if the energy and protein production per capita per day of the members of this household was larger than the daily requirements of 2500 kcal per capita and 48 g protein per capita. The latter was derived on the basis of a minimum daily protein requirement of 0.8 g kg^{-1} body weight and an average body weight of 60 kg (Trumbo et al. 2002). The minimum energy requirement was also derived based on this average body weight of 60 kg, and ranged from 1850 to 3500 kcal per day for men, and 1750 to 3050 kcal per day for women aging between 18 and 60 years old (FAO 2001). The number of adult equivalent was calculated by counting the number of members of each household, with children younger than 16 counting 0.5 and older members 1. The energy (protein) production was derived by multiplying the value of the production by the specific calorific value (protein content) of 1 kg of that production (Table 2.1).

The total household income was estimated by adding the profit generated from each staple crop production to the income from livestock, from cash tree crops production and from off-farm activities. The profit from the staple crop production was derived from the difference between the gross revenue from staple crop production and the production costs. The gross revenue was obtained by multiplying the value of the production by the unit price of the product as indicated by farmers during the detailed farm characterisation (Section 2.3.5.4).

The production costs were estimated for each crop using labour costs as indicated by farmers (Section 2.3.5.4). Labour costs for land preparation and weeding were shared by intercrops on the same field. No production cost was considered in deriving livestock income since investment in livestock production is negligible for most farmers. Annual livestock income was roughly obtained from the sale of owned livestock.

Table 2.1. Calorific value and protein content of some key crops. Source: FAO (1968).

Crop	Product	Calorific value (kcal kg^{-1})	Protein content (g kg^{-1})
Maize	Grain at 11.8% moisture	3570	94
Cassava	Dried	3570	13
Groundnut	Dried, shelled	5490	232
Cowpea	Dried grain	3360	204

The main cash tree in the Maritime and the Plateaux being oil palm trees, cash tree incomes were consisted of oil palm tree incomes. Those oil palm tree incomes were roughly estimated based on their production amounts and on their unit price at the farm gates. Given the difficulty of farmers to provide information about oil palm yields in this study, the production was roughly estimated by multiplying the national average value by the land size of the oil palm tree plantation. The national average yields ranged from 1.5 to 2.5 Mg ha^{-1} fresh fruits bunches (Carrère 2010). We used 1.5 Mg ha^{-1} fresh fruit bunches for the Maritime and 2.5 Mg ha^{-1} fresh fruit bunches for the Plateaux given the difference in rainfall amount and soil fertility between the two zones. The fresh oil palm nuts yields were derived from the fresh fruits bunches yields using a conversion factor of 0.725. The total income per household member was also calculated by dividing the total household income by the number of adult equivalents. This total income per capita (adult equivalent) was compared with the poverty line of 1.25 US$ per capita per day (Ravallion et al. 2009).

2.3. Results

2.3.1. Main indicators of diversity among households

The principal component analysis (PCA) revealed that similar indicators explained variability among households across the Maritime and Plateaux zones (Fig. 2.2 and Table 2.2). Among the indicators considered in the PCA, total land size had the largest loadings with the first principal component (PC) in the Maritime and the Plateaux (Table 2.2). Thus, total land size explained most the variations among households in both the Maritime and the Plateaux: 30% and 26%, respectively. The proportion of time devoted to off-farm activities and marketing of cassava were mostly correlated to the second PC in these zones (Fig. 2.2), raising the proportion of variation explained to 60% in the Maritime and to 58% in the Plateaux (Table 2.2). Variables regarding the proportion of cultivated land allocated to cassava production and the age of the household head were strongly related to the fourth PC in the Maritime and the Plateaux zones, respectively (Table 2.2).

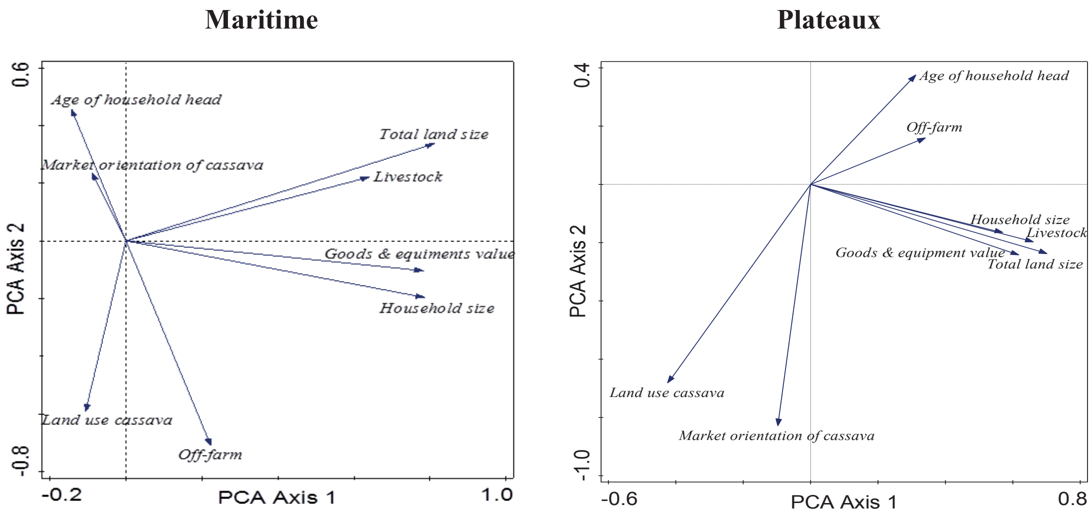

Fig. 2.2. PCA results showing the alignment of the studied variables to the first two principal components

Table 2.2. The loadings of the most correlated indicators to the first four principal components (PC), the Eigenvalues and the proportion of variation explained per PC in the Maritime and in the Plateaux. Values in bold indicate the largest loading per PC when absolute values are considered.

Zone / Indicators	PC1	PC2	PC3	PC4
Maritime				
Total land size (ha)	**0.813**	0.338	-0.003	-0.008
Proportion of off-farm (%)	0.223	**-0.709**	0.078	0.028
Market orientation (%)	-0.088	0.235	**0.882**	-0.255
Proportion of land use for cassava (%)	-0.105	-0.591	0.005	**-0.704**
Eigenvalues	*0.299*	*0.166*	*0.137*	*0.128*
Explained variation (cumulative)	*29.9*	*46.5*	*60.2*	*73.0*
Plateaux				
Total land size (ha)	**0.702**	-0.237	-0.062	-0.277
Market orientation (%)	-0.097	**-0.828**	0.066	-0.312
Proportion of off-farm (%)	0.341	0.159	**0.790**	-0.083
Age of household head	0.312	0.376	-0.330	**-0.734**
Eigenvalues	*0.255*	*0.187*	*0.139*	*0.114*
Explained variation (cumulative)	*25.5*	*44.2*	*58.1*	*69.5*

2.3.2. Resource endowment groups (REGs) of households

The REGs differed in size (Fig. 2.3): LRE households were expectedly the largest group, followed by MRE and then by HRE households (Fig. 2.3.a). The frequency distributions of the different households were right-skewed relatively to the total assets values (Fig. 2.3.b) and to the total land size (Fig. 2.3.c) with LRE households represented by the lowest values and the HRE households by the highest values. The unbalanced ANOVA of the indicators across the zones showed that the REGs diversely affected the number of adult equivalents, food self-sufficiency, fallow duration, land allocation to cassava cultivation according to cassava production zones (Table 2.3).

In the Maritime zone, the HREs had larger household members, more adult equivalents, and a greater number of months for food self-sufficiency than the MREs and LREs (Table 2.3). There were no significant differences among REGs in land allocation for cassava cultivation, fallow duration, proportion of time allocated to off-farm activities, and orientation of cassava production for market in the Maritime. In the Plateaux, the HREs also had larger household sizes with more available adult equivalents than the MREs and LREs. Longer fallow duration was observed for the HRE households. However, the LRE households appeared to allocate a larger proportion of their land to cassava cultivation compared with the HRE households in the Plateaux zone. The proportion of time allocated to off-farm activities and the orientation of cassava production to market was similar for all REGs in that zone. The land labour ratio (LLR: total land size divided by adult equivalent size) resulting from Table 2.3 was smaller in the Maritime with 0.68, 0.47 and 0.27 ha per adult equivalent than in the Plateaux with 2.14, 1.56 and 0.60 ha per unit adult equivalent for HRE, MRE and LRE, respectively.

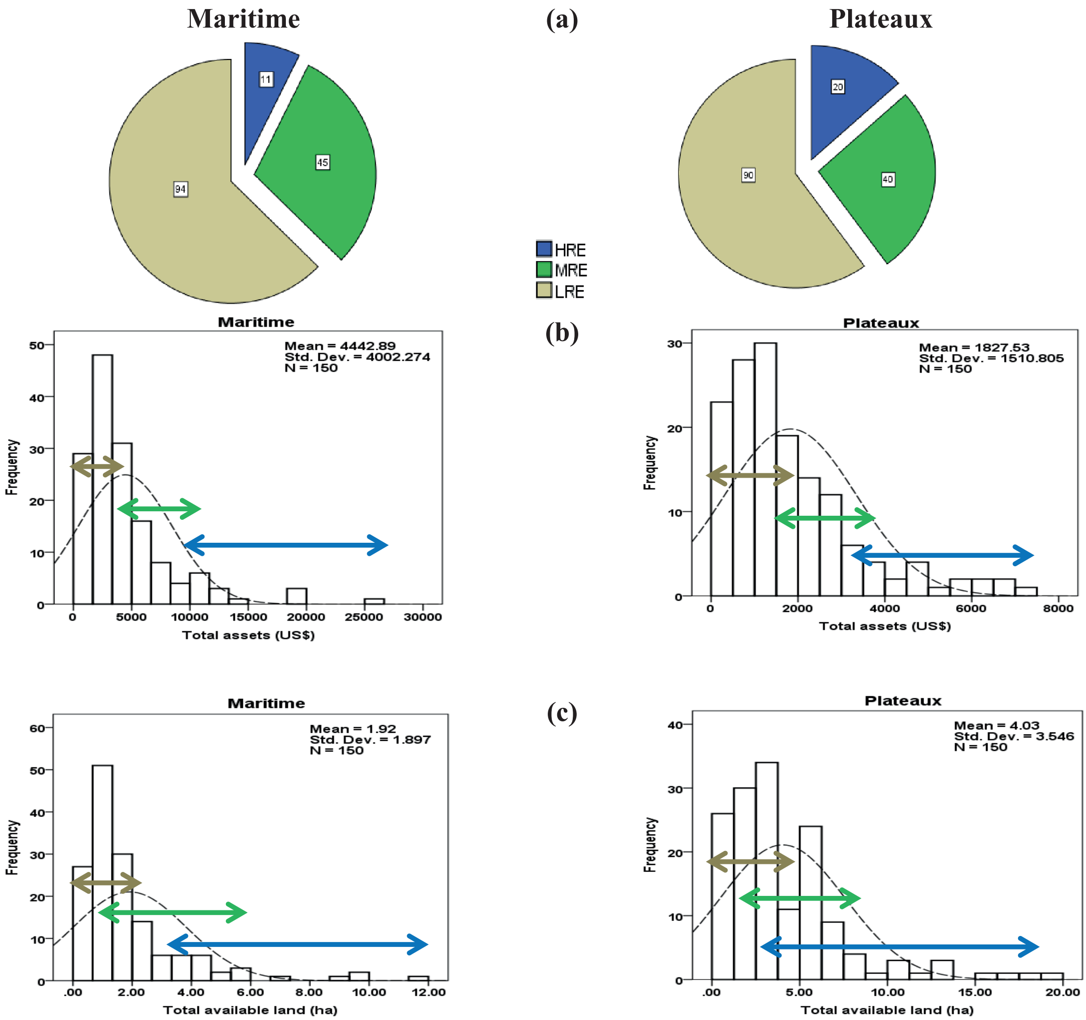

Fig. 2.3. Size of resource endowment groups (a) and frequency distribution of total asset values (b) and of total available land (c) per zone. On the frequency graphs (b and c), each arrow colour was matched with the colour of the corresponding REG, and the length of the arrow shows the distribution of households within a specific REG. The dashed line indicates the normal distribution curve. Its comparison with the frequency distribution shows the skewness of the household data.

Table 2.3. Characteristics of resource endowment groups in the Maritime and in the Plateaux zones. Variables in bold and italic were those included in the calculation of total assets values used to form the REGs. SEM stands for the standard error of means. TLU is the Tropical Livestock Unit. US$ is US dollar.

Zone / Variables	HRE	MRE	LRE	SEM	*P values*
Maritime					
Expensive goods and equipment (US$)	***1600***	***852***	***240***	***62.9***	***0.000***
Livestock owned (TLU)	***2.9***	***1.3***	***0.6***	***0.09***	***0.000***
Annual crops land size (ha)	***5.5***	***2.1***	***0.8***	***0.13***	***0.000***
Cash tree plantations size (ha)	***1.1***	***0.6***	***0.2***	***0.06***	***0.000***
Total land size (ha)	***6.7***	***2.6***	***1.0***	***0.15***	***0.000***
Total assets (US$)	**14943**	**6223**	**2362**	**327**	***0.000***
Age of the household head	52	49	50	1.0	*0.790*
Household size	13.4	8.3	5.4	0.3	*0.000*
Adult equivalents	11.0	6.6	4.2	0.2	*0.000*
Land allocated for cassava cultivation (%)	66.7	62.6	70.9	2.76	*0.399*
Fallow duration (years)	0.4	0.3	0.3	0.0	*0.532*
Proportion of time for off-farm activities (%)	27.3	27.3	20.0	1.78	*0.143*
Orientation of cassava production for market (%)	54.6	51.7	52.9	0.63	*0.497*
Food self-sufficiency (months)	10.6	9.3	8.8	0.1	*0.000*
Plateaux					
Expensive goods and equipment (US$)	***1001***	***273***	***84***	***49.1***	***0.000***
Livestock owned (TLU)	***0.6***	***0.4***	***0.2***	***0.03***	***0.000***
Annual crops land size (ha)	***7.6***	***3.9***	***1.7***	***0.22***	***0.000***
Cash tree plantations size (ha)	***2.7***	***1.4***	***0.3***	***0.10***	***0.000***
Total land size (ha)	***10.3***	***5.3***	***2.1***	***0.29***	***0.000***
Total assets (US$)	**4914**	**2354**	**908**	**123.4**	***0.000***
Age of the household head	49	49	46	1.0	*0.228*
Household size	6.9	6.1	5.0	0.2	*0.003*
Adult equivalents	5.2	4.7	3.9	0.2	*0.007*
Land allocated for cassava cultivation (%)	18.3	22.9	34.2	1.72	*0.001*
Fallow duration (years)	4.3	2.6	2.6	0.1	*0.000*
Proportion of time for off-farm activities (%)	22.5	13.1	13.1	1.68	*0.162*
Orientation of cassava production for market (%)	50.0	49.4	48.6	0.52	*0.622*
Food self-sufficiency (months)	9.6	9.5	9.1	0.1	*0.280*

2.3.3. Farmers perceptions of key constraints to cassava production

The key constraint to cassava production identified by the farmers was poor soil fertility in the Plateaux zone, and erratic rainfall in the Maritime (Table 2.4). In the latter zone, poor soil fertility was also perceived as a major constraint. These results were common across all REGs (data not shown).

2.3.4. Assessing soil fertility management practices for cassava production

The use of mineral fertilizers for cassava production was uncommon in both zones, irrespective of REGs (Table 2.5). However, mineral fertilizer application to maize was frequently practiced in the Maritime by all REGs. Manure was also frequently used in the Maritime. In the Plateaux, manure was rarely applied to cassava. Legumes were widely cultivated across the study zones by all REGs. The use of organic resources other than manure or legumes was also common in the Maritime. In this area, household wastes were highly valued for this purpose, which was not the case in the Plateaux.

Table 2.4. The three most common key constraints explaining low cassava yields according to farmers' perceptions (proportion of respondents mentioning this as a key constraint).

Zones	Key constraints	Proportion of respondents out of 150 (%)
Plateaux	Low soil fertility	70.0
	Poor management	8.7
	Erratic rainfall	4.7
Maritime	Erratic rainfall	55.3
	Low soil fertility	23.3
	Pressure on land	6.0

Table 2.5. Proportion of households (%) applying mineral fertilizers, manure and other organic resources and or cultivating legumes in their cassava fields, and proportion of households applying mineral fertilizers for maize production.

Zone	REG	Mineral fertilizer use		Manure use	Other organic resources use	Legumes cropping
		Cassava	Maize*			
Maritime	HRE	0	100	80	100	80
	MRE	0	100	64	89	81
	LRE	0	100	75	94	85
Plateaux	HRE	0	0	0	7	64
	MRE	0	0	0	3	77
	LRE	0	0	0	2	82

* Maize cultivation as sole crop or as intercrop in cassava production system.

2.3.5. Cassava production systems

2.3.5.1. Cassava cropping calendar

In the Maritime zone, cassava cropping started with land preparation in March, followed by planting in April by the majority of surveyed farmers (Table 2.6). Manure was applied throughout the year. Manure was regularly collected from owned livestock sheds. Most farmers did not apply mineral fertilizer to cassava. Weeding was carried out thrice: in April, May and June. No pesticides were applied. Harvest was mostly done in February and March of the following year, thus about 10-11 months after planting. In the Plateaux zone, land preparation started earlier, mainly from February to April, followed by the planting from March to May. Manure and mineral fertilizers were not applied. The first weeding occurred between April and June, and the second between July and November. The third weeding was practiced by few farmers between October and December. Pesticide application was also limited in this zone. Harvest was done throughout the year with a peak between December and March.

2.3.5.2. Crop productivity

Maize and cassava were major food crops grown in the two zones. Their production levels varied per zone and among REGs largely due to differences in land area since yields differences between REGs where not always significant (Table 2.7). In the Maritime, HRE farmers produced more storage roots than MRE and LRE households ($P = 0.06$), but there was no significant difference in terms of storage roots yields between these REGs. Contrarily, differences in maize grain productions and yields were significant between REGs: MRE households had the highest maize grain production ($P = 0.007$) and yield ($P = 0.096$) compared to HRE and LRE. No significant difference was found between REGs in terms of production level and yield of cassava and maize in the Plateaux.

Table 2.6. Timing and frequency (% of respondents) of field activities related to cassava production across 35 fields in the Maritime and 30 fields in the Plateaux zones

Zone	Activity	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maritime	Land preparation	0	0	97	0	0	0	0	3	0	0	0	0
	Planting	0	0	0	97	0	0	0	0	3	0	0	0
	Manure application	43	43	47	43	43	43	43	43	43	43	43	43
	Mineral fertilizer application	0	0	0	0	0	0	0	0	0	3	0	0
	First weeding	0	0	0	90	3	0	0	0	7	0	0	0
	Second weeding	0	0	0	0	90	3	0	0	0	7	0	0
	Third weeding	0	0	0	0	0	93	3	0	0	0	3	0
	Pesticide application	0	0	0	0	0	0	0	0	0	0	0	0
	Harvest	0	63	17	7	0	0	3	0	7	0	0	3
Plateaux	Land preparation	6	18	38	32	3	0	3	0	0	0	0	0
	Planting	0	0	14	34	40	3	3	6	0	0	0	0
	Manure application	0	0	0	0	0	0	0	0	0	0	0	0
	Mineral fertilizer application	0	0	0	0	0	0	0	0	0	0	0	0
	First weeding	0	0	3	11	26	37	9	3	3	0	0	0
	Second weeding	0	0	0	3	0	3	29	29	9	11	9	3
	Third weeding	9	3	0	0	3	0	0	0	0	9	14	6
	Pesticide application	0	0	0	0	0	0	0	0	0	3	3	0
	Harvest	14	16	14	8	4	4	4	6	2	4	6	16

Table 2.7. Cassava and maize production per household and yield.

Zone	REG	*n**	Cassava storage roots production (kg)	Cassava storage roots yield (kg ha^{-1})	Maize grain production (kg)	Maize grain yield (kg ha^{-1})
Maritime	HRE	5	1532	1160	1579	827
	MRE	5	888	1597	2350	1504
	LRE	9	604	1314	414	725
	P value		*0.060*	*0.642*	*0.007*	*0.096*
	SEM		165	164	285	154
Plateaux	HRE	3	3744	4398	278	1656
	MRE	8	5062	7955	614	1588
	LRE	9	3983	9796	563	1703
	P value		*0.873*	*0.529*	*0.318*	*0.992*
	SEM		1028	1560	83	368

* *n* represents the number of households (out of the ten involved per REG for the detailed farm characterisation) for which we were able to obtain reliable estimates of cassava production.

Table 2.8. Legumes production per household and yield in the Maritime zone

REG	n	Cowpea grain production (kg)	Cowpea grain yield (kg ha^{-1})	Groundnut grain production (kg)	Groundnut grain yield (kg ha^{-1})
HRE	5	236	362	308	382
MRE	5	150	121	67	418
LRE	9	62	138	53	194
P value		*0.262*	*0.165*	*0.281*	*0.653*
SEM		43.5	53.4	67.9	107.3

Apart from maize and cassava, cowpea and groundnut cultivation was practiced by most households in the Maritime (Table 2.8). However, their production level and yields did not differ significantly among REGs. The cultivation of legumes was uncommon among the households in the Plateaux according to the detailed characterisation survey results.

Other important crops cultivated in both areas were tree crops as shown by cash tree plantation sizes in Table 2.3. Those plantations included mainly oil palm in the Maritime (93% of the cash tree crop farms) and the Plateaux (72% of the cash tree crop farms, data not shown). Annual oil palm tree productions for HRE, MRE and LRE were 0.9, 0.3 and 0.2 Mg of fresh nut fruits, respectively in the Maritime, and 7.6, 2.3 and 0.4 Mg of fresh nut fruits in the Plateaux.

2.3.5.3. Soil fertility, fertilizer use and crop residue management

Soil fertility status of cassava fields differed between the two zones (Table 2.9). Soil organic carbon (SOC) and total N contents were expectedly larger in the Plateaux than in the Maritime, as the soil texture was sandier with less silt and clay in the latter zone. Contrarily, larger values of available P were obtained in the Maritime zone. Exchangeable K, Na and Ca were not statistically different between the zones, whereas exchangeable Mg was higher in the Maritime than in the Plateaux. Soils of cassava fields were acidic in the Plateaux zone and close to neutral in the Maritime. There were no significant differences in any of the soil chemical properties among REGs in the Maritime (data not shown). In the Plateaux, REGs were significantly different only in total N (1.9, 1.0 and 0.9 g kg^{-1} for HRE, LRE and MRE, respectively, $P = 0.041$), exchangeable Na (3.1, 2.6 and 2.4 mmol kg^{-1} for MRE, HRE and LRE, respectively, $P = 0.004$), exchangeable Ca (46.9, 39.3 and 39.1 mmol kg^{-1} for LRE, MRE and HRE, respectively, $P = 0.023$) and pH (6.1, 5.4 and 4.3 for MRE, LRE and HRE, respectively, $P = 0.068$) (data not shown).

While fertilizer and manure use was uncommon even in maize production in the Plateaux zone (Table 2.5), both fertilizer and manure were applied to maize intercrops in the Maritime zone (Table 2.10). NPK 15-15-15 and urea were commonly used. We did not find any differences among REGs in the amount of manure applied to maize per household or per hectare (Table 2.10). The amounts of NPK and urea applied per household were larger in the MRE and HRE than in the LRE. Nutrient amounts applied were similar on a per hectare basis (Table 2.10).

In general, crop residues were left on the ground in the field after harvest (Table 2.11). This was the case of maize, groundnut and cowpea in the Maritime, and maize and cassava in the Plateaux. However, in the Maritime, 87% of cassava residues were used to feed animals, and only 10% of them were left on the ground in the field, without incorporation into the soil.

Table 2.9. Soil chemical and physical characteristics of cassava fields in the study zones during the detailed farm characterisation survey.

Zone/Variables	*n**	SOC ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Olsen P ($mg\ kg^{-1}$)	K^+ ($mmol\ kg^{-1}$)	Na^+ ($mmol\ kg^{-1}$)	Ca^{2+} ($mmol\ kg^{-1}$)	Mg^{2+} ($mmol\ kg^{-1}$)	pH	Sand ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)
Maritime												
Mean	25	4.2	0.3	7.6	3.3	2.7	46.1	11.6	6.9	886	37	77
Minimum		3.1	0.2	2.7	2.3	1.9	30.3	7.9	6.2	812	28	47
Maximum		5.7	0.4	14.2	4.0	3.5	66.4	17.6	7.7	916	49	150
Plateaux												
Mean	15	17.2	1.1	4.7	3.6	2.8	40.8	13.8	5.6	682	151	167
Minimum		6.2	0.4	1.8	2.3	2.2	35.0	10.2	3.8	428	58	53
Maximum		34.3	2.6	17.4	4.3	3.4	52.4	16.8	7.7	871	281	341
P value for zone		*0.000*	*0.000*	*0.017*	*0.094*	*0.333*	*0.070*	*0.006*	*0.000*	*0.000*	*0.000*	*0.000*

**n represents the number of cassava fields that were sampled per zone.*

Table 2.10. Mineral and organic fertilizers use for maize production on the study sites in the Maritime.

REG	Manure over 3months (kg)	Manure over 3months ($kg\ ha^{-1}$)	NPK (kg)	NPK ($kg\ ha^{-1}$)	Urea (kg)	Urea ($kg\ ha^{-1}$)	N ($kg\ ha^{-1}$)	P ($kg\ ha^{-1}$)	K ($kg\ ha^{-1}$)
HRE	1473.6	1392.4	222.6	119.8	140.2	75.8	53.0	7.8	15.0
MRE	742.8	1154.2	256.6	163.8	101.6	67.0	55.2	10.8	20.6
LRE	979.0	2725.0	68.3	120.6	40.4	75.8	52.9	7.9	15.0
P value	*0.749*	*0.611*	*0.001*	*0.519*	*0.041*	*0.953*	*0.991*	*0.490*	*0.499*
SEM	341.6	704.4	27.2	16.1	17.5	11.7	7.0	1.0	2.0

Table 2.11. Crop residue management in the Maritime and Plateaux zones (% of respondents).

Zone	Crop	Burnt	Left on the Ground	Incorporated in the soil	Feed for Animals	Other uses (cutting, gift to other farmers)
Maritime	Maize	2.3	88.6	0.0	2.3	6.8
	Cassava	0.0	10.2	0.0	87.0	2.8
	Groundnut	9.1	90.9	0.0	0.0	0.0
	Cowpea	0.0	100.0	0.0	0.0	0.0
Plateaux	Maize	0.0	98.5	0.0	1.5	0.0
	Cassava	0.5	90.8	4.7	2.0	2.0

2.3.5.4. Farm profitability: profit and incomes repartition

Crop and livestock product prices and labour costs as indicated by farmers in the detailed farm characterisation were used in the economic analysis presented in Tables 2.12, 2.13 and 2.14. In the Maritime, cassava storage roots were expressed in “gari”, a processed product, which explained its greater price, compared to the fresh storage roots in the Plateaux (Table 2.12). Maize was more expensive in the Maritime than in the Plateaux, probably because of the higher population density implying higher demand, and because of the closeness to the capital city Lomé. Prices of livestock products also varied between zones. Farmers bred more livestock species in the Maritime compared to the Plateaux (Table 2.13). Labour costs varied a lot between the two zones (Table 2.14). Labour costs for harvesting were generally paid cash in the Plateaux, while harvest was commonly combined with processing into gari in the Maritime. About one third of the production was used to pay for cassava harvesting and processing into gari, and one fifth of maize production to pay for harvesting and shelling maize in the Maritime.

Households in the Plateaux got more profit from staple crop production than those in the Maritime zone (Fig. 2.4). In the Plateaux, a considerable part of this profit was achieved with cassava production. In the Maritime, the profit was made up with cassava, maize, cowpea and groundnut production. In both zones, the highest profit from staple crop production was attained by MRE households. In terms of total household incomes, the HRE households earned more compared to MRE and LRE households in both zones. In the Maritime, the main source of household income was made of off-farm activities for HRE and LRE households and of staple crop production for MRE households. The corresponding total income per capita per day were 0.62 US$ for HRE, 0.46 US$ for MRE and 0.46 US$ for LRE households. In the Plateaux, the main source of income was cash oil palm tree production and off-farm activities for the HRE households, staple crop production for MRE, and staple crop production and off-farm activities for the LRE households. The corresponding total income per capita per day were 2.58, 2.59 and 0.89 US$ for HRE, MRE and LRE households, respectively.

Table 2.12. Crop products price (US$ kg^{-1}) as indicated by farmers in the detailed farm characterisation.

Crops	Maritime			Plateaux		
	Product	Price	STDEV	Product	Price	STDEV
Maize	Grain	0.32	0.07	Grain	0.27	0.03
Cassava	Gari*	0.40	0.08	Fresh storage roots	0.08	0.04
Groundnut	Dried shelled	0.51	0.37			
Cowpea	Dried grain	0.60	0.12			
Oil palm**	Fresh nut	0.1856	0.004		0.1856	0.004

*Gari is a processed cassava storage roots into dry and roasted granules: 5 kg of fresh storage roots produce 1.5 kg gari, and 1 fresh storage root contains 0.30 to 0.40 kg dry matter. We used 0.36 kg dry matter per kg fresh storage roots in our calculations. **The price of oil palm fresh nuts were farm gates prices derived from CountrySTAT (2015) that were converted into US$ at the rate of 500 FCFA for 1 US$.

Table 2.13. Livestock products price (US$ $animal^{-1}$) as indicated by farmers in the detailed farm characterisation.

Animal	Maritime		Plateaux	
	Price	STDEV	Price	STDEV
Chicken	3.0	0.6	4.0	1.7
Duck	12.0	4.3		
Guinea fowl	5.2	0.4		
Goat	23.5	6.1	34.5	10.3
Sheep	52.5	4.6	42.3	25.0
Pig	58.0	21.5		

Table 2.14. Labour costs (US$ ha^{-1}) for farming operations per zone and the related standard deviation (STDEV).

Activity	Maritime		Plateaux	
	Price	STDEV	Price	STDEV
Land preparation	64.7	16.6	56.9	9.7
Sowing / planting	54.3	11.0	39.1	11.2
Fertilizer application	Family labour	-	-	
Weeding	48.2	16.2	70.7	7.0
Harvesting maize	-	-	29.3	4.6
Harvesting and shelling maize	1/5 of the production	-	-	
Harvesting cassava	-	-	59.0	11.1
Harvest and processing cassava into “gari”	1/3 of the production	-	-	

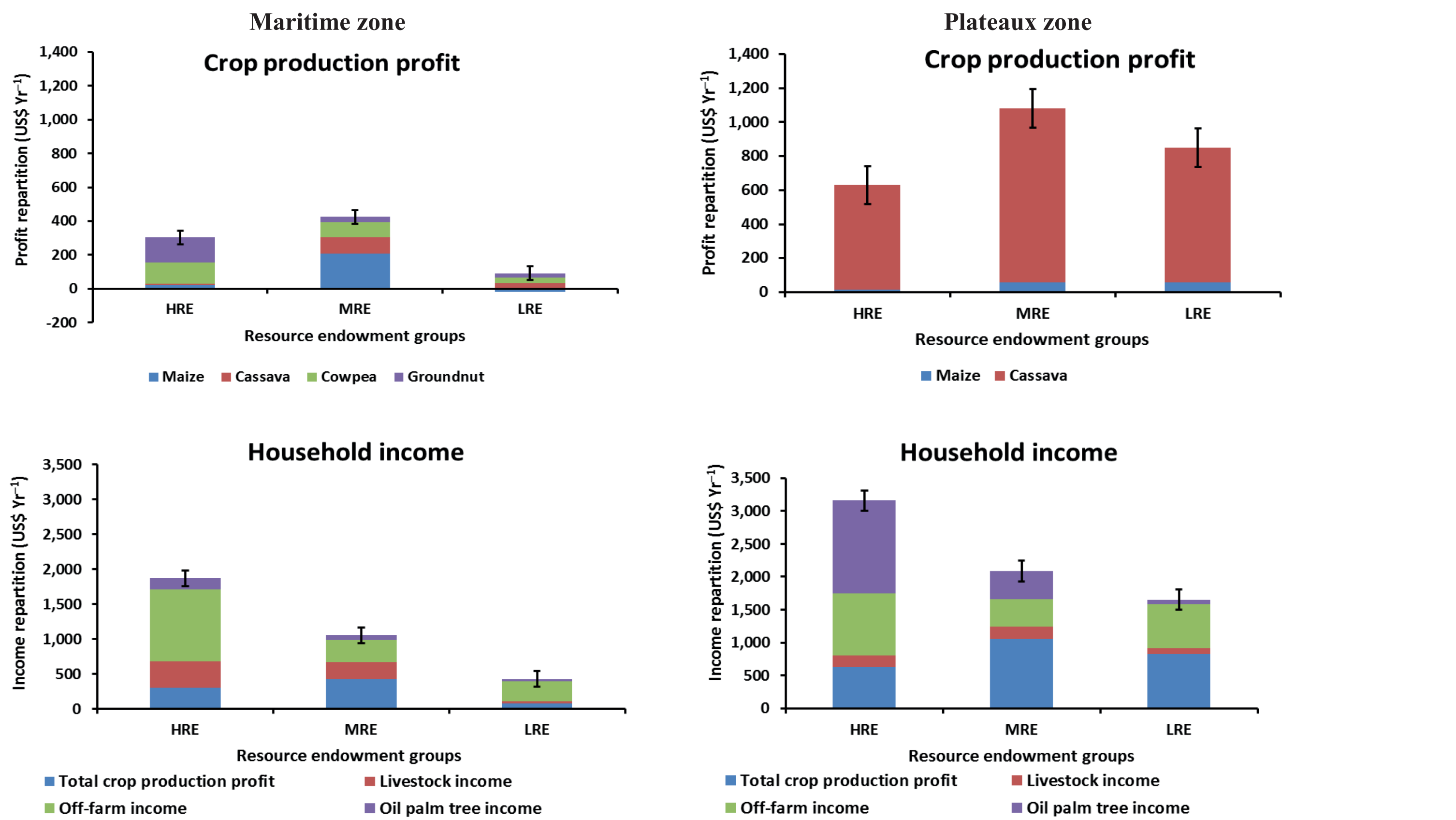

Fig. 2.4. Repartition of crop production profit per REG and distribution of household incomes between crop production, livestock production and off-farm activities in the Maritime and the Plateaux zones. Profit for each crop was obtained from the difference between gross revenue (product of production and unit price) and crop production costs. Error bars are standard error of means for the total household incomes.

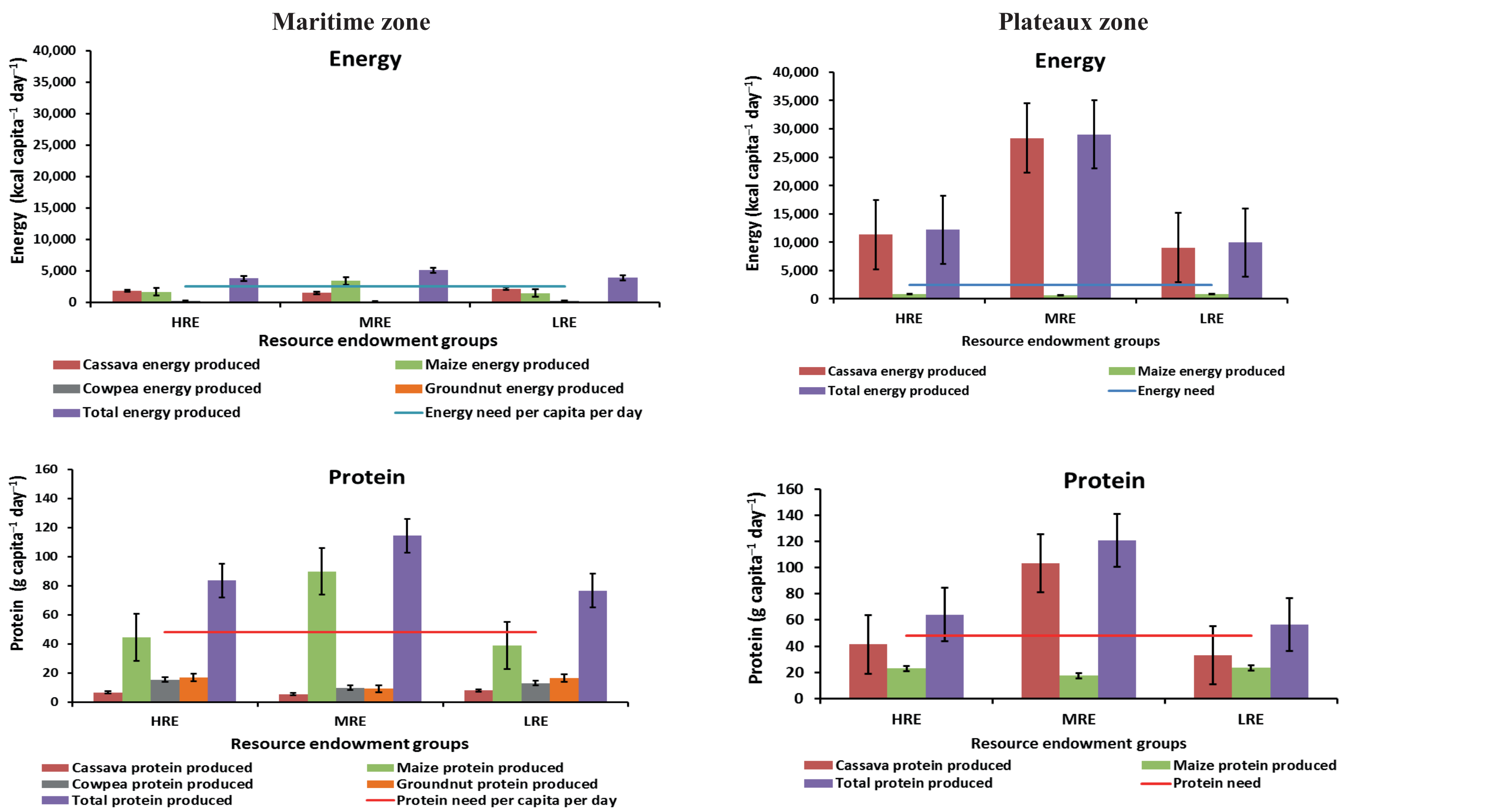

Fig. 2.5. Production of energy and protein per capita per day through crop production in the Maritime and Plateaux zones compared to their respective needs. The error bars represent standard error of means.

2.3.5.5. Food security

The production levels of energy and protein per capita per day varied among REGs and zones (Fig. 2.5). Energy production per capita per day was tremendously larger in the Plateaux than in the Maritime. In the Plateaux, most of the energy production was provided by cassava. Energy production in this zone per capita per day was higher than the need across the three REGs. This is also the case in the Maritime where energy need was met mainly by the combination of energy productions from cassava and maize. Energy contributions of cowpea and groundnut were minimal compared to those of cassava and maize.

Total protein production per capita per day exceeded protein need per capita per day in all REGs in the Maritime and the Plateaux. Protein production from any crop alone was not sufficient to meet the needs in either zone, except for cassava in the Plateaux MRE households, and for maize in the Maritime MRE households.

2.4. Discussion

Among the eight variables considered for the PCA (age of the household head, total size of the household, the economic value of goods and equipment owned by each household, the number of livestock owned, total land size, the proportion of land allocated for cassava production, the proportion of time devoted to off-farm activities and the proportion of cassava production oriented to market), total land size was the most strongly correlated variable with the first principal component. This indicated that total land size was the first main indicator of diversity among households within zone (Fig. 2.2; Table 2.2). However, the lack of distinct separation between REGs in Fig. 2.3.c compared with Fig. 2.3.b proved that other assets were also important to consider. This was confirmed in Fig. 2.2 by the positive correlation between the total land size and the livestock size in the Maritime, and between the total land size and livestock size, and values of goods and equipment in the Plateaux. Other indicators were the proportion of time devoted to off-farm activities and the level of orientation of cassava production for market. These latter indicators as well as total land size were also retained as the main indicators of diversity among households in cassava production systems in East Africa (Fermont 2009; Tittonell 2009). Most households produced cassava both for home consumption and markets as can be seen from the large quantity of storage roots produced beyond household food needs, and given the high degree of perishability of these roots. This may explain the commonness of processing cassava roots mainly into “gari” in the Maritime, and “agbelima” (fermented and wet cassava roots flour used for cooking the main maize based dish called “banku” in Ghana, “akumè” or “akple” in Southern Togo) in the Plateaux.

The agricultural potential of the zone proved to be a major determinant of differences in household livelihood strategies between the two study zones. The Maritime had lower agricultural potential for cassava production than the Plateaux. Besides being located in a lower rainfall area, the Maritime was characterised by smaller sizes of arable land and of cash tree plantation lands (Table 2.3), and by poorer soils (Table 2.9) compared with the Plateaux. However, household sizes were larger in the Maritime compared with the Plateaux, which implied less available land per adult equivalent in the Maritime (0.68, 0.47 and 0.27 ha per adult equivalent for HRE, MRE and LRE against 2.14, 1.56 and 0.60 ha per unit adult equivalent for HRE, MRE and LRE in the Plateaux). This indicated that households in the Maritime were more land resource constrained than those in the Plateaux.

The fact that households in the Maritime were more resource constrained had consequence for their livelihood strategies vis-à-vis the production constraints. In response to the erratic rainfall and poor soil fertility perceived as major constraints to cassava production in the Maritime zone, farmers diversified crop production and income sources. They cultivated legumes (cowpea, groundnut), which are quality sources of protein and of plant nitrogen through symbiotic fixation (Adjei-Nsiah et al. 2007; Giller and Cadisch 1995). They kept livestock and produced manure, which was applied in their crops. They also applied other organic resources such as household wastes. They applied mineral fertilizers as well on their fields, especially in maize. However, cassava yields ranging from 1.2 to 1.6 Mg storage roots dry matter ha^{-1} across REGs were low compared with those obtained in the Plateaux (Table 2.7), and smaller than the average national yield of 2.2 Mg ha^{-1} (FAOSTAT 2014). The main reason for poor yields can be attributed to the intercropping system. Cassava yields are generally reduced in intercropping systems compared to sole cropping systems due to competitions for light, water and nutrients with the intercrop (Mason and Leihner 1988; Mason et al. 1986). Moreover, the fact that yields were poor in the Maritime despite the use of mineral fertilizers and manure suggested that in addition to poor soil fertility, other factors limited cassava yields. Crop yields, soil fertility status and the amount of fertilizer used per ha were generally not affected by resource endowment. The average amounts of fertilizer used by households in all REGs of 53.7 kg N, 8.8 kg P and 16.9 kg K ha^{-1} were about 70% of the recommended blanket rate of 76 kg N, 13 kg P and 25 kg K ha^{-1}. This showed that farmers were using less than the recommended fertilizer rates, regardless of REGs and farm diversities. Another reason for poor crop yields can be attributed to sub-optimal crop residues management. Large proportions of cassava residues were exported from the fields as animal feed, while most residues from maize, groundnut and cowpea were left in the field (Table 2.11). While cassava roots export high amounts of K from the soil (Howeler 1991), removing stems and leaves from the fields as well will further deteriorate soil fertility on these fields (Howeler 2002). However, since animal manure was returned to the field (Table 2.6), some recycling of nutrients would be taking place. Another cause of poor yield can be ascribed to the sub-optimal timing of crop management activities. However, planting cassava in April in the Maritime seemed to match the on-set of the rainy season, and weeding three times before harvest (Table 2.6) followed well the national recommendations. The profit (gross revenue minus production costs) generated from staple crop production varied between REGs, with the largest profit made by the MREs and the smallest by the LREs (Fig. 2.4). The profit from maize and cassava production was less in the Maritime than in the Plateaux mainly because of higher production costs including the use of fertilizer and extra labour for weeding in the Maritime. In this latter zone, weeding was generally implemented three times against twice in the Plateaux zone. The absence of a third weeding in the Plateaux can be explained by the faster soil coverage by cassava canopy due to high SOC contents (Pellet and El-Sharkawy 1997). Staple crop production was not the major source of income for most households in the Maritime zone (Fig. 2.4).

The livelihood strategy is completely different in the Plateaux compared to the Maritime. Although soil fertility decline was perceived as a major constraint to cassava production (Table 2.4), little was done to restore soil fertility (Table 2.5). Fertilizer use (mineral and or organic) was uncommon, even on the intercrops. Legume cultivation was less frequent compared with the Maritime zone. The limited or lack of soil improvement initiatives can be explained by the large SOC of their soils (Table 2.9). Hence, greater yields were obtained in the Plateaux (Table 2.7). The average yields of 4.4 to 9.8 Mg ha^{-1} in REGs exceed the national average yield of 2.2 Mg ha^{-1}, and the regional yield of 4.0 Mg ha^{-1} in West Africa (FAOSTAT 2014). However, soil related issues in this zone were low soil P and pH. Cassava may be relatively insensitive to low available P values as 3-8 mg kg^{-1} (Olsen) (Howeler 2002). The low pH indicated soil acidity issues, which could be the reason why soil fertility was perceived as a major constraint in this zone. This can be attributed to the hilly topography of the study sites in the Plateaux, with slopes in crop fields ranging from 1-10% (measured using GPS in farmers' fields: data not shown). Improved soil and water conservation practices like planting according to contour lines, terracing, etc. should be encouraged to reduce soil erosion and achieve higher yields.

In the Plateaux, the HREs generated their incomes mainly through cash tree crops production (oil palm tree) and off-farm activities (Fig. 2.4). The LREs got most incomes from off-farm activities and crop production, whereas the MREs relied mostly on crop production. In the Maritime, HRE and LRE households gained their incomes mainly through off-farm activities, whereas the MRE households counted more on crop production to generate incomes. The average total income per capita per day was larger in the Plateaux (2.6, 2.6 and 0.9 US$ for HRE, MRE and LRE) than in the Maritime (0.6, 0.5 and 0.5 US$ for HRE, MRE and LRE, respectively). None of the REGs in the Maritime had sufficient incomes to meet all basic needs for decent livelihood for which 1.25 US$ per capita per day were required according to Ravallion et al. (2009). In the Plateaux, this requirement was met by the HRE and the MRE households contrarily to the LRE households. By contrary, energy and protein productions per capita per day were above the energy and protein needs per capita per day for all REGs in the Maritime and the Plateaux (Fig. 2.5). Households in the Maritime met their energy and protein needs through crop production diversification (Fig. 2.5). In the Plateaux, energy contribution of cassava production alone was largely sufficient to meet energy needs per capita per day. However, cassava production alone was not sufficient to meet the protein needs per capita per day in this zone because of the low protein content of cassava (Table 2.1). This stresses the necessity to promote the cultivation of protein-rich crops like grain legumes in cassava production systems in the Plateaux.

Many studies have reported that HRE households are more capable of adopting crop intensification options (Fermont 2009; Giller et al. 2006; Tittonell 2009; Wopereis et al. 2006). The results of our study showed, however, that the decision of adopting cassava intensification was highly dependent on the agricultural potential of the study zone. The fact that the Maritime had lower agricultural potential for cassava production compared to the Plateaux in terms of rainfall amount, arable lands size and soil fertility status, the former had a higher need for intensification of cassava production. This was confirmed by the systematic use by all REGs of manure and other organic resources, and the use of mineral fertilizers for maize that was generally intercropped with cassava. However, these results are supported by the proximity of the regional markets within 9 km radius around the study villages in the Maritime zone, which provides access to inputs, and opportunities for marketing the farm produces. We did not find any difference between REGs in terms of amounts of mineral fertilizers used, which were about 70% of the blanked rate recommended by the National Research System. This showed that when there was a need for intensification, farmers tended to follow existing recommendations, which were identical irrespective of soil diversities and management practices in the Maritime. Thus, it is important for those recommendations to be soil or agro-ecology specific and sound to ensure enhanced nutrient use efficiency and return on investments. The MRE households proved to be more suitable for adopting cassava intensification options since they relied more on staple crop production as a source of income than the HRE and the LRE households. These intensification options should include the use of site-specific mineral and organic fertilizers, improved cultivars, improved soil and water conservation practices, and good crop management practices. The use of these intensification options was reduced in the Plateaux, where rainfall amount and soil fertility were more favourable for cassava production. Cassava intensification options in this zone should focus on promoting improved cultivars, improved soil and water conservation practices, good crop management practices, and increased integration of grain legumes cultivation for enhanced food security.

2.5. Concluding remarks

The combined effect of the agricultural potential of the area for cassava production and the proximity to regional market was a major determinant of livelihood strategies in the study zones. These determining factors affected the perception of key constraints to cassava production, and had consequence for crop yields, farm incomes and food security of households. By contrary, REG did not influence the perception of farmers of cassava production constraints. There was no significant effect of REG on crop yields. However, household incomes were larger in the HRE households than in the MRE and LRE households in the Maritime and in the Plateaux. Cassava production alone was not sufficient for REGs to be food secure in the Maritime, and household income per capita per day was below the poverty line. In the Plateaux, HRE and MRE households earned enough income to pass the poverty line, unlike the LRE households. Energy needs of households were satisfied across zones, whereas protein needs were not met through cassava production alone. Crop diversification as practiced in the Maritime zone should be encouraged in the Plateaux zone with more legume cultivation in order to improve protein supply to the household. Crop production should be intensified in the Maritime and Plateaux through site-specific soil management practices to achieve higher yields and incomes.

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CHAPTER THREE

3.0. Understanding cassava yield response to soil and fertilizer nutrient supply in West Africa

Abstract

Accurate assessment of crop yield response to nutrient supplies is key to optimal fertilizer rates recommendations. We adapted the model for the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) to estimate cassava yields as affected by harvest index, indigenous soil nutrient supplies, fertilizers and physiological nutrient use efficiency (PhE, kg storage roots dry matter kg^{-1} nutrient uptake) in West Africa. Data from three on-station experiments in Davié (Southern Togo), Kumasi (Southern Ghana) and Nyankpala (Northern Ghana) were used for model calibration. The model testing was performed using data from on-farm experiments in southern Togo and northern Ghana. Indigenous soil nutrient supply estimated in the on-station experiments varied among sites ranging 86 – 177, 18 – 24 and 70 – 104 kg ha^{-1} of N, P and K, respectively. Apparent maximum recovery fraction (MRF) values also varied: 0.33 – 0.69, 0.03 – 0.44, 0.10 – 1.05 for N, P and K. In the original approach, the QUEFTS key parameters of PhEmax for maximum dilution and PhEmin for maximum accumulation of nutrients in the plant are based on yield to uptake ratios. Model predictions for Davié and Kumasi were improved by accounting for the harvest index (*HI*) in deriving PhEmax and PhEmin. The model overestimated yields in Nyankpala where drought stress caused low yields. Estimated values for PhEmin and PhEmax at *HI* of 0.50 were 41 and 96 kg kg^{-1} N taken up, 232 and 589 kg kg^{-1} P, and 34 and 160 kg kg^{-1} K. At a *HI* of 0.70, these values were 70 and 170 kg kg^{-1} N, 365 and 848 kg kg^{-1} P and 53 and 233 kg kg^{-1} K. When testing the model, estimated yields in response to fertilizer applications were in good agreement with measured yields for the on-farm experiments. The model was further improved by the use of site specific MRF values. We conclude that the QUEFTS model can be used for site-specific estimates of cassava yield responses to fertilizers under rain-fed conditions in West Africa, provided that yield is primarily constrained by the supply of N, P and K, and not by drought or other nutrients.

Keywords: *Soil nutrient supply, fertilizer recovery fractions, QUEFTS, Togo, Ghana.*

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3.1. Introduction

The differences between potential and actual yields, known as yield gaps, are large for cassava (*Manihot esculenta*, Crantz) in West Africa. Yields of fresh storage roots in smallholder farmers' fields average only 11.2 Mg ha^{-1} (average 2000-2013) (FAOSTAT 2014), equal to about 4 Mg ha^{-1} storage root dry matter (DM), which is far less than yields of 60 Mg ha^{-1} (20-24 Mg ha^{-1} storage root DM) recorded in researcher-managed field experiments in the region (Odedina et al. 2009). A primary constraint is poor soil fertility resulting from the combination of inherently small soil nutrient stocks (Smaling et al. 1997) and continuous cropping with negligible nutrient inputs (Sanchez et al. 1997). Furthermore, soil fertility exhibits strong variability, both among and within farms (Adjei-Nsiah et al. 2007) and fields, making blanket fertilizer recommendations inappropriate. Accurate assessment of nutrient supplies on a site-specific basis is important for enhanced estimates of crop yields. A sound understanding of nutrient uptake and nutrient conversion into crop yield is also required.

Despite the importance of cassava as a staple food and cash crop, there has been little attention for cassava yield predictions in response to nutrient supplies, uptakes and physiological use efficiency. The process-oriented dynamic model CROPSIM cassava (Matthews and Hunt 1994; Singh et al. 1998) was designed to simulate cassava growth and development was restricted to the assessment of potential, water-limited and nitrogen-limited yields. Thus, CROPSIM assumes that P and K are not limiting cassava growth, and is therefore not suited to assess nutrient limited yields in the nutrient depleted production systems of West Africa. Particularly, K deficiency is important in such low external nutrient use systems since cassava as a root crop has a high K demand (El-Sharkawy and Cadavid 2000; Howeler 2002; Pellet and El-Sharkawy 1997). The QUEFTS (QUantitative Evaluation of the Fertility of Tropical Soils) model could be a practical tool to assess nutrient requirements in cassava production systems. QUEFTS is a relatively simple and static model that predicts crop yields based on the interactions between the three macronutrients N, P and K, the physiological nutrient use efficiency (*PhE*) of the crop and the climate and location specific maximum yield as boundary condition (Janssen and Guiking 1990; Janssen et al. 1990). QUEFTS was originally developed for soil fertility evaluation, nutrient requirements assessment and yield prediction for maize under tropical conditions (Janssen et al. 1990). It has been successfully tested in East Africa (Smaling and Janssen 1993), and thereafter adapted for other crops including rice (Haefele et al. 2003; Sattari et al. 2014; Witt et al. 1999), wheat (Pathak et al. 2003), grain legumes (Franke et al. 2014) and cassava (Byju et al. 2012) in various parts of the world.

The *PhE*, a key crop specific parameter of QUEFTS also called the internal nutrient use efficiency, is defined as the mass ratio of the economic components of a crop (grain, storage roots) to the quantity of nutrient uptake in the whole crop. As such, it is sensitive to harvest index ((*HI*, kg dry matter yield kg^{-1} total biomass dry matter), and to differences in the nutrient content of edible and other crop components (Sattari et al. 2014). For cassava, differences in HI between cultivars can be large, but these were not considered in the QUEFTS model developed for cassava grown under Indian agro-ecological conditions (Byju et al. 2012). Although *HI* is measured at harvest, its value is known *a priori* for every cultivar as provided by breeders. However, besides genetics, *HI* strongly depends on the environment and management practices.

The current paper aims to enhance cassava yield estimates as affected by *HI*, indigenous soil nutrient supplies, fertilizers and physiological nutrient use efficiency (*PhE*) in West Africa using the QUEFTS model. We hypothesized that accounting for the effects of *HI* improves the yield prediction of cassava in West Africa, where different cultivars are grown with varying *HI*. We investigated the relationships between N, P and K uptake and cassava yield and the relationship between soil parameters and quantities of soil N, P and K supplies. This allowed us to calibrate and test the QUEFTS model and predict cassava yields for different soil conditions and fertilizer amendments. For this purpose data from five different field experiments conducted between 2007 and 2010 in West Africa were used.

3.2. Material and Methods

3.2.1. Model calibration

3.2.1.1. Dataset for model calibration

The dataset used for model calibration was collected in three field experiments conducted over two years in three agro-ecological zones (AEZ) of West Africa. The sites were Davié in Togo in the Coastal Savannah, Kumasi in the Humid Forest and Nyankpala in the Southern Guinea Savannah AEZ of Ghana (Table 3.1). Prior to crop establishment, soil samples were collected at five positions in each site up to 20 cm soil depth. Per site, these samples were mixed and a composite sample of 500g was taken for laboratory analysis. Soils were analysed for soil organic carbon (SOC), soil total nitrogen, exchangeable cations, soil texture, pH-water, and available phosphorus (P-Bray-I) (Table 3.2), using the procedures described by Houba (1995).

Table 3.1. Characteristics of the experimental sites for model parameterization

Site	Davié	Kumasi	Nyankpala
Country, district	Togo, Maritime Region	Ghana, Ashanti Region	Ghana, Northern Region
Geographic coordinates	6.385° N, 1.205°E	6.686° N, 1.622° W	9.396°N, 0.989°W
Altitude (m above sea level)	89	267	170
Soil type	Rhodic Ferralsols	Ferric Acrisol	Gleyi-ferric lixisol
Agro-ecological zone	Coastal Savannah	Humid Forest	Southern Guinea Savannah
Rainfall distribution	Bi-modal	Bi-modal	Mono-modal
Season 1	May10-March 17, 2007-8	June 28–March 22, 2008-9	June 29 - Feb. 25, 2007-8
Season 2	April 26– Feb. 23, 2008-9	June15–March15, 2009-10	May 23 - Dec. 03, 2008
Rainfall (mm, season 1 and 2)	731, 813	986, 938	731, 1017
Cultivar	Gbazekoute	Afisiafi	Afisiafi

The Rhodic Ferralsols at Davié is a loamy sand with known K deficiency (Table 3.2), the Ferric Acrisol at Kumasi is a silt loam with high SOC content, and the Gleyi-ferric lixisol at Nyankpala is sandy loam with low SOC content (Table 3.2) according to soil characteristics classification by Howeler (2002).

The experiments ran for two consecutive seasons at each site between 2007 and 2010 (Table 3.1). A randomised complete block design (RCBD) with replicates in four blocks and 10 fertilizer N-P-K rates (kg N, P and K ha^{-1}: 0-0-0, 0-40-130, 40-40-130, 80-0-130, 80-20-130, 80-40-0, 80-40-65, 80-40-130, 40-20-65 and 100-50-170) was used. N was applied as urea (46%N, Davié and Kumasi) or sulphate of ammonia (21%N, Nyankpala), P as triple super phosphate (TSP: 20%P) and K as muriate of potash (MOP: 50%K). All the TSP and one third of the urea and MOP were applied 30 days after planting (DAP); the remaining urea and MOP at 45 days after the first application. Soil bunds were constructed around each experimental plot to prevent lateral fertilizer contamination between plots.

At each site, a locally popular, improved cassava cultivar was planted at the recommended planting density: “Gbazekoute” cultivar (TME-419) in Togo with a planting scheme of 0.8 × 0.8 m (15625 plants ha^{-1}) in 6.0 × 5.6 m plots, and “Afisiafi” cultivar (TME-3281 or TME-771) in Ghana with a planting scheme of 1.0 × 1.0 m (10000 plants ha^{-1}) in 7.0 × 7.0 m plots. Hand weeding was carried out four times during the growing season.

Table 3.2. Initial soil properties (0-20 cm soil depth) of the experimental sites used for model parameterisation and verification

Category and unit	Parameter	Model parameterisation sites			Model verification sites (Togo, Maritime Region)				
		Davié	Kumasi	Nyankpala	Gbave	Davié Tekpo	Sevekpota Black Soil	Sevekpota White Soil	Sevekpota Red Soil
Organic, $g\ kg^{-1}$	SOC	8.9	12.6	4.3	4.7	6.1	18.0	12.7	14.1
	SON	0.7	1.5	0.3	0.3	0.4	1.4	0.9	1.1
	C:N	13.2	8.4	14.7	13.9	15.0	12.7	14.1	12.7
Cations, $mmol\ kg^{-1}$	K	1.5	3.8	3.1	2.2	1.9	6.2	4.0	4.3
	Na	0.5	1.0	2.8	-	-	-	-	-
	Ca	24.7	56.1	15.5	15.0	22.0	58.2	55.5	46.0
	Mg	10.1	10.7	4.9	6.0	11.0	16.0	19.0	16.0
	CEC	34.6	73.1	23.3	23.0	28.0	48.4	43.0	42.3
Texture, $g\ kg^{-1}$	Sand	837	428	728	858	878	566	755	608
	Silt	52	531	206	43	49	198	147	202
	Clay	111	41	66	99	73	236	99	190
Others	pH-H_2O (1:2.5)	5.5	5.7	5.2	5.8	6.2	6.8	6.9	6.5
	P-Bray-I ($mg\ kg^{-1}$)	5.0	3.0	4.5	15.0	6.0	37.8	9.6	5.0

Dry matter (DM) yields of storage roots and aboveground biomass (stem and leaves) were measured at final harvest on a harvest plot of 5.12 m^2 (eight plant stands) per experimental plot excluding the two border rows. Sub-samples of each harvested plant part (leaf, stem, roots) of each treatment were oven-dried at 70^{o}C to constant weight and DM mass fractions were determined. Dried plant organs were ground and digested using a H_2SO_4 – salicylic acid – H_2O_2 – Selenium mixture. Total N concentration was measured in this extract using a colorimetric method based on Berthelot's reaction (Sommer et al. 1992), total P concentration based on the method of the molybdo-phosphate complex with ascorbic acid as a reducing agent and K concentration by atomic absorption spectrophotometry using the Perkin Elmer model Analyst 400 (Houba 1995).

3.2.1.2. Yield prediction procedure of the original QUEFTS model

The prediction of crop yield in response to nutrient supplies by QUEFTS follows four main steps (Janssen and Guiking 1990; Janssen et al. 1990). Step 1: the nutrient supply from soil and inputs of organic materials or fertilizer is estimated. Step 2: the actual uptake of a nutrient is calculated as a function of the total supply of that nutrient, and the interaction with the two other macronutrients; Step 3: for each nutrient uptake, two yields are calculated by the model, one corresponding to a situation where the nutrient is maximally diluted in the crop, and another one corresponding to a situation of maximum accumulation of that nutrient in the crop. Step 4: using the yield ranges defined in Step 3, the yield is calculated for each pair of nutrients, and the average yield of all pairs of nutrients is retained as the final yield estimate of the crop. These yields are calculated considering the climate and location specific maximum yield of the cultivar as boundary condition.

3.2.1.3. Calibration of QUEFTS for cassava

This section summarises the procedures for calibrating each of the four steps of QUEFTS for the purpose of this study.

3.2.1.3.1. Assessment of soil and input supplies of available nutrients (Step1)

The supply of the total available nutrient (denoted as $TA\beta$ for a given nutrient β) for the crop was estimated from the supply of soil available nutrients ($SA\beta$) and the supply from fertilizer inputs ($SI\beta$) as follows:

$$TA\beta = SA\beta + SI\beta \text{ with } SI\beta = MRF\beta \times I\beta \quad \text{(Eq. 3.1)}$$

Where $TA\beta$ is the total amount of available β; β stands for a given nutrient (N, P or K); *MRF* for the apparent maximum recovery fraction of that nutrient; *I* the amount of input (fertilizer nutrient) applied.

We first used the original equations of QUEFTS (Janssen et al. 1990) and its modified version by Sattari et al. (2014) for assessing $SA\beta$ values based on initial soil chemical properties comprising pH, SOC, available P and exchangeable K (measured before planting). This resulted in $SA\beta$ estimates varying between 10 and 250% of the observed values (not shown). Subsequently, the values of $SA\beta$ and $SI\beta$ were graphically determined by plotting the measured maximum uptake (*y* axis) against fertilizer application rates (*x* axis) of a given nutrient. All treatments with the same application rate of the relevant nutrient were used to calculate $SA\beta$ and $SI\beta$. For instance, the treatments assessed at 0 kg N ha^{-1} were 0-0-0 and 0-40-130; at 40 kg N, these were 40-20-65 and 40-40-130; at 80 kg N ha^{-1}, these were 80-0-130, 80-20-130, 80-40-0, 80-40-65 and 80-40-130. Among these treatments, the nutrient uptake in the treatment with the highest yield was taken as a proxy for $SA\beta + SI\beta$, as the relevant nutrient was expected to be more limiting in this treatment than in the others. In addition, various percentiles (75th and 87.5th) of the distribution of N, P and K uptakes were tested, as well as nutrient uptake in the treatments theoretically most appropriate for the purpose (e.g. 0-40-130, 40-40-130 and 80-40-130 for N). This was done per replicate as well as for the average of the four replicates. After these tests, it was decided to take the 75th percentile uptake found in all treatments with an equal application of the relevant nutrient. This selection was based on the fit between measured nutrient uptake and actual nutrient uptake calculated in Step 2 of QUEFTS (Section 3.2.1.3.2). Where only two treatments could be compared (e.g. 0-0-0 and 0-40-130), the 75th percentile equalled: $L + 0.75 \times (H\text{-}L)$, where L and H stand for the lower and the higher value found in the two treatments. Plotting the calculated nutrient uptake (y-axis) versus the fertilizer application rates of a nutrient (x-axis) provided a linear regression of which the value of the intercept with the y-axis was used as *SAβ*, and the slope was considered as *MRFβ*.

3.2.1.3.2. Actual uptake in relation to supply of nutrients (Step 2)

To calculate the uptake of each of the three nutrients, the original procedure of QUEFTS was followed (Janssen et al. 1990; Sattari et al. 2014). The uptake of nutrient 1 is calculated twice: i) as a function of the supplies of nutrients 1 and 2, and ii) as a function of the supplies of nutrients 1 and 3. The lesser of the two outcomes is considered more realistic and referred to as 'actual uptake'. Actual uptakes were calculated for each site based on specific *SAβ* and *SIβ* values, and compared to the observed uptakes.

3.2.1.3.3. Relations between yield and nutrient uptake (Steps 3 and 4 of QUEFTS)

In Step 3, actual nutrient uptake is converted into estimates of yield ranges based on the minimum and maximum *PhE* of the relevant nutrient. Two approaches were tested to derive the minimum and maximum *PhE* values from the model calibration dataset. The first approach (Approach 1) consisted of plotting observed nutrient uptake (*Uβ*) in storage roots and tops (leaves plus stems) against observed storage root yield (*Y*), and to determine upper and lower boundary lines (Byju et al. 2012; Janssen et al. 1990; Pathak et al. 2003; Witt et al. 1999). Following Witt et al. (1999), boundary lines for yields at maximum dilution (Y_d) and maximum accumulation (Y_a) were drawn based on data within the upper and lower 2.5 percentiles, respectively. The ratio of $Y\beta_d/U\beta$ represents the maximum *PhE* (*PhEmax*), and the ratio $Y\beta_a/U\beta$ the minimum *PhE* (*PhEmin*) of a given nutrient *β*. As recommended by several studies (Byju et al. 2012; Witt et al. 1999), to ensure that crop growth was mainly limited by nutrients, observations with an *HI* less than 0.40 were removed (six observations were removed, corresponding to 2.5% of the dataset with in total 240 observations). It was assumed that the intercepts of the boundary lines with the x-axis, describing the minimum nutrient uptakes required to produce measurable yield (Janssen et al. 1990) were nil since even the smallest nutrient uptakes values in our dataset were enough to produce storage roots yields.

The alternative approach (Approach 2) to derive *PhEmin* and *PhEmax* was introduced recently for situations with strongly varying values of *HI* (Sattari et al. 2014). For cassava it holds:

$$HI = Mass_{roots} / (Mass_{roots} + Mass_{tops}) = Mass_{roots} / Mass_{total} \quad \text{(Eq. 3.2)}$$

where $Mass_{roots,}$ $Mass_{tops}$ *and* $Mass_{total}$ stand for roots mass, tops mass and total biomass respectively. $Mass_{total}$ is the sum of roots and tops masses.

Total uptake of a nutrient ($U\beta$) is:

$U\beta = (Mass_{roots} \times C\beta_{roots} + Mass_{tops} \times C\beta_{tops})/1000$ or

$$U\beta = [HI \times Mass_{total} \times C\beta_{roots} + (1 - HI) \times Mass_{total} \times C\beta_{tops}]/1000 \quad \text{(Eq. 3.3)}$$

where $C\beta_{roots}$ and $C\beta_{tops}$ are the mass fractions (g nutrient kg^{-1} DM) in cassava roots and tops, respectively, and $U\beta$ is expressed in kg β per ha. 1000 is a conversion factor from g to kg.

$PhE\beta$, expressed in kg DM kg^{-1} nutrient, is:

$$PhE\beta = Mass_{roots} / U\beta = HI \times Mass_{total} / U\beta \quad \text{(Eq. 3.4)}$$

Substitution of Eq. 3.3 in Eq. 3.4 yields:

$$PhE\beta = 1000 \text{ x } HI / (HI \times C\beta_{roots} + (1 - HI) \times C\beta_{tops}) \quad \text{(Eq. 3.5)}$$

PhEmax and *PhEmin* values can be calculated as:

$$PhE\beta max = 1000 \text{ x } HI/(HI \times C\beta_{roots,min} + (1 - HI) \times C\beta_{tops,min}) \quad \text{(Eq. 3.6)}$$

$$PhE\beta min = 1000 \text{ x } HI/(HI \times C\beta_{roots,max} + (1 - HI) \times C\beta_{tops,max}) \quad \text{(Eq. 3.7)}$$

where $C\beta_{min}$ and $C\beta_{max}$ denote the minimum and maximum values of mass fractions (g kg^{-1}) of a given nutrient. These values were obtained either from literature (Nijhof 1987) or derived from our model calibration experiments. We used $C\beta_{min}$ and $C\beta_{max}$ values of the entire dataset (model calibration experiments) to calculate *PhEmax* and *PhEmin,* since *PhE* is assumed to be crop specific but not cultivar specific (Witt et al. 1999).

The two approaches to derive *PhEmin* and *PhEmax* values were tested based on the assumption that the best approach will provide the most accurate estimate of the yield if the estimates of the uptake of N, P and K are accurate (good fit between calculated and observed uptake of N, P and K). On that basis, Steps 3 and 4 were run to calculate yields with observed uptake of N, P and K as input variables, and subsequently the calculated yields were compared with observed yields. The approach providing the most accurate estimates of observed yields was applied in Step 2 of QUEFTS to calculate actual uptakes as a function of supplies. The medium *PhE* denoted as *PhEmed*, was calculated as the average value between *PhEmax* and *PhEmin*. As a climate and location specific maximum yield of the cultivar of interest, required as a boundary condition to run QUEFTS, the maximum yields obtained per site for each of the two growing seasons in the model calibration experiments were used.

3.2.2. Model testing

Data collected in two additional on-farm fertilizer trials in Togo and Ghana were used to test model performance. Different rates of NPK fertilizers (kg ha^{-1}) were used: 0-0-0, 20-10-80, 40-20-65, 60-25-120 and 100-40-150 at Davié-Tekpo, Gbave and Sevekpota in Southern Togo, and NPK: 0-0-0, 48-0-95, 68-28-155, 82-28-155, 98-55-183 in Savelugu and Gbanlahi in Northern Region of Ghana. Fertilizer applications methods were the same as in the experiments described above. Except for Sevekpota where individual farmers hosted a single replicate of the 5 treatments (7 farmers in total), each farmer field at the other locations had four replicates laid out following a RCBD. Planting density followed recommended practices of each area. Healthy cuttings of 'Gbazekoute' cultivar were planted April 26, 2010 in southern Togo at a density of 15625 plant ha^{-1} (0.8×0.8 m on 6.0×5.6 m sub-plots), and the storage roots were harvested March 22, 2011. In Ghana, the planting of Afisiafi cultivar cuttings was performed on June 21, 2011 in Gbanlahi and on June 22, 2011 in Savelugu at a density of 10000 plant ha^{-1} (1.0×1.0 m on 7.0×7.0 m sub-plots) and the harvest on December 18, 2012 and December 12, 2012 respectively. Data were collected on dry matter yields of storage roots, stems and leaves at all sites, and soil chemical data (obtained as described above in Section 3.2.1.1) from the Togolese sites only (Table 3.2).

The performance of the model was tested using the *PhEmin* and *PhEmax* values found to be best in the comparison of the two approaches (Section 3.2.1.3.3.). We assessed how well the model estimates cassava yield response to mineral fertilizer rates when *SAβ* was assumed well estimated. Since no plant chemical data and no minus one fertilizer nutrient treatments (nutrient omission treatments) were available in the model testing experiment, *SAβ* values were derived from control plots (no fertilizer plots) at each site. For this reason, yield from control plots were excluded when testing the model performance. The values of *SAβ* obtained in the model calibration experiments were used as starting values. These starting values of *SAβ* were subsequently adjusted until good agreements were found between calculated and observed yields on the control plots. After *SAβ* values were obtained, the model's ability to estimate cassava yield in response to fertilizer applications was evaluated using the treatments that did receive fertilizer in the model testing trials. The evaluation was done first with *MRF* values derived from the model calibration trials. In following runs, *MRF* values were adjusted per site to test model sensitivity to *MRF* values and their effects on yield predictions of the model. Model calculations were compared to observations using: the

Root Mean Squared Error (*RMSE*), the Normalised Root Mean Squared Error (*NRMSE)(Loague and Green 1991)*, the Willmott index of agreement (Willmott et al. 1985), the comparison with the *1:1* line, and the coefficient of determination (R^2) and the regression line slope. Differences between sites in observed yields and uptake of N, P and K were quantified using linear mixed models, with site as fixed factor, and year and block as random factors. The analysis of the differences in yields and uptake of N, P and K between years was done per site using general linear models. A probability threshold P of 0.05 was used in all analyses to assess significance.

3.3. Results

3.3.1. Model calibration

3.3.1.1. Measured cassava storage roots yield and nutrient uptake

Storage roots yields (± standard deviation) significantly differed between sites ($P < 0.001$) when averaged over all 10 treatments in the model calibration experiments, and amounted 13248±3144, 10544±3591 and 6538±2228 kg ha^{-1} in Davié, Kumasi and Nyankpala, respectively. Yields obtained in 2008 were larger than those achieved in 2007 at Davié (14043 *vs* 12453 kg ha^{-1} respectively, $P = 0.023$) and at Nyankpala (7745 *vs* 5331 kg ha^{-1} respectively, $P < 0.001$) (Fig. 3.1); higher yields were also obtained in 2008 than in 2009 in Kumasi (13269 *vs* 7749 kg ha^{-1} respectively, $P < 0.001$). The amount of rainfall during the growing season was higher in 2008 compared to 2007 in Davié and Nyankpala, and to 2009 in Kumasi (Table 3.1). Differences in nutrient uptakes between seasons reflected yields (Fig. 3.1). The largest total N and P uptake was found in Davié ($P < 0.001$) and the smallest in Nyankpala, whereas the smallest K uptake was obtained in Kumasi and the largest in Davié ($P < 0.001$). Averaged over all 10 treatments and growing seasons, total nutrient uptakes (± standard deviation) per growing season were 196.3±62.4 kg N, 33.3±10.8 kg P and 152.7±69.9 kg K ha^{-1} in Davié, 100.8±26.9 kg N, 22.3±6.8 kg P and 68.0±24.4 kg K ha^{-1} in Kumasi, 103.5±35.5 kg N, 17.1±6.4 kg P and 121.1±47.4 kg K ha^{-1} in Nyankpala.

3.3.1.2. Supply of available soil and fertilizer nutrients (Step 1)

Initial soil properties (Table 3.2) resulted in *SAβ* and *MRFβ* values that differed between sites (Table 3.3), especially for N and K. The *SAβ* of N (*SAN*) decreased in the order of Davié > Kumasi > Nyankpala. Similarly, *SAβ* of K (*SAK*) decreased in the order of Nyankpala > Davié > Kumasi. The variation in *SAP* (*SAβ* for P) between sites was small, since all three sites had soils with a low available P status (Table 3.2) according to Howeler (2002).

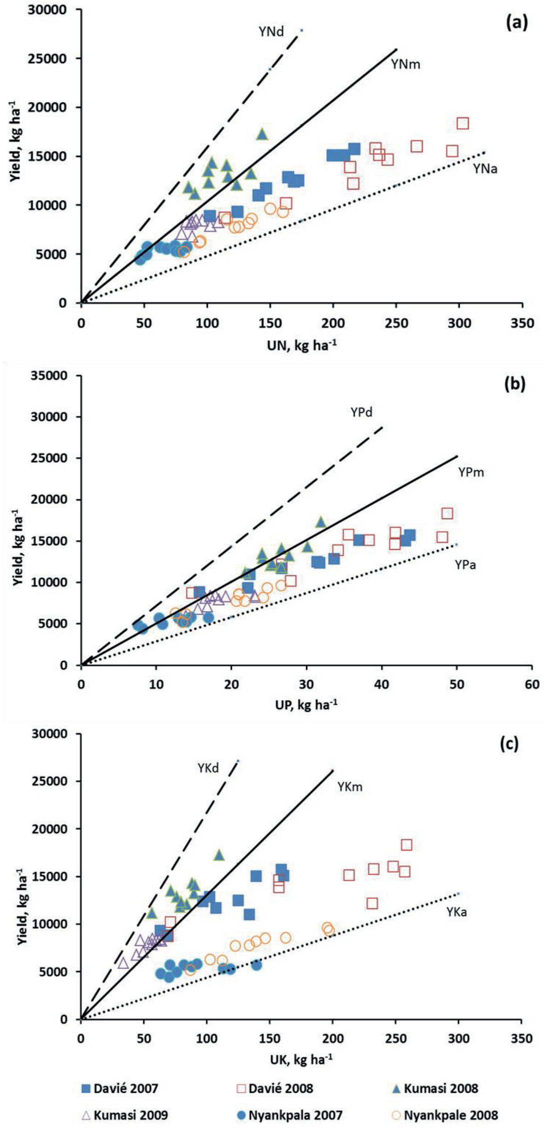

Fig. 3.1. Relationships between N, P and K uptakes and roots DM yields, and the estimated yields at maximum dilution and maximum accumulation of a nutrient (*Yβd* and *Yβa*), and the medium value between *Yβd* and *Yβa (Yβm)*. Each point represents the average value of four replicates. Data from all the treatments (10 fertilizer combinations) of the model parameterisation experiment are included. The dry matter of cassava was on average 38% and 36% of fresh matter for Gbazekoute and Afisiafi respectively.

Table 3.3. R^2 values of linear regression equations relating maximum nutrient uptake to the rate of applied nutrients, the maximum recovery fractions (*MRF*) and the soil supply of available nutrients ($SA\beta$) derived from the regression analyses. Maximum uptake was calculated as the 75th percentile of the uptakes of the plots with the same application rate of the relevant nutrient.

Variables	Davié			Kumasi			Nyankpala		
	N	P	K	N	P	K	N	P	K
R^2	0.886	0.895	0.997	0.752	0.960	0.669	0.998	0.994	0.721
MRF, %	69	44	105	33	15	10	49	3	33
$SA\beta$, kg ha^{-1}	177	24	70	94	21	65	86	18	104

In Davié, MRF for K was very large (Table 3.3), confirming soil K deficiency there. However, a MRF for K above 100% was not expected, though this phenomenon has also been reported by Pellet and El-Sharkawy (1997) as the result of the ability of the crop to remove large amounts of K from the soil. MRF values at Kumasi were very small, suggesting limited external nutrient uptake and little nutrient limitations for cassava production. The SOC content on this site was larger than elsewhere (Table 3.2). The smaller MRF for K at Nyankpala with a larger exchangeable K content when compared to Davié was expected. No strong relationship was found between SAβ and measured soil parameters (not shown). The use of the equations described in the original QUEFTS (Janssen et al. 1990) and its modified version (Sattari et al. 2014) to assess SAβ for cassava also resulted in SAβ values that were generally well below measured uptakes (not shown).

3.3.1.3. Actual nutrient uptake in relation to the total supply of nutrients (Step 2)

Nutrient uptakes calculated with Step 2 of QUEFTS were in good agreement with the measured uptakes of N, P and K as indicated by the value of the slope of the regression line and R^2 close to 1 (Fig. 3.2). Regression analyses for each site separately gave slightly smaller R^2 values (not shown) than a single analysis for all sites together.

3.3.1.4. Physiological nutrient use efficiency (Steps 3 and 4)

The two approaches for deriving *PhEmin* and *PhEmax* are illustrated in Fig. 3.1 (Approach 1, not *HI* related) and Fig. 3.3 (Approach 2, *HI* related). In Approach 1, *PhEmin* and *PhEmax* values (Fig. 3.1) represent 2.5 and 97.5th percentiles of all points and correspond to the boundary line for maximum accumulation (Y_a) and for maximum dilution (Y_d) respectively. The six site/year combinations have different positions in the envelopes, with Kumasi 2008 being closer to the boundary line for maximum dilution (Y_d) for N (Fig. 3.1a) and K (Fig. 3.1c), and Nyankpala closer to the boundary line of maximum accumulation (Y_a), especially for K. The points in the scatter graph of P uptake and roots yield (Fig. 3.1b) are closer together than those for N and K (Figs 3.1a and 3.1c, respectively), especially at low P uptake.

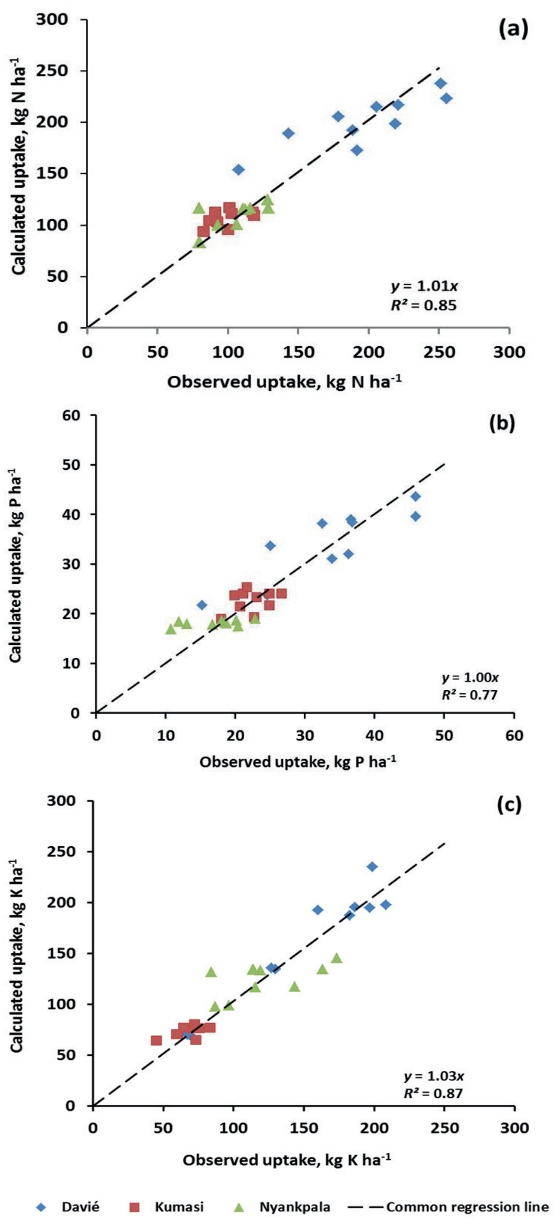

Fig. 3.2. Uptake of N (a), P (b) and K (c) as calculated in Step 2 in relation to observed uptake, and the associated regression line. Input variables for Step 2 were the soil and input supplies of nutrients estimated in Step 1. Each point represents the average observed uptake of eight values (four replicates, two seasons).

In Approach 2, the *HI* and minimum and maximum mass fractions in roots and tops (Table 3.4) were used in Eqs. 3.6 and 3.7 to derive *PhEmax* and *PhEmin* (Table 3.5). Measured root nutrient mass fractions were generally within the ranges given by Nijhof (1987). Fig. 3.3 shows that *PhE* varies with *HI* across sites and years. It also shows that *PhE* of N was small compared with literature since all points are situated between *PhEmed* and *PhEmin* of Nijhof (1987). Fig. 3.3 also shows that *PhE* of P is within a comparable range across the three sites, and that *PhE* of K is generally large at Davié and Kumasi but small at Nyankpala, pointing out large K supply at the latter site. Furthermore, the largest values of *PhE* of K were achieved at high *HI* values, and *vice versa*, indicating that *PhE* of K increases with *HI*.

The comparison of the two approaches to determine *PhEmin* and *PhEmax* suggested that Approach 2 worked better at Davié and Kumasi (Table 3.6). Although the performances of the two approaches were comparable in terms of R^2, Approach 2 provided more accuracy in the prediction with smaller *RMSE* and *NRMSE*, and a *Willmott index* closer to 1. These results stress the importance of accounting for the influence of *HI* on *PhEmax* and *PhEmin* in predicting cassava yields.

Model performance was best for Davié with calculated and observed yields scattered around the 1:1 line and poorest for Nyankpala with an overestimation of observed yields by the model (Fig. 3.4). Since average values of *HI* were used by QUEFTS whereas *HI* varied over seasons, observed yields were overestimated in case the real *HI* was smaller than the average *HI*, and underestimated in case the real *HI* was larger than the average *HI*. At Nyankpala, calculated yields were much larger than observed yields (Figs 3.4 and 3.5). This is in agreement with the low *PhE* values observed at this site, which suggests an inefficient use and luxury uptake of nutrients. Planting was late in Nyankpala in the first year (June 29, 2007), whereas the rainy season ran from April to October, meaning that the crop benefited from four months of rain at most. The second half of the growing season the crop likely suffered from drought, causing a low *PhE*.

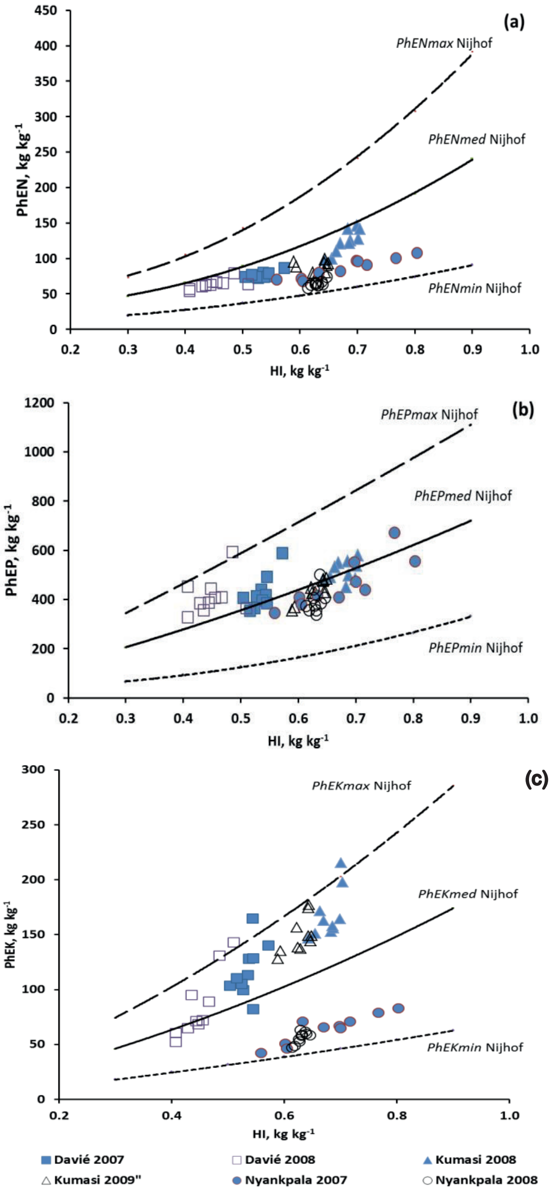

Fig. 3.3. Physiological nutrient use efficiency (*PhE*) of N, P and K in relation to harvest index (*HI*). PhEmax and PhEmin represent physiological nutrient use efficiency at maximum dilution and maximum accumulation, respectively, and PhEmed the medium value between PhEmax and PhEmin. Each point is calculated with Eq. 3.6, Eq. 3.7 and measured nutrient mass fractions of both cultivars combined (Table 3.4). It represents the average of four replicates. Nijhof curves were also based on these equations, but with nutrient mass fractions from Nijhof (1987) (Table 3.4).

Table 3.4. Ranges between 2.5th and 97.5th percentiles of nutrient mass fractions (g nutrient kg^{-1} DM) in cassava roots and tops, as found in literature (Nijhof 1987) and in the present study for each cultivar and both cultivars combined.

Source	Roots			Tops		
	N	P	K	N	P	K
Nijhof	2.0 – 9.0	0.8 - 2.4	3.0 – 14.0	5.0 – 18.0	0.9 -5.5	4.5- 18.0
Gbazekoute	2.8 – 5.1	0.7– 1.7	2.8 – 7.7	7.9 – 12.8	0.9 – 1.7	3.5 – 9.5
Afisiasi	2.5 – 6.9	0.8 – 1.5	3.0 – 11.0	7.9 – 18.4	1.2- 2.8	3.4 – 19.8
Both cultivars	2.5 – 6.6	0.8 – 1.5	2.8 – 11.0	7.9 – 17.9	0.9 – 2.8	3.4 – 18.8

Table 3.5. The *HI* and the corresponding *PhEmin* and *PhEmax* used in model calculations. The abbreviations par and ver stand for parameterisation and verification experiments. To allow comparison with values found in India (Byju et al. 2012), *PhE* values were also calculated for a hypothetical cultivar with an *HI* of 0.40.

Cultivar	*HI*	*PhEmin*			*PhEmax*		
		N	P	K	N	P	K
Gbazekoute-par	0.50	41	232	34	96	589	160
Gbazekoute-ver	0.55	47	262	38	112	653	178
Afisiafi-par	0.65	61	329	47	148	782	214
Afisiafi-ver	0.70	70	365	53	170	848	233
Hypothetical	0.40	30	175	26	70	465	126
India	0.40	35	250	32	80	750	102

Table 3.6. The ability of QUEFTS to predict observed yields using two different approaches to derive *PhEmin* and *PhEmax*. Slope and R^2 are relative to the linear regression line between calculated (y-axis) and measured (x-axis) yields. The number of observations per site was 20, with replicates averaged per season.

***PhE* boundary lines approaches**	**Parameter**	**Davié**	**Nyankpala**	**Kumasi**
Approach 1: Yield to uptake ratio	*Slope*	1.28	1.42	0.86
	R^2	0.84	0.85	0.69
	RMSE (kg ha^{-1})	4226	3046	1843
	NMSE (%)	32	47	18
	Willmott's index	0.742	0.690	0.872
Approach 2: *HI* related *PhEmin* & *PhEmax*	*Slope*	1.00	1.55	0.95
	R^2	0.82	0.85	0.67
	RMSE (kg ha^{-1})	1702	3941	1354
	NMSE (%)	13	60	13
	Willmott's index	0.932	0.604	0.930

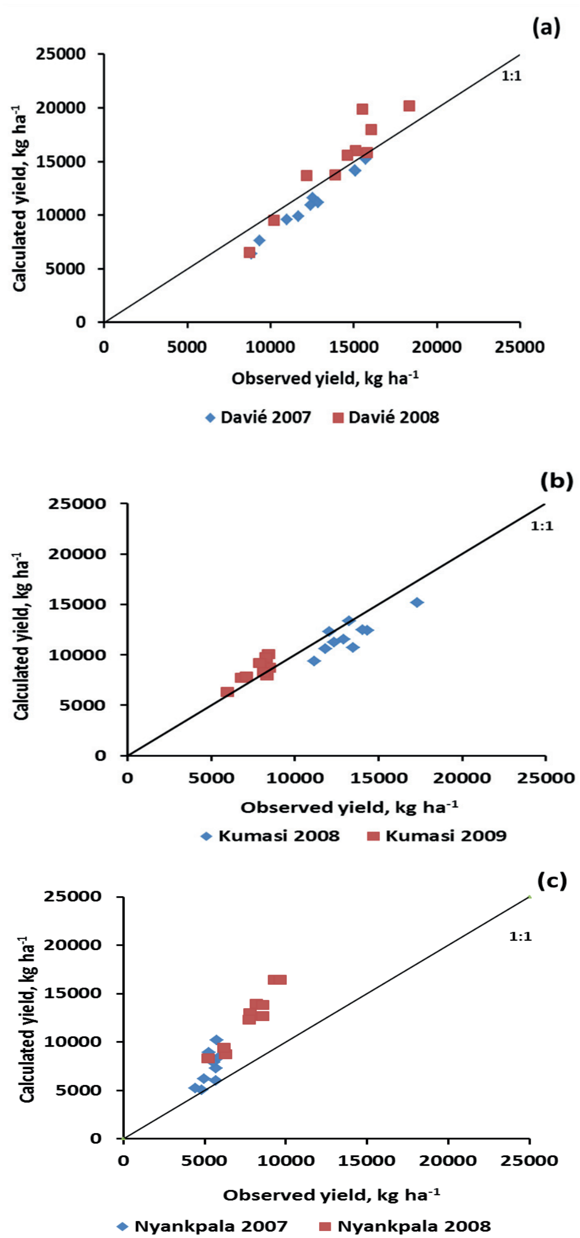

Fig. 3.4. Relations between yields calculated with Step 3 and 4 of QUEFTS using *HI* related *PhE* boundary lines (Approach 2) and observed yields for Davié (a), Kumasi (b) and Nyankpala (c). Input variables for Step 3 were the observed nutrient uptakes. *HI* values were set at 0.50 for Davié and at 0.65 for Kumasi and Nyankpala. Each point represents the average yield of four replicates.

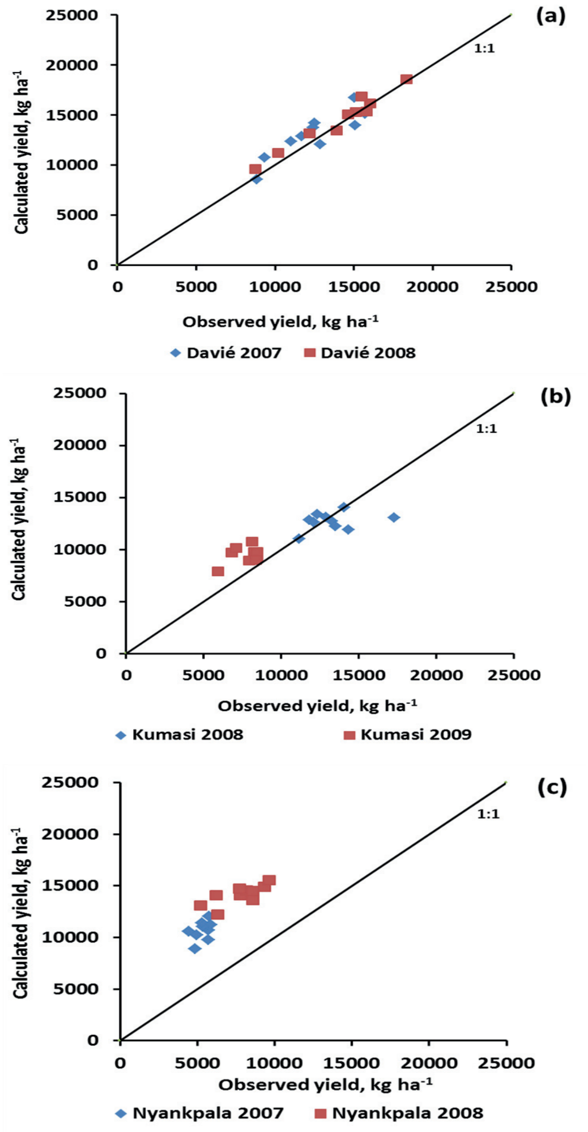

Fig. 3.5. Yields calculated on the basis of estimated soil and input supplies of nutrients in relation to observed yields in Davié (a), Kumasi (b) and Nyankpala (c). Each point represents the average yield of four replicates.

The comparison of *PhE* values using an hypothetical cultivar with an *HI* value of 0.4 (Table 3.5) to those reported under Indian agro-ecological conditions by Byju et al. (2012) revealed that *PhE* values are higher in India, especially for P, pointing to stronger P dilution than in West Africa. Only *PhE*K*max* was higher in West Africa, reflecting poor K availability, which was especially evident on the Ferralsols in Davié (Fig. 3.3).

3.3.1.5. Yields in relation to the total supply of available nutrients (Steps 1 - 4)

Using the calibrated QUEFTS (*PhEmin*, *PhEmax* and *HI*; Table 3.5), *SAβ* and *MRF* values (Table 3.3), the best fit between observed and simulated yields were obtained at Davié (Fig. 3.5). At Kumasi, simulated and observed yields agreed better in 2008 than in 2009 (Fig. 3.5) when observed yields were smaller than calculated yields. The smaller observed yields in 2009 compared to 2008 were likely due to smaller amounts and inadequate distribution of rainfall in 2008. About 49% of total rainfall in the growing season (Table 3.1) occurred in the first month after planting (not shown). Most of this water was likely lost through evaporation as soil coverage by cassava was small in the first month after planting. At Nyankpala, calculated yields were strongly overestimated in both years (Figs 3.4 & 3.5). As suggested above, the growth conditions in Nyankpala during the first part of the growing seasons allowed the crop to take up available nutrients, while drought likely limited growth later in the season, strongly affecting root biomass.

3.3.2. Model testing

Calculated yields agreed well with observed yields (Fig. 3.6). This indicates that the model can effectively estimate cassava response to fertilizer N, P and K (Fig. 3.6a), provided that *SAβ* values are estimated in such a way to adequately assess yields on control plots. However, the use of site specific *MRF* values improved the similarity (Fig. 3.6b), indicating that the difference between calculated and observed yields were at least partly due to differences in *MRF* values between sites.

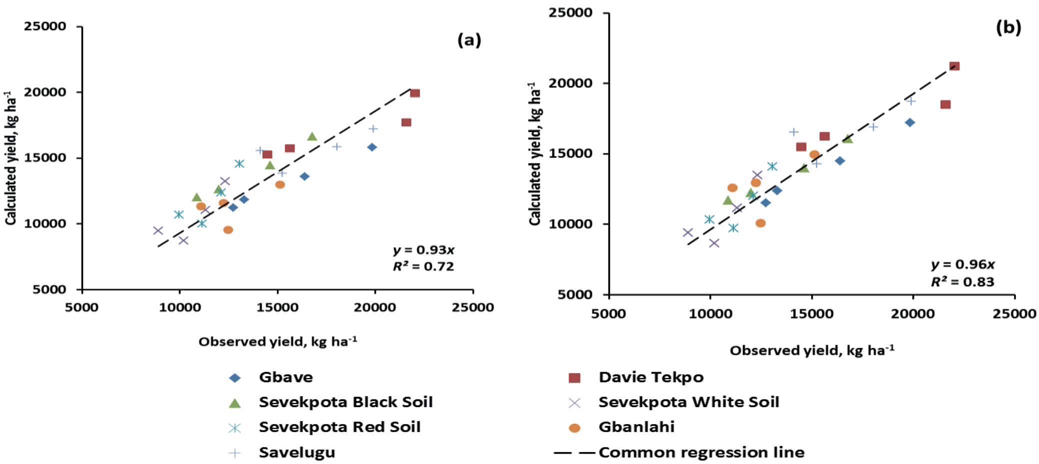

Fig. 3.6. Calculated yields in relation to observed yields in the model verification trials with common *MRF* values (a) or adjusted per site (b). Input variables for Step 1 were estimated soil supplies of available nutrients of Table 3.7 and maximum recovery fractions of Table 3.3 (Fig. 3.6a) and Table 3.7 (Fig. 3.6b). Each point represents the average yield of two to five replicates.

Table 3.7. Soil supplies of available N, P and K (*SAβ*), yields from control plots without fertilizer application (Y_0) in the verification experiment, and the apparent maximum recovery fractions of fertilizer nutrients (*MRFβ*) estimated with the help of the model (Table 3.5).

Sites	Y_0	*SAβ*, kg ha^{-1}			*MRFβ*		
	kg ha^{-1}	N	P	K	N	P	K
Gbave	7682	170	23	67	0.95	0.60	0.95
Davié Tekpo	11801	250	34	99	0.95	0.60	0.95
Sevekpota Black Soil	8728	186	25	74	0.69	0.44	0.80
Sevekpota White Soil	5752	122	17	48	0.81	0.51	0.80
Sevekpota Red Soil	6927	147	20	58	0.69	0.44	0.80
Average Togo	*8178*	*175*	*24*	*69*	*0.82*	*0.52*	*0.86*
Gbanlahi	7955	74	15	89	0.69	0.21	0.46
Savelegu	12190	113	24	136	0.64	0.20	0.43
Average Ghana	*10073*	*93*	*20*	*113*	*0.66*	*0.20*	*0.45*
General average	*9125*	*134*	*22*	*91*	*0.74*	*0.36*	*0.65*

3.4. Discussion

This paper showed that the model can accurately estimate cassava yields when *SAβ* and *MRFβ* are accurately assessed and that *PhEβ* is estimated based on *HI* in areas where *HI* is very variable. The use of equations in the original (Janssen and Guiking 1990) and modified (Sattari et al. 2014) versions of QUEFTS underestimated *SAβ* because such relationships were described for non-irrigated cereal crops. There are two probable causes why the QUEFTS equations did not work for cassava. Firstly, the growth period of cassava is much longer than that of cereals, allowing nutrient uptake over a prolonged period. Secondly, cassava is more effective than cereals in the uptake of P from P-limited soils due to cassava's strong mycorrhizal symbiosis in its roots (Kang and Okeke 1984; Sieverding and Leihner 1984).

The derivation of *SAβ* from graphs of the measured maximum uptakes versus the application rate of the concerned nutrient provided a better estimate of *SAβ*. Estimated *SAβ* values reflected differences between sites, especially for N and K. The largest value of *SAβ* for N (*SAN*) was obtained at Davié, rather than Kumasi which had larger SOC, because Kumasi had larger *PhE* N for the same amount of N uptake (Fig 3.1a). The highest *SAK* was estimated at Nyankpala, because of the high availability of K in the soil (Table 3.2). Similar *SAP* values were obtained across all sites since all sites were poor in available P.

Estimated *MRF* values reflected soil nutrient availability across sites. The strong K deficiency explained the high *MRF* of K at Davié. The large SOC at Kumasi with large soil N supply resulted in a relatively small *MRF* of N at this site. The *MRF* of P varied across sites, with the smallest value obtained at Nyankpala and the largest at Davié. Since all sites had soils with low available P, the difference in *MRF* of P may be attributed to differences in P requirements to meet the yield potential across sites, and to mycorrhizal enhancing effects on P use efficiency of cassava (Kang and Okeke 1984; Sieverding and Leihner 1984).

The evaluation of the relationships between nutrient uptakes and yields of cassava showed that accurate estimates of nutrient uptakes resulted in accurate assessments of yields in Davié and Kumasi (Fig. 3.4). This suggests that relationships characterized by *PhEmax*, *PhEmin* and *HI* (Equations 3.6 and 3.7) provided a satisfying description of reality. The situation was different at Nyankpala where QUEFTS-calculated yields were one and a half times larger than observed yields, which can be ascribed to the occurrence of drought while the crop was still in the active vegetative stage (Alves 2002). This can also be attributed to nutrient deficiencies (other than N, P and K): the small concentration of magnesium (4.9 mmol kg^{-1}) below the critical value of 6.0 mmol kg^{-1} for cassava (Snapp 1998), could have contributed to the overall weak response of cassava at this site. Strong yield responses to magnesium were obtained in Colombia on depleted soils (CIAT 1985).

The comparison of the studied cultivars with the Indian cultivars used by Byju et al. (2012) on the basis of an *HI* value of 0.40 revealed that our cultivars had lower *PhEmax* for P and higher *PhEmax* for K (Table 3.5). In other words they diluted less P and more K than the Indian cultivars. This suggests that the physiological use efficiency of P can be further improved in West Africa. It also suggests that K deficiency is apparent at the study sites, such as on the Ferralsols in Davié, as also demonstrated in Southern Benin (Carsky and Toukourou 2005).

Calculated yields were close to observed values in the model testing experiments (Fig. 3.6). With *SAβ* estimates set at a value that QUEFTS compared best to observed control plot yields, the model was able to properly predict cassava responses to combined N, P and K applications. The absence of plant and soil chemical analyses data to derive *SAβ* is common in sub-Saharan Africa. The method used in this paper of deriving *SAβ* from control plots without fertilizer can be used when observed yield data from these plots are available. In case yields and plant N, P and K content data from nutrient omission trials (Dobermann et al. 2002; Witt et al. 1999) are available (but no soil chemical data), the method used in the model parameterization trial in this paper can also be applied. However, the availability of plant and soil chemical data is fundamental to be able to relate *SAβ* to soil parameters as in Step 1 equations of the original version of QUEFTS. The calculations were further improved by use of site specific *MRF* values (Fig. 3.6b), highlighting the importance of location specific soil nutrient management for cassava production.

3.5. Conclusions

The QUEFTS procedures proved useful to estimate cassava yield and responses to mineral fertilizers under rain-fed conditions in West Africa. In years with normal rainfall, the model calculations produced yield estimates close to those observed, but the model overestimated yields under drought conditions. While the current model could be improved with further model testing experiments in other locations in West Africa and with the development of equations for estimating *SAβ* to cassava based on soil properties, it provides an accurate tool for estimating cassava yield response to fertilizer applications. The strong crop responses to N, P and K highlight the importance of replenishing soil nutrients through external nutrient supplies in cassava production systems. Moreover, our study confirmed the relevance of relating the estimate of *PhE* for maximum accumulation and maximum dilution to *HI* when cultivars with different *HI* are used. Since *PhE* increased with *HI*, plant breeders should work towards developing cultivars with higher *HI* to enhance nutrient use efficiency and yields in cassava production systems in West Africa.

Acknowledgements

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CHAPTER FOUR

4.0. Fertilizer requirements for balanced nutrition of cassava across eight locations in West Africa

Abstract

Insufficient and unbalanced fertilizer use widens cassava yield gaps. We assessed the spatial variability of optimal fertilizer requirements of cassava for enhanced nutrient use efficiency and increased yield using the balanced nutrition approach of the QUEFTS model. We used two datasets comprised of five fertilizer experiments conducted at eight locations across Southern Togo, Southern Ghana and Northern Ghana from 2007 to 2012. The ratio of storage roots dry matter yield over the sum of available N, P and K expressed in crop nutrient equivalent from the soil and nutrient inputs was used as a proxy to estimate nutrient use efficiency. Nutrient use efficiencies of 20.5 and 31.7 kg storage roots dry matter per kilo crop nutrient equivalent were achieved at balanced nutrition at harvest index (*HI*) values of 0.50 and 0.65, respectively. N, P and K supplies of 16.2, 2.7 and 11.5 kg at an *HI* of 0.50, and 10.5, 1.9 and 8.4 kg at an *HI* of 0.65 were required to produce 1000 kg of storage roots dry matter. The corresponding optimal NPK supply ratios are 6.0 – 1.0 – 4.2 and 5.3 – 1.0 – 4.2. Nutrient use efficiencies decreased above yields of 77-93% of the maximum. Evaluation of the performance of blanket fertilizer rates recommended by national research services for cassava production resulted in average benefit:cost ratios of 2.4±0.9, which will be unattractive to many farmers compared to 3.8±1.1 for the balanced fertilizer rates. The indigenous soil supply of nutrients revealed that, at balanced nutrition, K was the most limiting nutrient to achieve storage roots yields up to 8 Mg dry matter ha^{-1} at most sites, whereas N and P were needed at greater yields. Dry weights of storage roots measured on the control plots in our researcher managed experiment ranged from 5.6 to 12.2 Mg ha^{-1}, and were larger than the average weight in farmers' fields in West Africa of 4 Mg ha^{-1}. Substantial yield increase could be attained in the region with improved crop management and fertilizer requirements formulation on the basis of balanced nutrition.

Keywords: *QUEFTS, nutrient use efficiency, crop nutrient equivalent, nitrogen, phosphorus, potassium, harvest index.*

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4.1. Introduction

Cassava (*Manihot esculenta* Crantz) has long been considered a subsistence crop, but is becoming increasingly commercialised. The world production of fresh cassava storage roots increased tremendously from 176 to 277 million Mg between 2000 and 2013 (FAOSTAT 2014). West Africa produces 28% of the world's cassava and the rest of Africa a further 26% (FAOSTAT 2014). The increase in production was achieved through both expansion of the cultivated area and enhanced yields of cassava. Although average yields in West Africa increased between 2000 and 2013 from 9.7 to 13 Mg ha^{-1} of fresh storage roots (FAOSTAT 2014), a large yield gap remains, given that yields close to 60 Mg ha^{-1} have been attained in researcher-managed fields in the region (Odedina et al. 2009).

Plausible reasons for this yield gap are nutrient limitations due to poor soil fertility. In general, fertilizer use on roots and tuber crops in Sub-Saharan Africa is negligible. However, nutrient removal for cassava production is on average 4.5 kg nitrogen (N), 0.83 kg phosphorus (P) and 6.6 kg potassium (K) per 1000 kg dry matter of storage roots (Howeler 1991). The insufficient use of external nutrients leads to soil nutrients depletion (Howeler 2002). Application of external fertilizers is necessary to replenish the soil with nutrients removed through harvested products and exported crop residues. The fertilizer recommendations for cassava production found in most countries in West Africa and elsewhere in SSA are usually blanket recommendations, regardless of agro-ecological or soil diversity. The use of blanket fertilizer recommendations for cassava production is likely to generate unbalanced crop nutrition since cassava is cultivated on diverse soils in West Africa, and soils on farmers' fields are highly heterogeneous (Adjei-Nsiah et al. 2007). Unbalanced nutrition may lead to increased nutrient losses (Cassman et al. 2002), which can hamper the productivity and profitability of the farm (Angus et al. 2004), and cause environmental pollution. Appropriate fertilizer recommendations based on balanced nutrition may contribute to reduce cassava yield gaps.

Balanced nutrition of a given nutrient refers to supplying that nutrient to the plant in accordance with the plant's need while maximizing the use efficiency of this nutrient. When more than one nutrient is considered, e.g. N, P and K together, balanced nutrition refers to the optimization of the use efficiency of these nutrients together giving the strongest response to their supply in congruence with plant needs. The term optimising is used given the difficulty of maximising the use efficiency of several nutrients simultaneously. The method developed by Janssen (Janssen 1998; Janssen 2011) can handle several nutrients simultaneously by assuming that balanced nutrition is achieved when the supplies of all nutrients expressed in crop nutrient equivalent

(CNE) units are equal. As a unit, 1 kilo CNE (kCNE) or 1000 CNE of a nutrient is defined as the quantity of that nutrient that has the same effect on yield as 1 kg of N under conditions of balanced nutrition. The concept of CNE allows summing up the total supply of N, P and K and quantitatively describing balanced nutrition as the situation where the supplies of each of the three nutrients are equal. Both CNE and balanced nutrition concepts were also applied by Maro et al. (2014) for coffee production in Tanzania using QUEFTS model.

The model for the quantitative evaluation of the fertility of tropical soils (QUEFTS) (Janssen et al. 1990) accounts for the interaction between N, P and K to derive the balanced nutrition, which explains its widespread use in tropical agro-ecologies where these nutrients can seriously hinder crop production. Originally developed for maize (Janssen et al. 1992), QUEFTS has been also adapted to rice (Witt et al. 1999; Xu et al. 2013), wheat (Chuan et al. 2013; Pathak et al. 2003), highland banana (Nyombi et al. 2010) apart from coffee. Literature on the balanced nutrition of cassava is scarce, with only one case study from India (Byju et al. 2012). Site-specific fertilizer requirements for balanced nutrition of cassava in the region and their relative performance compared to existing blanket fertilizer rates have yet to be assessed. In this paper we assess the spatial variability in fertilizer requirements of cassava under balanced nutrition conditions in West Africa in order to increase nutrient use efficiency and yields.

4.2. Materials and methods

4.2.1. Field experiments

Two datasets, referred to as Set 1 and Set 2, were used in this study. Set 1 was collected in three field experiments at three locations in southern Togo (Davié), southern Ghana (Kumasi) and northern Ghana (Nyankpala, Table 4.1). The trials were laid out in a randomised complete block design (RCBD) with four blocks at each site containing 10 NPK fertilizer combinations (Table 4.2). N, P and K rates were defined in Set 1 to assess the indigenous supply of nutrients by the soil (S1, S3 and S5 in Table 4.2), as well as the response of the crop to different rates of fertilizers (other treatments). N was applied as urea (46%N, Davié and Kumasi) or sulphate of ammonia (21%N, Nyankpala), P as triple super phosphate (TSP: 20%P) and K as muriate of potash (MOP: 50%K). All the TSP and one third of the urea and MOP were applied 4 weeks after planting, the remaining urea and MOP at 10 weeks after planting. Set 2 was collected in two other field experiments at five locations across southern Togo (Gbave, Davié Tekpo and Sevekpota) and northern Ghana (Gbanlahi and Savelugu) (Table 4.3) in agro-ecological zones that are similar to those in Set 1. Set 2 experiments comprised five NPK fertilizer combinations (Table 4.2).

Table 4.1. Characteristics of the sites in the Set 1 experiments

Site	Davié	Kumasi	Nyankpala
Country, district	Togo, Maritime Region	Ghana, Ashanti Region	Ghana, Northern Region
Geographic coordinates	6.385°N, 1.205°E	6.686°N, 1.622°W	9.396°N, 0.989°W
Altitude (m above sea level)	89	267	170
Soil type	Rhodic ferralsol	Ferric acrisol	Gleyi-ferric lixisol
Agro-ecological zone	Coastal Savannah	Humid Forest	Southern Guinea Savannah
Rainfall distribution	Bi-modal	Bi-modal	Mono-modal
Season* 1	May 10-March 17, 2007-2008	June 28–March 22, 2008-2009	June 29 - Feb. 25, 2007-2008
Season 2	April 26– Feb. 23, 2008-2009	June 15–March 15, 2009-2010	May 23 - Dec. 03, 2008
Rainfall (mm, seasons 1 and 2)	731, 813	986, 938	731, 1017
Cultivar	Gbazekoute**	Afisiafi**	Afisiafi
Planting density (per stem cutting)***	0.8 x 0.8 m	1 x 1 m	1 x 1 m

* Season refers to the period from planting to harvest of the crop. ** Gbazekoute is TME-419; Afisiafi is TME-771. *** Planting schemes follow the recommended densities for cassava in the study sites. These correspond to 15625 and 10000 plants ha^{-1}, respectively for 0.8 x 0.8m and 1 x 1m.

These fertilizer combinations were used to evaluate performance of the QUEFTS model in simulating yields in response to fertilizer applications. At each site, Set 2 experiments were laid out following a RCBD with four blocks in a single field, except for Sevekpota where seven farmers each harboured a single block (replication) of the full set of treatments. Fertilizer was applied in a similar way in both Set 1 and Set 2.

4.2.2. Description, parameterisation and verification of QUEFTS

The original QUEFTS model simulates crop yields in response to nutrient supplies following four steps (Janssen et al., 1990, Janssen and Guiking, 1990). In Step 1, QUEFTS estimates nutrient supplies from soil and inputs of organic materials or fertilizer. In Step 2, the actual uptake of a nutrient is calculated as a function of the total supply of that nutrient, and of the interaction with the two other macronutrients. In Step 3, two yields are calculated by the model for each nutrient uptake, one corresponding to a situation where the nutrient is maximally diluted in the crop, and another one corresponding to a situation of maximum accumulation of that nutrient. The relation between yield and nutrient uptake is indicated by the physiological nutrient use efficiency (*PhE*), which varies between PhEmin and PhEmax. PhEmax represents the situation where the nutrient is maximally diluted in the crop; PhEmin the situation of maximum nutrient accumulation. In Step 4, the yield is calculated for pairs of nutrients (*Y12*, yield in response to nutrient 1 with PhEmin and PhEmax of nutrient 2 as boundary conditions) denoted by *YNP, YNK, YPN, YPK, YKN* and *YKP* using the yield ranges defined in Step 3; the average yield of all pairs of nutrients is retained as the final yield estimate of the crop. In this paper, the calculation of *Y12* was modified in two ways, as compared with the original QUEFTS version. Firstly, the value of the constant *r* representing the minimum nutrient uptake required to produce any grain yield in the equations relating yield (*Y*) to uptake (*U*) was assumed to be zero (Janssen et al. 1990). In our study, *U* was always large enough to produce a yield of cassava storage roots. The second modification refers to imposing a restriction that *Y12* does not exceed *YMAX* nor the minimum value of the yield at maximum dilution of N, P and K (*YdN*, *YdP, YdK*), as recently suggested by Sattari et al., (2014) and Maro et al. (2014). Thus, if *Y12* is greater than *YMAX*, or than *YdN*, *YdP or YdK*, the calculated *Y12* is replaced by the minimum value among *YMAX, YdN, YdP* and *YdK*. *YMAX* is the maximum yield dictated by radiation, water availability and genetic properties of the crop.

Table 4.2. Fertilizer rates applied in Set 1 and 2 experiments.

Experiment	Location	Treatment number	N	P	K
			(kg ha^{-1})		
Set 1	Davié, Kumasi & Nyankpala	S0	0	0	0
		S1	0	40	130
		S2	40	40	130
		S3	80	0	130
		S4	80	20	130
		S5	80	40	0
		S6	80	40	65
		S7	80	40	130
		S8	40	20	65
		S9	100	50	170
Set 2	Gbave, Davié-Tekpo and Sevekpota	S10	0	0	0
		S11	20	10	80
		S12	40	20	65
		S13	60	25	120
		S14	100	40	150
	Savelugu and Gbanli	S15	0	0	0
		S16	48	0	95
		S17	68	28	155
		S18	82	28	155
		S19	98	55	183

Table 4.3. Characteristics of the sites in the Set 2 experiments.

Site	Gbave	Davié Tekpo	Sevekpota	Gbanlahi	Savelugu
Country, district	Togo, Maritime Region	Togo, Maritime Region	Togo, Maritime Region	Ghana, Northern Region	Ghana, Northern Region
Geographic coordinates	6.459° N, 1.586°E	6.385° N, 1.205°E	6.437° N, 0.959°E	9.436°N, 0.755°W	9.641°N, 0.840°W
Altitude (m above sea level)	80	89	121	159	156
Soil type	Rhodic ferralsol	Rhodic ferralsol	Alfisol	Gleyi-ferric lixisol	Gleyi-ferric lixisol
Agro-ecological zone	Coastal Savannah	Coastal Savannah	Coastal Savannah	Southern Guinea Savannah	Southern Guinea Savannah
Rainfall distribution	Bi-modal	Bi-modal	Bi-modal	Mono-modal	Mono-modal
Season (Planting to harvest)	April 26, 2010 to March 22, 2011	April 26, 2010 to March 22, 2011	April 26, 2010 to March 22, 2011	June 21, 2011 to Dec 18, 2012	June 22, 2011 to Dec 12, 2012
Rainfall during the season (mm)	1017	1039	845	1920	1920
Cultivar	Gbazekoute	Gbazekoute	Gbazekoute	Afisiafi	Afisiafi
Planting density (per stem cutting)	0.8 x 0.8 m	0.8 x 0.8 m	0.8 x 0.8 m	1 x 1 m	1 x 1 m

Table 4.4. Harvest index (HI), physiological nutrient use efficiency for maximum accumulation (PhEmin) and maximum dilution (PhEmax), and the conversion factors for P (CFP) and K (CFK) used in model calculations for two cultivars (Gbazekoute and Afisiafi) in Set 1 and Set 2 experiments.

Cultivar	*HI*	*PhEmin*			*PhEmax*			*PhEmed*			CFP	CFK
		N	P	K	N	P	K	N	P	K		
Gbazekoute-Set 1	0.50	41	232	34	96	589	160	69	411	97	0.167	0.706
Gbazekoute-Set 2	0.55	47	262	38	112	653	178	80	458	108	0.174	0.736
Afisiafi-Set 1	0.65	61	329	47	148	782	214	105	556	131	0.188	0.801
Afisiafi-Set 2	0.70	70	365	53	170	848	233	120	607	143	0.198	0.839

Data from Set 1 were used to derive *PhEmax* and *PhEmin* values for each nutrient (Table 4.4). *PhEmin* and *PhEmax* depend on harvest index (*HI*) (Sattari et al. 2014), which is the ratio of the weight of the economic plant component (grain for cereals, and storage roots in the case of cassava in this study) over the weight of the whole plant (total biomass including stems, leaves and storage roots). *PhEmax* and *PhEmin* were obtained using the following equations:

$PhEmax = 1000 \text{ x } HI/(HI \times C_{min,roots} + (1 - HI) \times C_{min,tops})$ (Eq. 4.1)

$PhEmin = 1000 \text{ x } HI/(HI \times C_{max,roots} + (1 - HI) \times C_{max,tops})$ (Eq. 4.2)

C_{min} and C_{max} are the minimum and maximum values of mass fractions (g kg^{-1}) in the roots ($C_{min,roots}$ *and* $C_{max,roots}$) and in the top biomass including stems and leaves ($C_{max,tops}$ and $C_{max,tops}$). C_{min} and C_{max} values of 2.5 and 6.6 for N, 0.8 and 1.5 for P and 2.8 and 11.0 g kg^{-1} for K in the storage roots, and 7.9 and 17.9 for N, 0.9 and 2.8 for P and 3.4 and 18.8 for K in the tops obtained from Set 1 were used.

Set 2 data were used to test the model's ability to estimate observed yields. Soil supplies of available N, P and K (*SAN*, *SAP* and *SAK*) used as input data for model testing are presented in Table 4.5. In Set 1 dataset, *SAN*, *SAP* and *SAK* were calculated as the intercept of the linear regression between the maximum total uptake of the relevant nutrient and the nutrient application rate. The slope of this regression line was considered the maximum recovery fraction (*MRF*), indicating the proportion of the fertilizer nutrient taken up by the crop.

Since no plant chemical data were measured in Set 2 experiments, *SAN*, *SAP* and *SAK* values were estimated by the model from control plots (S10 and S15 in Table 4.2) at each site. *SAN*, *SAP* and *SAK* values obtained in Set 1 experiments were used as starting values. These starting values were subsequently adjusted until good agreements were found between simulated and observed yields on the control plots. After *SAN*, *SAP* and *SAK* values were obtained for Set 2 sites, the model's ability to estimate cassava yield in response to fertilizer applications was evaluated with treatments that did receive fertilizer in Set 2 experiments (S11-14 and S16-19, Table 4.2). This was first implemented with the average *MRF* values derived from Set 1 experiments (Table 4.5). In following runs, *MRF* values were adjusted per site to achieve good agreement between observed and QUEFTS calculated yields (Table 4.5).

This adjustment of *MRF* values was implemented to check the need of site-specific *MRF* values and its influence on the model's performance.

4.2.3. Determination of balanced nutrition

The prerequisite for balanced nutrition assessment is the conversion of kg of N, P and K into crop nutrient equivalent (CNE), assuming that balanced nutrition is achieved when the supplies of these nutrients, expressed in CNE , become equal to each other. The conversion is based on the average or medium value of *PhE* denoted by *PhEmed*. *PhEmed* equals *(PhEmax +PhEmin)/2*. Since 1 kilo CNE (1 kCNE) of a nutrient is the quantity of that nutrient that has the same effect on yield as 1 kg of N under conditions of balanced nutrition, 1 kCNE equals 1 kg N.

Table 4.5. Soil supply of available N, P and K (SAN, SAP and SAK in kg ha^{-1}) and maximum recovery fractions (*MRFN, MRFP* and *MRFK*).

Dataset	Sites	*SAN*	*SAP*	*SAK*	*MRFN*	*MRFP*	*MRFK*
Set 1	Davié	177	24	70	0.69	0.44	1.05
	Kumasi	94	21	65	0.33	0.15	0.10
	Nyankpala	86	18	104	0.49	0.03	0.33
	Average				*0.50*	*0.21*	*0.49*
Set 2	Gbave	170	23	67	0.95	0.60	0.95
	Davié Tekpo	250	34	99	0.95	0.60	0.95
	Sevekpota Black Soil	186	25	74	0.69	0.44	0.80
	Sevekpota White Soil	122	17	48	0.81	0.51	0.80
	Sevekpota Red Soil	147	20	58	0.69	0.44	0.80
	Gbanlahi	74	15	89	0.69	0.21	0.46
	Savelegu	113	24	136	0.64	0.20	0.43

Conversion factors for P and K (*CFP* and *CFK*) were calculated using the ratio of *PhEmed* of N and *PhEmed* of P or K: *CFP* = *PhENmed/PhEPmed*, and *CFK* = *PhENmed/PhEKmed*. Hence, 1 kCNE of P (kCNEP) equals CFP kg P, and 1 kCNEK equals CFK kg K. In Set 1 experiment for instance, at *HI* = 0.50, 1kCNEP = 0.167 kg P, and 1kCNEK = 0.706 kg K (Table 4.4).

Total available N, P and K (*TAN*, *TAP* and *TAK*) were calculated by summing up available nutrients supplied by the soil and external fertilizer input ($TAN = SAN+MRFN \times I_N$; $TAP = SAP+MRFP \times I_P$; $TAK = SAK+MRFK \times I_K$, with *MRFN*, *MRFP* and *MRFK* standing for the maximum recovery fractions of N, P and K fertilizers applied and I_N, I_P and I_K for the respective amounts of fertilizers applied) and converted into CNE.

Cassava storage roots yields were calculated using the QUEFTS model for the following situations:

1. Without external nutrient applications. In this situation, *TAN, TAP* and *TAK* equals the soil supply of available N, P and K (*SAN, SAP* and *SAK*, Table 4.5). This is generally an unbalanced nutrient supply situation since nutrients are available in different proportions and quantities in the soil, resulting in unequal quantities of *TAN, TAP* and *TAK* as expressed in CNE.
2. Balanced nutrition situation at which *TAN* = *TAP* = *TAK* (as expressed in CNE): from the unbalanced nutrition situation, the balanced nutrition is reached by adding required quantities of fertilizer input (*I*) that raise the smallest amounts of available nutrients among *TAN, TAP* and *TAK* to the level of the largest amount in CNE. For instance, if *TAN*, *TAP* and *TAK* were 75, 25 and 40 kCNE, respectively, we need to

increase TAP by 50 kCNE and *TAK* by 35 kCNE by adding P and K fertilizers to reach the level of *TAN*, hence attaining the balanced nutrition with *TAN* = *TAP* = *TAK* = 75 kCNE. The sum (*TAN*+*TAP*+*TAK*), denoted by *ΣA*, is then 225 kCNE.

3. From the situation of balanced nutrition (*TAN* = *TAP* = *TAK*), identical quantities of available nutrients from input fertilizers (*MRF* x *I*), expressed as CNE, are continuously and simultaneously added to *TAN, TAP* and *TAK* until the maximum yield (*YMAX*) is approached.

By plotting calculated yields (*Y*) against *ΣA*, a curve is obtained that is used for estimating optimal nutrient use efficiency at balanced nutrition. The slope of the linear part of this curve (*Y/ΣA*) is used as proxy of the optimal nutrient use efficiency of the three nutrients, which is expressed in storage roots DM per kCNE.

4.2.4. Assessing nutrient supply and fertilizer requirements for different target yields

At balanced nutrition, yield calculated by QUEFTS is *α*% of the product of *PhEmed* and *ΣA* expressed as CNE, where *α* is smaller than, but close to 100%. That *α* is smaller than 100% as the result of the procedure used for the calculation of *Y12* (see section 4.2.2). As a consequence, the maximum yield per kCNE of available N, P and K is α% of the product of *PhEmed* and *ΣA*.

For a certain target yield (*TgY*, Mg ha^{-1}), the required supply of available nutrient (*TgA*) can be calculated as follows:

$$TgA = (TgY/PhEmed)/\alpha \qquad \text{(Eq. 4.3)}$$

TgA is expressed in kCNE and *PhEmed* in kg storage roots DM per kCNE of a given nutrient.

If *TgA* for N (*TgAN*) is more than the soil supply of available nitrogen (*SAN*), the target input of available nitrogen (*TgIAN*) is:

$$TgIAN = TgAN - SAN \qquad \text{(Eq. 4.4)}$$

The target inputs of available P and K can be found as *TgIAP* = *TgAP* – *SAP* and *TgIAK* = *TgAK* – *SAK*. Because *TgIAN*, *TgIAP* and *TgIAK* are expressed in kCNE, they must for practical agriculture be converted into kg; this is done by multiplying them by their respective conversion factors for a given *HI* (Table 4.4). *SAN*, *SAP* and *SAK* values used are presented in Table 4.5. At balanced nutrition, the values of both *TgAP* and *TgAK* expressed in CNE are equal to those of *TgAN*.

Only a fraction of the applied N, P and K, at most the maximum recovery fraction of N, P and K (*MRFN, MRFP, MRFK*), is available to the crop. Assuming the recovery fraction is optimal for the three nutrients at balanced nutrition, the total required inputs of N, P and K (*RIN*, *RIP* and *RIK*) expressed in kg are calculated as:

$$RIN = TgIAN/MRFN \quad \text{(Eq. 4.5)}$$

$$RIP = CFP \times TgIAP/MRFP \quad \text{(Eq. 4.6)}$$

$$RIK = CFK \times TgIAK/MRFK \quad \text{(Eq. 4.7)}$$

For *MRFN*, *MRFP* and *MRFK*, we used the average values of 0.50, 0.21 and 0.49, respectively obtained in Set 1 experiments to facilitate the comparison among sites.

4.2.5. Data analysis and economic assessment

The performance of the QUEFTS model used was first assessed by comparing simulated with observed yields using different indicators: the Normalised Root Mean Squared Error (*NRMSE)* (Loague and Green 1991), the slope of the regression line between measured and simulated values, the Pearson coefficient of correlation (r) and the probability of the correlation (P value at 0.05). The calculated fertilizer rates at balanced nutrition were compared to existing national blanket fertilizer recommendations, referred to as blanket rates. This comparison was implemented based on the values of nutrient use efficiency ($Y/\Sigma A$), of the relative NPK availability over the sum of available nutrients (ΣA) and of the fertilizer nutrient requirements. Furthermore, a profitability analysis was conducted by calculating the gross revenues, costs and benefit:cost ratios (BCR) of the two types of fertilizer recommendations. Gross revenues were obtained as the product of the unit price of fresh storage roots at farm gate and fresh yields per site. Costs included fertilizer costs only and were calculated as fertilizer unit price multiplied by the quantity of fertilizer applied. No transportation nor application cost were considered. The BCR values were calculated by dividing the increase in gross revenue due to fertilizer application by the fertilizer costs. The increase in gross revenue due to fertilizer application is the difference between the gross revenue with fertilizer application and that of the control (no fertilizer application). National average values ± standard deviation of fertilizer prices were used: 1.72 ± 0.10 USD kg^{-1} N, 3.48 ± 0.37 USD kg^{-1} P and 1.82 ± 0.19 USD kg^{-1} K in Togo (average monthly fertilizer prices, October 2011 to January 2015, africafertilizer.org), and 1.05 ± 0.19 USD kg^{-1} N, 2.62 ± 0.64 USD kg^{-1} P and 1.37 ± 0.34 USD kg^{-1} K in Ghana (average of monthly fertilizer prices, June 2010 to October 2014, africafertilizer.org). Fresh storage roots prices at farm gates of 0.118 ± 0.040 USD kg^{-1} in Togo (annual average values, 2000 to 2014, CountrySTAT (2015)) and 0.051 ± 0.024 USD kg^{-1} in Ghana were considered (annual average values, 2005 to 2012, CountrySTAT (2015)). Three scenarios were compared for the economic evaluation of the recommended and the balanced fertilizer rates: i) Scenario 0: average fertilizer price and average fresh storage roots price; ii) Scenario 1: maximum fertilizer prices and minimum storage roots price; iii) Scenario 2: the same fertilizer prices as Scenario 1 but with maximum storage roots price. The minimum and maximum prices refer to the average price minus and plus the standard deviation, respectively.

4.3. Results

4.3.1. QUEFTS model performance

Simulated storage roots yields were in good agreement with the measured yields on fertilised plots in Set 2 sites for a common average *MRF* for NPK of 0.50 – 0.21 – 0.49 (Fig. 4.1a). The slope of the regression line between simulated and observed yields was 0.84, with a strong positive correlation (r = 0.80; P <0.001), and an acceptable *NRMSE* of 0.21, indicating that root mean squared errors represented 21% of the average observed yield. Model performance was further improved by using site-specific *MRF* values (Fig. 4.1b) resulting in a smaller NRMSE (0.10), a regression line slope (0.96) closer to 1 and a stronger positive correlation (r = 0.93; P <0.001) between simulated and observed yields.

4.3.2. Relations between yield and nutrient supply at balanced nutrition

The relation between yield and nutrient supply from soil and inputs is depicted in the curves of yield (Y) versus the sum of available nutrients (ΣA) for the varieties Gbazekoute and Afisiafi (Fig. 4.2). The slopes of the linear part of the two curves are different because the two cultivars have different harvest indices (*HI*) and hence different values for *PhEmax* and *PhEmin* (Table 4.4).

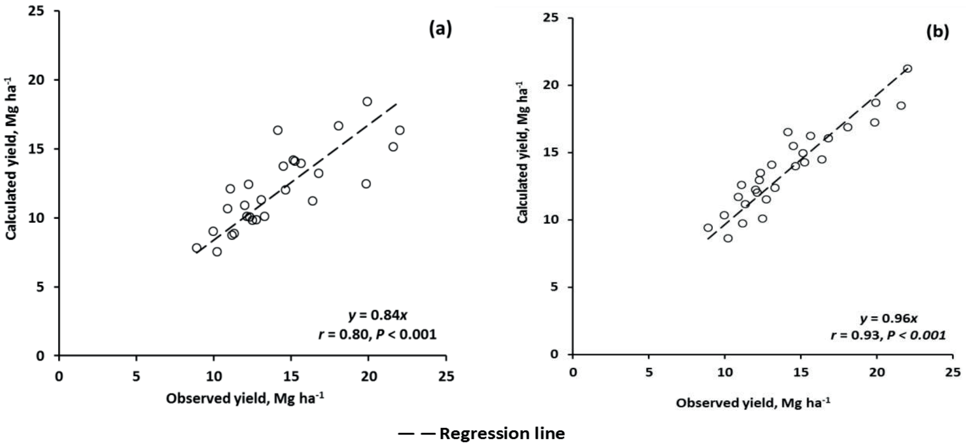

Fig. 4.1. Observed vs calculated storage roots DM yields of cassava on Set 2 sites with average (a) and site-specific *MRF* values (b). The average MRF NPK values used were 0.50 – 0.21 – 0.49. The specific MRF values are presented in Table 4.5.

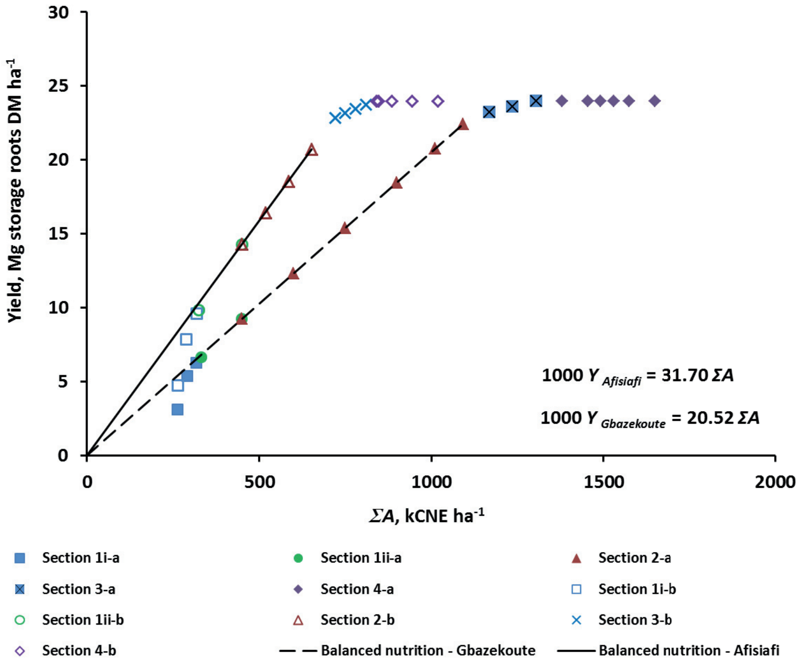

Fig. 4.2. Simulated relations of cassava storage roots yield to the sum of available N, P and K expressed in CNE (ΣA) for cultivars Gbazekoute and Afisiafi. 1000 Y expresses the linear relationship between the yield (Y) and ΣA at balanced nutrition for each cultivar. The slope of this linear regression (1000Y/ΣA) is considered as the nutrient use efficiency of the cultivar for a specific harvest index (0.50 for Gbazekoute and 0.65 for Afisiafi in this graph) and is expressed in kg storage roots DM per kCNE. Sections 1i-a, 1ii-a, 2-a, 3-a and 4-a refer to Gbazekoute and Sections 1i-b, 1ii-b, 2-b, 3-b and 4-b refer to Afisiafi.

In the two *Y* versus *ΣA* curves (Fig. 4.2), four sections can be distinguished for the common situation that soil available N, P and K (*SAN, SAP* and *SAK*) are not balanced. Since the values of the soil available nutrient do not affect nutrient use efficiency determined at balanced nutrition, *SAN*, *SAP* and *SAK* were arbitrarily set at 150, 84 and 28 kCNE ha^{-1}, giving a sum of 262 kCNE ha^{-1}. This represents an unbalanced situation, where K is the most limiting nutrient, followed by P. A balanced nutrition was reached by supplying first K, then P to achieve the same quantity as the supply of available N expressed in CNE. In Section 1i of Fig. 4.2 (with Section 1i-a for Gbazekoute and Section 1i-b for Afisiafi), only the most limiting nutrient K was applied, increasing *TAK* (supply of K from soil and input) from 29 to 84 kCNE ha^{-1}, which equals the value of *SAP*. In Section 1ii (Fig. 4.2), the most limiting two nutrients (K and P) are added in balanced proportions. At the border between Section 1ii and Section 2, both *TAK* and *TAP* have increased to the level of *SAN*, which is 150 kCNE ha^{-1}. Hence, here *ΣA* is three times 150 equalling 450 kCNE ha^{-1}. The second section of Fig. 4.2 is a straight line representing balanced nutrition, with equal input of available nutrients expressed as CNE. The third section of the graph is curvilinear. At the border between Section 2 and Section 3, the estimated storage-roots yield (*YE*) is 22.4 Mg dry matter (DM) ha^{-1} for cultivar Gbazekoute, and 20.7 Mg DM ha^{-1} for Afisiasi, which is 93 and 86% of *YMAX,* respectively. The fourth section of the graph is a plateau where *Y* equals *YMAX* (set at 24 Mg storage roots DM ha^{-1}). Further inputs of nutrients do not increase yield, but only the nutrient mass fractions of the crop components.

The regression lines for Section 2 (Fig. 4.2) have the same slopes (*Y/ΣA*) as the lines for balanced nutrition, drawn between the origin and the border of Sections 1ii and 2. These lines differ between the two varieties: 20.5 and 31.7 kg DM yield / kCNE for Gbazekoute and Afisiasi respectively. Further simulations showed that changing the starting value of *SAN, SAP* and *SAK* did not change these balanced nutrition slopes (not shown). Simulations also showed that the linear part of the graph (Section 2, Fig. 4.2) ends at 77-93% of *YMAX* with various values of *YMAX* (16 to 24 Mg DM ha^{-1} for *SAN, SAP* and *SAK* values of 150, 84 and 28 kCNE ha^{-1}) (not shown). Above this target yield threshold of 77-93% *YMAX*, the slope rapidly decreases (Section 3, Fig. 4.2).

The slope of the regression lines for Section 2 was used as a proxy to estimate nutrient use efficiency. The values of 20.5 and 31.7 kg storage roots DM per kCNE correspond to the supply (from soil and input) of 16.2 kg N, 2.7 kg P and 11.5 kg K to produce 1000 kg storage roots DM of Gbazekoute and 10.5 kg N, 1.9 kg P and 8.4 kg K for Afisiafi. The resulting optimal NPK supply ratios are 6.1 – 1.0 – 4.2 and 5.3 – 1.0 – 4.2 for Gbazekoute and Afisiafi, respectively.

4.3.3. Fertilizer requirements for different target yields at the experimental sites

At balanced nutrition, yield calculated by QUEFTS was 90-91% (α) of the product of *PhEmed* and *ΣA*. For Gbazekoute, *PhEmed* of N equals 68.5 kg DM per kCNE of N, or 22.8 kg DM per kCNE of *ΣA*. The maximum value of *Y/ΣA* (Fig. 4.2) is 20.5, which is 90% of 22.8. For Afisiasi, *PhEmed* of N equalled 104.5 per kCNE of N, or 34.8 kg per kCNE of *ΣA*. The maximum value of *Y/ΣA* (Fig. 4.2) is 31.7, which is 91% of 34.8.

Table 4.6 presents additional plant needs of N, P and K for different target yields at balanced nutrition, as calculated with Equations 3 to 7, with α set at 90% for a range of sites in Togo and Ghana. Nutrient requirements varied between target yields and sites. K was the nutrient most in demand at all sites in Togo at target yields of 8 and 12 Mg ha^{-1}. N and P were required to supplement indigenous soil nutrient supplies at larger target yields: 12 Mg ha^{-1} at Davié, Sevekpota White Soil and Sevekpota Red Soil, and 16 Mg ha^{-1} at Gbave and Sevekpota Black Soil. At the sites in Ghana, no nutrient input was needed to achieve 8 Mg ha^{-1} since simulated yields without fertilizer application were larger than or equal to 8 Mg ha^{-1} (8.0 Mg ha^{-1} at Gbanlahi, 9.0 Mg ha^{-1} at Kumasi, 9.4 Mg ha^{-1} at Nyankpala and 12.4 Mg ha^{-1} at Savelugu). N was most needed at larger target yields at Nyankpala, Gbanlahi and Savelugu. At Kumasi, both N and K were limiting with target yields from 12 Mg ha^{-1}.

4.3.4. Performance of recommended blanket fertilizer rates

The recommended blanket fertilizer rates (blanket rates) for cassava in Togo and Ghana did not provide balanced proportions of N, P and K at most sites (Table 4.7). $Y/\Sigma A$ ratios achieved with these blanket rates were in general smaller than those of the site-specific balanced nutrition (referred to as balanced rates). This result implies that fertilizer application based on balanced nutrition leads to larger yield increases per unit of fertilizer applied than the blanket rates. Blanket rates in Southern Togo supplied too much N and too little K as revealed by the proportion of these nutrients over ΣA (Table 4.7). In Ghana, blanket rates supplied too much K and too little P, except in Kumasi. Fertilizer requirements calculated at balanced nutrition were different to the blanket rates to attain the same yields as simulated for the blanket rates (Table 4.7). One exception, however, was Kumasi where the blanket rate provided the $Y/\Sigma A$ ratio required at balanced nutrition. The variation in fertilizer requirements from site to site indicates large differences in soil fertility, which is confirmed by the variation in yields obtained without fertilizer at these sites (Table 4.7).

The economic analysis of the recommended and balanced fertilizer rates (Table 4.8) revealed a larger benefit of the balanced rates over recommended rates in terms of costs of fertilizers and benefit:cost ratio (BCR) ($P < 0.001$). BCR of the balanced fertilizer rates were 1.1 to 2.0 times greater than those of the blanket rates, except in Kumasi where similar BCR values were obtained. Average BCR values of 2.4±0.9 and 3.8±1.1 were obtained for the blanket rates and the balanced rates, respectively, when average unit prices of fertilizer and of fresh storage roots (Scenario 0) were considered. BCR values were sensitive to fluctuations in fertilizer and fresh storage roots prices. The worst case scenario was the drop in BCR values caused by an increase in fertilizer prices on the market and a reduction in farm-gate prices of storage roots (Scenario 1). The best scenario for farmers consisted of a reduction in fertilizer prices and an increase in storage roots farm-gate prices (Scenario 2).

Table 4.6. Additional plant nutrient requirements to achieve balanced nutrition for different target yields for variety Gbazekoute (Togo sites) and Afisiafi (Ghana sites).

Site	Target yield (Mg storage roots DM ha^{-1})	Additional nutrients required (kg ha^{-1})		
		N	P	K
Davié	8	0	0	22
	12	18	8	67
	16	83	19	113
Gbave	8	0	0	15
	12	0	6	56
	16	54	16	98
Davié Tekpo	8	0	0	0
	12	0	0	24
	16	0	5	66
Sevekpota Black Soil	8	0	0	8
	12	0	4	49
	16	38	14	91
Sevekpota White Soil	8	0	2	34
	12	46	12	75
	16	102	22	117
Sevekpota Red Soil	8	0	0	24
	12	21	9	65
	16	77	19	107
Kumasi	8	0	0	3
	12	34	3	37
	16	76	11	71
Nyankpala	8	0	0	0
	12	42	6	0
	16	84	14	32
Gbanlahi	8	0	0	0
	12	37	7	4
	16	74	14	35
Savelegu	8	0	0	0
	12	0	0	0
	16	35	5	0

Table 4.7. Blanket rates, observed dry storage-yields without fertilizer, simulated yields, relative NPK availability over ΣA at recommended blanket fertilizer rates, $Y/\Sigma A$ and balanced nutrient requirements to reach the same yields as for the recommended rates at the study sites. Indigenous soil supply values in Table 4.5 were used with the average MRF for NPK of 0.50 – 0.21 – 0.49. ΣA is the sum of available N, P and K expressed in crop nutrient equivalent. A relative NPK availability proportion of about 33% for each of the nutrients N, P and K is expected at balanced nutrition. $Y/\Sigma A$ is a proxy for overall nutrient use efficiency.

Site	Blanket rates, kg ha^{-1}			Observed yield without fertilizer, Mg DM ha^{-1}	Simulated Yield for blanket rates, Mg DM ha^{-1}	Relative NPK availability over ΣA when blanket rates are used, %	$Y/\Sigma A$		Balanced rates, kg ha^{-1}		
	N	P	K				Blanket rate recommendation	Balanced nutrition	N	P	K
Davié	76	13	25	8.8	9.8	44-33-24	20.0	20.5	0	13	87
Gbave	76	13	25	7.7	9.5	45-32-23	20.5	23.9	0	0	63
Davié Tekpo	76	13	25	11.8	13.3	44-32-23	20.5	23.9	0	0	78
Sevekpota Black Soil	76	13	25	8.7	10.3	45-32-23	20.5	23.9	0	0	65
Sevekpota White Soil	76	13	25	5.8	7.3	45-32-23	20.4	23.9	0	3	55
Sevekpota Red Soil	76	13	25	6.9	8.4	45-32-23	20.5	23.9	0	2	58
Kumasi	68	20	57	8.6	12.0	34-35-31	31.7	31.7	67	14	75
Nyankpala	68	20	57	5.6	12.2	30-29-41	30.3	31.7	88	31	0
Gbanlahi	68	20	57	8.0	10.8	31-28-40	31.3	36.5	52	23	0
Savelegu	68	20	57	12.2	15.2	30-29-40	31.4	36.5	56	19	0
P (0.05)*							*<0.001*				

* P is the probability of differences between paired samples t-test with 95% confidence interval across all locations.

Table 4.8. Partial budget analysis for the application of blanket and balanced fertilizer rates for cassava production at the study sites following different scenarios of input and product prices. This budget was based on yields (converted in fresh storage roots) and fertilizer rates provided in Table 4.7.

Site	Scenario 0						Scenario 1		Scenario 2	
	Gross revenue without fertilizer	Gross revenue with fertilizer (blanket and balanced rates)	Cost for blanket rates	Cost for balanced rates	BCR for blanket rates	BCR for balanced rates	BCR for blanket rates	BCR for balanced rates	BCR for blanket rates	BCR for balanced rates
	USD ha^{-1}									
Davié	2730	3058	221	203	1.5	1.6	0.9	1.0	1.8	2.0
Gbave	2385	2949	221	115	2.5	4.9	1.6	2.9	3.2	5.9
Davié Tekpo	3665	4145	221	142	2.2	3.4	1.3	2.0	2.7	4.1
Sevekpota Black Soil	2710	3189	221	118	2.2	4.1	1.3	2.4	2.7	4.9
Sevekpota White Soil	1786	2256	221	110	2.1	4.3	1.3	2.6	2.6	5.2
Sevekpota Red Soil	2151	2614	221	114	2.1	4.1	1.3	2.4	2.6	4.9
Kumasi	1211	1696	202	210	2.4	2.3	1.0	1.0	2.9	2.8
Nyankpala	788	1730	202	172	4.7	5.5	2.0	2.4	5.6	6.6
Gbanlahi	1127	1527	202	113	2.0	3.5	0.9	1.5	2.4	4.3
Savelegu	1727	2157	202	107	2.1	4.0	0.9	1.8	2.6	4.9
Average ± STDEV**	2028±878	2532±821	214±10	140±40	2.4±0.9	3.8±1.1	1.3±0.4	2.0±0.7	2.9±1.0	4.6±1.4
*P**	*< 0.001*		*< 0.001*		*< 0.001*		*< 0.001*		*< 0.001*	

* *P* is the probability value of differences between paired samples t-test with 95% confidence interval across all locations; ** STDEV is the standard deviation.

4.4. Discussion

We obtained optimum nutrient use efficiencies of 20.4 and 31.4 kg storage roots dry matter per kCNE supplied for Gbazekoute and Afisiafi cultivars, respectively (Fig. 4.2). This implies that supplies of 48.9 and 31.8 kCNE are required to produce 1000 kg of cassava storage roots DM. These values are equivalent to 16.3 kg N, 2.7 kg P and 11.3 kg K and 10.6 kg N, 2.0 kg P and 8.3 kg K for the production of 1000 kg storage roots DM of Gbazekoute and Afisiafi, respectively. The cultivar Afisiafi had relatively high nutrient use efficiency, but it is difficult to attribute this to the cultivar itself or to site effects, since cultivar and location of the trials were confounded. It follows from Equations 1 and 2 that nutrient use efficiencies increase with *HI*. Afisiafi had higher average *HI* (0.65) than Gbazekoute (0.50). N supply was especially high at Davié where Gbazekoute was grown, and large N uptakes may have resulted in a relatively small *HI* through large top biomass production at the expense of storage roots (Howeler 2002). Therefore, differences in nutrient use efficiencies obtained may be attributed more to differences in *HI* rather than cultivar differences.

The optimal NPK supply ratios simulated at balanced nutrition are 6.1 – 1.0 – 4.2 at *HI* 0.50 (Gbazekoute) and 5.4 – 1.0 – 4.2 at *HI* 0.65 (Afisiafi). Expressed in N-P_2O_5-K_2O, these are 2.7 – 1.0 – 1.8 and 2.4 – 1.0 – 1.8 at *HI* 0.50 and 0.65, respectively. These ratios are quite similar to the ratios of 2 – 1 – 2 or 2 – 1 – 3 reported by Fermont (2009) for inorganic fertilizer recommendations in East Africa. However, the supply in these latter ratios refers to fertilizer only, whereas in our study it refers to fertilizer as well as the soil supplies of nutrients.

The calculated optimal fertilizer nutrient requirements increased with target yields and varied between sites (Table 4.6). At all sites in Togo, K was the most limiting nutrient for cassava production, especially at a target yield of 8 Mg ha^{-1} storage roots DM. This indicates that K deficiencies are important and probably widespread in Southern Togo, especially on the Ferralsols (Davié, Davié Tekpo and Gbave). Carsky and Toukourou (2005) also reported K deficiencies in cassava production systems on Ferralsols in Southern Benin. However, K deficiency is not limited to Ferralsols only. This issue can arise in the long term in any other soil where cassava production is practised frequently with insufficient supply of external K fertilizer because cassava extracts more K than any other nutrient from the soil (Hillocks et al. 2002). Therefore, K management should be optimised to ensure good yields. K deficiency was less obvious on the Ghana sites, especially at Nyankpala, Gbanlahi and Savelugu indicating a good supply of this nutrient from the soil. N was the most needed nutrient at these sites. The small soil organic carbon (SOC) content (4.3 g kg^{-1}) and the high exchangeable K content (3.1 mmol kg^{-1}) of the Nyankpala soil support this conclusion. Unfortunately, no soil chemical analysis data are available for Gbanlahi and Savelugu sites.

We observed that blanket fertilizer rates were in general unbalanced (Table 4.7). The rates of 76 kg N, 13 kg P and 25 kg K ha^{-1} in Southern Togo and of 68 kg N, 20 kg P and 57 kg K ha^{-1} in Ghana were rather different from the site-specific optimal needs of input that we calculated for the same target yields. The blanket rate of Ghana was quite balanced and suitable for use in Kumasi only. A key reason for this difference between the performance of the blanket rates and the calculated optimal nutrient needs is the difference in soil fertility among these sites, as reflected by the difference in measured yields without fertilizer application (Table 4.7) and in indigenous soil supplies (Table 4.5). The application of blanket rates irrespective of indigenous soil nutrient supplies not only leads to less yield, but is also likely to generate nutrient losses where the applied nutrient is not needed. Nutrient losses will be prominent for instance for N in southern Togo, and K in Northern Ghana where those nutrients were not limiting yet, if blanket rates of fertilizer were used. The application of blanket rates irrespective of plant needs also leads to lower returns to investments in fertilizer. An average BCR value of 2.4±0.9 obtained at blanket fertilizer rates will be less attractive to farmers than a BCR of 3.8±1.1 achieved at balanced fertilizer rates. The sub-optimal economic performance at blanket rates can discourage farmers to invest in fertilizer use for cassava production.

External P fertilizer supply requirements were fairly small at a target yield of 8 Mg ha^{-1} across all sites, even at Davié, Kumasi and Nyankpala, which have soils with small concentrations of available P (3-5 mg kg^{-1}). Cassava is efficient at capturing soil P at small concentrations through vesicular mycorrhizal symbiosis (Kang and Okeke 1984; Sieverding and Leihner 1984).

In summary, with the exception of K in southern Togo sites, no external fertilizer is required to produce 8 Mg storage roots DM ha^{-1}, which is twice the current average yield in West Africa. The simulation results are supported with the assumption of improved crop management practices including planting healthy cuttings, planting on time, maintaining well the plot with weeding, and a good control of pest and diseases. Yields measured under improved management conditions on our fields experiments without fertilizer applications (5.6 – 12.2 Mg ha^{-1}; Table 4.7) were by far superior to the national average yields in farmers' fields of 2.2 and 4.9 Mg ha^{-1} storage roots DM in Togo and Ghana (FAOSTAT 2014), assuming a DM content of 36% in the fresh roots. This suggests that substantial increase of cassava storage roots yields could be achieved in the region by promoting good crop management practices. However, the positive effect of good management practices can be undermined by drought. This was the key reason for the relatively poor yield in Nyankpala compared with the other sites in Ghana. External P as well as external N fertilizer requirements arose at or beyond target yields of 12 Mg ha^{-1}.

These findings apply to sole cassava which generally provides larger yields compared with intercropped cassava. Apart from yields, nutrients requirements of cassava may be different in the intercropping system due to competition for nutrients, water and light with the intercrop. N deficiency can be exacerbated in Northern Ghana when cassava is intercropped with cereals without applying external N fertilizers (Carsky et al. 2001). Legume integration (intercrop or rotation crop) in such systems can reduce the need for external N fertilizers through atmospheric nitrogen fixation, although legumes need sufficient P for adequate growth and symbiotic N_2-fixation (Giller and Cadisch 1995). Since intercropping cassava with cereals and or legumes is common in West Africa, further research is needed to determine the balanced nutrition needs of intercropping systems.

The formulation of site-specific fertilizer recommendations based on optimal NPK supply ratios requires a good assessment of (indigenous) soil nutrient supplies and of fertilizer recovery fractions. Nutrient omission trials are the best way to quantify indigenous soil nutrient supplies (Dobermann et al. 2002). Nevertheless, in the absence of data on indigenous soil nutrient supplies, yields from farmers' plots without fertilizer application can be used to estimate them, preferably when good management of these plots was carried out (planting of healthy cuttings at the right time, at the recommended planting density, providing good weed and pest control, etc.) and rainfall amount and distribution was reasonable. In general, soil nutrient supply determined from farmers' plots yields without fertilizer application are smaller than the potential soil nutrient supply values expected from nutrient omission trials. In Set 1, the measured soil supply of nutrients was on average 1.3, 1.6 and 1.2 times as large, for N, P and K, respectively in the nutrient omission plots (treatments S1, S3 and S5 for zero N, zero P and zero K in Table 4.2) compared with the control plots (S0) (not shown). These multiplication factors are indicative of the relevance to correct for the estimates of soil supply of nutrients derived from farmers' plots yields without fertilizer applications. When yields on plots without fertilizer application and the harvest index are known, the estimate of actual soil nutrient supply can be performed using the reciprocal nutrient supply efficiency, which is the nutrient supply requirement to produce 1 Mg ha^{-1} of storage roots DM. In this study, this reciprocal nutrient supply efficiency was (16.3 kg N, 2.7 kg P and 11.3 kg K for HI = 0.50 and 10.6 kg N, 2.0 kg P and 8.3 kg K for HI=0.65). For other values of HI, the reciprocal nutrient supply efficiency (1000/$PhEm$) can be derived from Equations 4.1 and 4.2. Fertilizer recovery fractions (MRF) are sometimes assessed in any fertilizer trial comprising a treatment without fertilizer. But this leads to an overestimation of *MRF*. *MRF* are ideally estimated in nutrient omission trials. On the sites of our own trials (Set 1), *MRF* values varied between 33 – 69% for N, 3 – 44% for P and 10 – 100% for K with average values of 50% for N, 21% for P and 49% for K (Table 4.5). In the same trials, the indigenous soil supplies ranged between 74 – 250 kg N, 15 – 34 kg P and 48 – 136 kg K ha^{-1} (Table 4.5). These wide ranges of *MRF* and indigenous soil supplies emphasise the need of site-specific fertilizer recommendations for cassava production. However, it will be unrealistic to provide unique fertilizer recommendations to individual farmers or fields, especially to smallholder farmers who generally do not have financial capacity to pay for plant and soil chemical analyses. Another key challenge is that single fertilizers, which allow a farmer to apply exactly the estimated required amount of nutrients, are generally more expensive compared with standard blended fertilizers (NPK: 15-15-15 for instance), except for urea that costs often as much as (subsidised) blended fertilizer in West Africa. Fertilizer recommendations on the basis of major soil types and agro-ecological zones can be more practical than recommendations for individual farms. This could also increase the demand of specific fertilizer nutrients on the input market and result in more affordable fertilizer prices for farmers. The assessment of nutrient supplies per major soil type in main cassava production agro-ecological zones and the balanced nutrition approach used in this study will be useful for formulating soil type and agro-ecologically specific fertilizer recommendations for enhanced cassava production in West Africa.

4.5. Conclusions

The QUEFTS model proved useful to assess balanced nutrition, to derive optimum fertilizer requirements for target yields and to explore diversity among sites in West Africa. We showed how the use of balanced fertilizer rates following NPK supply ratios of 6.1 – 1.0 – 4.2 at *HI* of 0.50 and 5.4 – 1.0 – 4.2 at *HI* of 0.65 enhanced nutrient use efficiency of NPK and increased value to cost ratios compared with recommended blanket rates. We found that K is the most needed nutrient to achieve a target yield of 8 Mg ha^{-1} of storage roots DM, especially on the Togo sites. The need for N and P fertilizer inputs became necessary at larger target yields on most sites. These results suggest that good management practices are key to substantial improvement of cassava production below a target yield of 8 Mg ha^{-1}, and that external nutrients are needed to produce beyond a target yield of 12 Mg ha^{-1} depending on the indigenous soil fertility status of the soil. The variation in indigenous soil fertility status and in nutrient input needs highlighted a key disadvantage of recommended blanket rates. Shifting from these blanket rates to soil or agro-ecologically specific recommendations will be a great accomplishment towards enhancing nutrient use efficiency and yields in cassava production systems in West Africa, in addition to promoting good management practices.

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CHAPTER FIVE

5.0. Water and radiation use efficiencies explain the effect of potassium on the productivity of cassava

Abstract

We studied the effects of potassium (K) and its interactions with nitrogen (N), phosphorus (P) and harvest time on the productivity, water use efficiency (WUE) and radiation use efficiency (RUE) of cassava under rain-fed conditions. A field experiment was conducted during two consecutive years on K-deficient soils in Djakakope and on relatively K-rich soils in Sevekpota in Southern Togo, West Africa. Fifteen fertilizer combinations involving K and N rates of 0, 50 and 100 kg ha^{-1} each, and P rates of 0, 20 and 40 kg ha^{-1} were tested. Monthly measurements of leaf area index from 3 to 11 months after planting and daily weather data were used to estimate light interception, RUE, potential water transpiration and WUE of cassava. Overall WUE was 3.22 g dry matter kg^{-1} water transpired and RUE was 1.16 g dry matter MJ^{-1} intercepted photosynthetic active radiation (PAR). On the K-deficient soils, application of K increased WUE and RUE by 36-41% compared with 2.81 g dry matter kg^{-1} water transpired and 0.92 g dry matter MJ^{-1} intercepted PAR achieved without K, respectively. However, the effect of K on cassava growth depended on N availability. Applications of N had relatively weak effects on RUE and WUE, but induced a positive correlation between RUE / WUE and K mass fractions in the plant, and increased the cumulative amount of light intercepted by 11-51%, and the cumulative amount of water transpired through increased leaf area by 13-61%. No significant effect of P on WUE and RUE was observed. Increased cassava yields could be achieved under rain-fed conditions in West Africa through enhanced K management to increase RUE and WUE, along with sufficient N supply for improved light interception and water transpiration by the crop.

Keywords: *Light interception, potential water transpiration, leaf area index, nitrogen, phosphorus, Togo.*

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5.1. Introduction

Potassium is a key determinant of the productivity of root crops, including cassava (*Manihot esculenta*, Crantz). It plays many roles such as stimulating the photosynthetic activity of leaves, increasing the translocation of photosynthates to the storage roots (Hillocks et al. 2002), and regulating stomatal aperture and closure (Chérel et al. 2014), which helps to minimise water losses during drought. Potassium deficiency can lead to reduced yield and starch content of storage roots (Nair 1986). A lack of K can also lead to an increased hydrogen cyanide (HCN) content of cassava roots, especially when N supplies are inadequate (Marschner and Marschner 1995). High HCN content in storage roots constitutes a serious health hazard, since fresh cassava roots are popular food in West Africa.

Cassava productivity can be measured as function of the radiation use efficiency (RUE) and the amount of light intercepted (Pellet and El-Sharkawy 1997). It can also be expressed as the product of water use efficiency (WUE) and the amount of water transpired (El-Sharkawy and Cock 1986). Thus, a linear relationship is assumed under favourable conditions between biomass production and light interception, which defines RUE (Pellet and El-Sharkawy 1997; Sinclair and Muchow 1999; Veltkamp 1985), and between biomass production and water consumption by the crop, which determines WUE (Yao and Goué 1992). The amount of water consumed by the crop can be calculated as the amount of rainfall received during the growing season (generally unreliable method, as it neglects drainage, run-off, and changes in soil moisture), or as the amount of water evapo-transpired, or transpired during the growing season. When WUE is based on water transpiration, it is also referred to as transpiration efficiency (Siahpoosh and Dehghanian 2012; Zhang et al. 1998). El-Sharkawy and Cock (1986) reported WUE value of 2.9 g total biomass DM per kg of water transpired for cassava. Reported values of WUE based on evapo-transpiration range from 0.4 to 4.8 g DM per kg water (Lemon (1969) as cited by Yao and Goué (1992)). Thus, it is important to define the units used to assess WUE. Pellet and El-Sharkawy (1997) obtained RUE values between 1.15 and 2.30 g DM per MJ intercepted light under a high rainfall regime of 1800 mm per year. Both light interception and water transpiration depend on the dynamics of the leaf area index (LAI) of the crop, highlighting the importance of LAI in assessing RUE and WUE. We are not aware of any studies to the RUE and WUE dynamics of cassava cultivars commonly promoted in West Africa such as TME 419 (highly promoted in the cassava belt in Nigeria, and referred to as “Gbazekoute” in Togo) and TMS 30572 (“Afisiafi” in Ghana, also grown in Nigeria). Assessing these parameters will inform cassava growth models simulating potential and water-limited yields of cassava in West Africa.

The application of K fertilizers increases cassava productivity on K-deficient soils (Ezui et al. 2016; Howeler 1991; Kang 1984; Sogbedji et al. 2015). It is however poorly documented how K affects the interaction between RUE, light interception and cassava productivity. Similarly, information on the effect of K on WUE and water transpiration by cassava productivity is scarce. It is unclear whether K is most active in light interception or in efficient use of light or in both. Moreover, the dynamics of K impacts on RUE and light interception as well as on WUE and water transpiration during cassava crop life as affected by the availability of N and P is poorly reported. This hinders our ability to improve K management in relation to N and P availability, needed to increase cassava productivity in West Africa. In this paper, we address these knowledge gaps.

This paper aims to assess the interaction between K and the availability of N and P on the RUE, light interception, WUE, transpiration, dry matter and harvest period of cassava under rain-fed conditions in West Africa. We hypothesised that: i) K increases either RUE or light interception through its interaction with N and P; ii) K increases WUE or water transpiration through its interaction with N and P.

5.2. Material and methods

5.2.1. Location, climate and soils

A field experiment was carried out at two locations in the Coastal Savannah agro-ecological zone of Southern Togo: Sevekpota (6.437°N, 0.959°E, with an elevation of 121 m above sea level – masl) and Djakakope (6.464°N, 1.597°E, 86 masl). This agro-ecological zone has a bi-modal rainfall distribution, which favours two growing seasons from mid-March through July and from September through mid-November. The experiment was conducted on Ferralsols (Ferrallitic soil with a depth over 200 cm) with a low exchangeable K capacity in Djakakope and on Alfisols (Ferruginous, shallow soils with a hard pan at about 50-80 cm depth) with a relatively better K supplying capacity in Sevekpota.

5.2.2. Experimental design

A randomised complete block design was used with three blocks of 15 NPK treatments defined to account for interactions among nutrients (Table 5.1). In total 45 plots of 5.6 × 8 m (44.8 m^2) were laid out at a planting density of 0.8 × 0.8 m (15,625 plants ha^{-1}) as recommended for cassava production in the area. Spacing was 1 m between plots and 2 m between blocks.

5.2.3. Crop establishment and management

Gbazekoute (TME 419) was selected for this experiment as the main improved cultivar adopted by farmers in Southern Togo. It is generally grown for 10 to 12 months and yields on average 20-25 Mg ha^{-1} of fresh storage roots (30-40% dry matter content). This variety can produce 56 Mg ha^{-1} under optimal management (Odedina et al. 2009). Healthy cuttings were planted on May 22, 2012 (Year 1) and April 23, 2013 (Year 2) in Sevekpota, and May 25, 2012 and May 03, 2013 in Djakakope. Fertilizer was applied as urea (46% N), triple-super phosphate (TSP: 46% P_2O_5, 20% P) and muriate of potash (MOP: 60% K_2O, 50% K). Triple-super phosphate was given in one application at planting, whereas one-third of the urea and MOP were applied 21 days after planting (DAP). The remaining two-thirds were applied at 60 DAP just after weeding. Weeding was carried out four times during the growing season. Harvests in Sevekpota took place on the following dates: 127, 245 and 317 DAP in Year 1 and 139, 238 and 322 DAP in Year 2; in Djakakope the crop was harvested at 318 DAP in Year 1, and at 136, 231 and 322 DAP in Year 2.

5.2.4. Data collection

Soil samples were composed of five sub-samples per sampling depth before crop establishment on each site at the following depths: 0 – 20 cm, 20 – 40 cm and 40 – 60 cm. These samples were air-dried and ground to pass through a 2-mm mesh sieve. Particle size was determined using the hydrometer method, pH (H_2O, 1:2.5) using a glass electrode pH meter, organic carbon by the Walkley-Black method, total N using Kjeldahl digestion, and available P by the method of Bray 1.

Table 5.1. N, P and K fertilizer rates in kg ha^{-1} in the experimental treatments.

Treatments	N	P	K
P1	0	0	0
P2	100	0	0
P3	0	0	100
P4	100	0	100
P5	0	40	0
P6	100	40	0
P7	100	40	100
P8	0	40	100
P9	0	20	50
P10	50	0	50
P11	50	20	0
P12	50	40	50
P13	50	20	100
P14	100	20	50
P15	50	20	50

Exchangeable cations (K^+, Na^+, Ca^{2+} and Mg^{2+}) were extracted using a single extraction with dilute Silver-Thiourea (AgTU) solution (0.01 M Ag^+) and measured using an atomic absorption spectrophotometer for Ca^{2+} and Mg^{2+}, and a flame spectrophotometer for Na^+ and K^+. All analyses were conducted by the ICRISAT laboratory, Niamey, Niger.

Daily rainfall was measured on each site using manual rain gauges. Daily minimum and maximum temperatures, air humidity, and wind speed data were provided by the nearest weather station at Lomé (6.167°N, 1.250°E, 19.6 masl) for Sevekpota and Tabligbo weather station (6.583°N, 1.500°E, 40 masl) for Djakakope. Daily solar radiation was not measured in the area and therefore, satellite data provided by NASA were used (http://power.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi?email=agroclim@larc.nasa.gov).

Canopy dimensions were measured monthly from 2 to 3 months after planting (MAP) to final harvest using measuring tapes. Light interception was assessed through measurements of the Photosynthetic Active Radiation (PAR) above and below the plant canopy from 3 to 11 MAP using Decagon's AccuPAR model LP-80 PAR/LAI Ceptometer. AccuPAR LP-80 measures PAR in the 400-700 nm wavebands, and derives plant canopy leaf area index (LAI) from these readings. An external sensor was wired to it and held above the canopy with a stick, so that PAR above and below canopy are measured simultaneously. Measurements of PAR were taken at four locations in each plot. At each location, values of PAR below the canopy were measured in the space between two cassava plant stands at 40, 20 and 2 cm away from a selected plant stand. Thus, in total 12 PAR measurements were taken per plot and the average values (PAR above, PAR below) were retained. In addition, average values of the zenith angle of the sun (θ) and the beam fraction of the PAR above canopy (f_b) were provided by AccuPAR per plot assuming a default leaf angle distribution (x) value of 1, since no value of this parameter was provided for cassava. Assuming an ellipsoidal leaf angle distribution, we then used canopy dimension measurements to estimate x and used it to derive the light extinction coefficient (*k_ext*) and LAI of cassava following Norman (1979). Adjusting the x value to the range associated with the crop of interest and the growing conditions is important to ensure sound assessment of *k_ext* and LAI. The overall value of *k_ext* was determined by plotting ln (PAR below / PAR above canopy) versus LAI where the slope was calculated from the regression line following Kiniry et al. (2005). The method of determination of those parameters is described in Section 5.2.5.

At harvest, cassava storage root, stem and leaf weights were measured per plot. Each plot contained 10 rows with seven plants per row. Three successive harvests were made per plot. Each harvest concerned two consecutive rows, excluding border rows (10 plants harvested in total: five plants per row). From the harvested plants, three per plot were randomly selected for the following measurements: number of leaves, leaf weight, number of leaf scars, number of storage roots, storage root weight. Samples of storage roots, stems and leaves per harvested plot were oven dried at 68–70°C until constant weight and analysed for their NPK content by ICRISAT. Dried plant organs were ground and digested in H_2SO_4 – salicylic acid – H_2O_2 – Selenium solution. Total N concentration was measured from this extract using a colorimetric method based on Berthelot's reaction (Sommer et al. 1992), total P concentration based on the method of the molybdo-phosphate complex with ascorbic acid as a reducing agent and K concentration by atomic absorption spectrophotometry using Perkin Elmer model Analyst 400 (Houba 1995).

5.2.5. Parameters calculations

The dry matter (DM) of the total biomass, also referred to as biomass produced, was obtained by summing up DM yield of storage roots, stems, and harvested leaves and fallen leaves for each treatment. Dry matter of fallen leaves was estimated at a given harvest time as:

Fallen leaves (kg ha^{-1}) = average single leaf weight [kg] × number of leaf scars [ha^{-1}] (Eq. 5.1)

Average single leaf weight (kg) = harvested leaves weight [kg ha^{-1}] / number of harvested leaves [ha^{-1}] (Eq. 5.2)

Dry matter of storage roots, stems, and harvested leaves were calculated as follows:

DM (kg ha^{-1}) = (DM per plot [kg] / number of plants harvested per plot) × number of plants per hectare [ha^{-1}] (Eq. 5.3)

The calculation of light interception (*IPAR* expressed in MJ PAR m^{-2}) was based on the assumptions that PAR exponentially decreases with depth, that *IPAR* results from the difference between PAR above (incident radiation) and PAR below the canopy and that PAR above is about 50% of the daily total radiation (*DTR*):

$$IPAR = 0.5 \text{ x } DTR \text{ x } (1 - e^{-K\_ext \text{ x } LAI}) \quad \text{(Eq. 5.4)}$$

DTR is expressed in MJ m^{-2} d^{-1}, 0.5 gives the ratio MJ PAR MJ^{-1} DTR, *LAI* is the leaf area index in m^2 leaf m^{-2} ground, and *K_ext* the light extinction coefficient. We calculated *K_ext* for each AccuPAR measurement using Eq. 5.5 assuming an ellipsoidal leaf angle distribution (Campbell 1986):

$$K\_ext = \frac{\sqrt{x^2 + tan\,\theta^2}}{x + 1.744(x + 1.182)^{-0.733}} \quad \text{(Eq. 5.5)}$$

θ is the zenith angle of the sun estimated by AccuPAR; x is the leaf angle distribution parameter, defined as the ratio of horizontal to vertical axes of ellipsoidal leaf distribution (Campbell 1986). We calculated x based on cassava canopy dimensions measurement as:

$$x_i = \frac{CW1_i + CW2_i}{2CT} \quad \text{(Eq. 5.6)}$$

$CW1$ and $CW2$ (cm) are the largest and the smallest horizontal width of the canopy; CT (cm) is the vertical thickness of the canopy. $CW1$, $CW2$ and CT were measured on each plot on the same day that PAR measurements took place.

With the measured x and the resulting k_ext values, LAI was determined using Eq. 5.7 derived from the model for canopy light transmission by Norman and Jarvis (1975). The mechanism for retrieving LAI from this model while accounting for leaf angle distribution, canopy transmission and scattering is described in the operational guide of the AccuPAR ceptometer (Decagon Devices 2004).

$$LAI = \frac{\left[\left(1 - \frac{1}{2K\_ext}\right) f_b - 1\right] ln\tau}{A(1 - 0.47 f_b)} \quad \text{(Eq. 5.7)}$$

f_b is the beam fraction of the incident radiation, τ the ratio PAR below / PAR above canopy. Values of f_b, PAR below and PAR above canopy are measured by AccuPAR. Since the variables of Equation 5.7 were measured, we refer to the calculated LAI values as "measured LAI" throughout the paper. A is a term for primary and secondary canopy absorption that is empirically related to the leaf absorptivity in the PAR band:

$$A = 0.283 + 0.785a - 0.159a^2 \quad \text{(Eq. 5.8)}$$

The leaf absorptivity is denoted as a. We used an a value of 0.85 (Sinclair and Muchow 1999).

For the calculation of RUE, cumulative light interception (cumulative *IPAR,* MJ PAR m^{-2}) was derived by numerical integration of *IPAR* over time with measured LAI values (Eq. 5.9). A Fortran Simulation Translator (FST) program was developed to facilitate the implementation of this calculation.

$$Cumulative\ IPAR = \int_0^t (0.5 \text{ x } DTR(t) \text{ x } (1 - e^{-K\_ext \text{ x } LAI(t)}))\, dt \quad \text{(Eq. 5.9)}$$

Since the LAI(t) values are measured only at certain points in time (monthly from 3 to 11 MAP), LAI(t) in between these points were estimated by linear interpolation.

Cumulative *IPAR* calculated on a daily basis from planting to a specific harvest was plotted against the associated amount of biomass produced (leaves + stems + storage roots + fallen leaves). Here, we combined all treatments. The slope of the linear regression was used to estimate RUE (g DM MJ^{-1} IPAR) for the whole cropping season (Pellet and El-Sharkawy 1997; Sinclair and Muchow 1999; Veltkamp 1985). The intercept of this regression line was set to zero given there is no cassava biomass production without light interception. To assess the dynamics of RUE between two consecutive harvests, changes in RUE were estimated by dividing the difference in biomass by the difference in cumulative *IPAR* between the two harvests. To investigate the effect of fertilizer and harvest time, RUE was also calculated for individual treatments at a given harvest by dividing biomass by accumulated *IPAR*.

Water use efficiency (g DM kg^{-1} water) was estimated at each harvest as the weight of the biomass produced from planting over the cumulative amount of water transpired from planting. We limited the calculation of WUE to potential water transpiration since actual transpiration was not measured. This is likely to result in smaller WUE compared with WUE based on actual transpiration, especially under drought conditions. Potential transpiration (*PTRAN*) as well as potential evaporation (*PEVAP*) were based on the Penman equation (Penman 1948) using daily LAI values (Appendix 5.1). Cumulative *PTRAN* and cumulative *PEVAP* were obtained by integrating *PTRAN* and *PEVAP* over time from planting to the different harvests. We assumed LAI to be zero at emergence at about 15 days after planting. The cumulative *PTRAN* at each harvest was plotted against the amount of biomass produced at that harvest. The slope of the regression line of this graph is taken as the WUE for cassava. As in the case of RUE, WUE was also calculated for individual treatments at a given harvest by dividing the accumulated biomass by the accumulated *PTRAN*. The sum of *PTRAN* and *PEVAP* was denoted as potential evapotranspiration (*PET*).

5.2.6. Statistical analyses

Genstat statistical package (version 17) was used for analysis of variance and regression using mixed models. The analyses were done for each experimental year and site separately, since site and year were confounded and only one final harvest was done in Djakakope Year 1. Hence, a mixed linear model was used to analyse the data from Djakakope in Year 1 using N, P, K, and their interactions as fixed factors and block as random factor. For Year 2 in Djakakope and Year 1 and Year 2 in Sevekpota where three consecutive harvests were done, we used repeated measurements with plots nested in blocks as subject, harvest time expressed in MAP as time points and harvest time x (N, P, K, and their interactions) as fixed factors. These models were fitted for correlation within subjects across time using antedependence model order 1 (Kenward 1987), which accounts for heterogeneity in time. Pearson correlation analyses were conducted to assess the significance of the relationship between RUE, WUE and K mass fractions of cassava total biomass.

5.3. Results

5.3.1. Cassava growing conditions and LAI dynamics

5.3.1.1. Water availability and soil characteristics

In Sevekpota in Year 1, less rain was received than in Year 2 (574 and 731 mm rain water), unlike in Djakakope where Year 1 was wetter than Year 2 (736 and 649 mm rain water) (Fig. 5.1). Accumulated rainfall was above potential evapotranspiration (PET) at the beginning of the cropping season in Djakakope, especially in Year 1. This indicates a sufficient supply of water during the early phase of vegetative growth. In Sevekpota, the rainfall curve was continuously below the PET curve, especially in Year 1, probably resulting in water stress. Potential evaporation (PEVAP) was greater than potential transpiration (PTRAN) on both sites. The overall ratio of PTRAN over PET varied between 0.17 and 0.60, and averaged 0.35, thereby indicating about 65% soil water evaporation across the growing season.

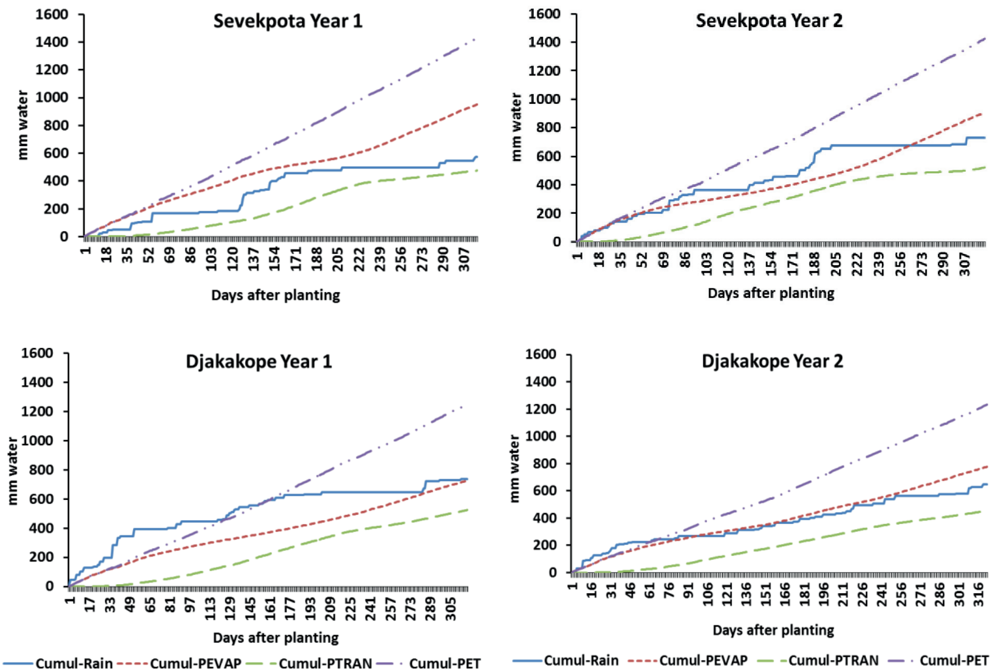

Fig. 5.1. Cumulative rainfall (Cumul-Rain), potential evaporation (PEVAP), potential transpiration (PTRAN) and potential evapotranspiration (PET) from planting to final harvest in Sevekpota and Djakakope in two years.

Soil chemical characteristics show large differences between the two sites (Table 5.2). Sevekpota site had larger soil organic carbon (SOC) and exchangeable K and Na contents but less available P and exchangeable Mg than in Djakakope. Soil Mg, Ca and Na contents are medium on both sites (Howeler 2002). The pH was slightly below 7 at both sites. Soil textures were sandy clay loam to sandy loam in Sevekpota, and loamy sand to sandy in Djakakope.

5.3.1.2. LAI dynamics

The determination of LAI required the prime assessment of light extinction coefficient (*K_ext,* Equation 5.5), which dependent on leaf angle distribution parameter (x). Estimated x values ranged from 1.3 to 4.0 (Table 5.3), hence larger than 1, which was the default value of AccuPAR. These values of x were quite similar from 2 to 5 or 6 MAP with an average value of 1.6 (1-6 MAP), but tremendously increased from 7 to 8 MAP with an overall average of 2.1. We used an x value of 1.6 for the estimation of *K_ext* and LAI since canopy establishment of cassava takes place during the first 6 MAP (Alves 2002). Calculated *K_ext* values range of 0.66-0.77 for different treatments with an overall value of 0.66. A comparable range of *K_ext* values of 0.50-0.78 for cassava was reported earlier (Pellet and El-Sharkawy 1997).

Calculated LAI values spread from 0.62 to 3.64 m^2 m^{-2} in Djakakope, against 0.06 to 3.82 m^2 m^{-2} in Sevekpota. Peak LAI values were reached around 5 MAP in Djakakope and 6 MAP in Sevekpota (Fig. 5.2). The development of LAI over time is related to the dynamics of the cassava canopy in response to water availability. The months with low LAI values around 4 MAP in Sevekpota and from 8-10 MAP at both sites (Fig. 5.2) coincided with dry seasons in August and December to February. The canopy suffered more from LAI reduction at 4 MAP in Sevekpota than in Djakakope, probably because the soil in Sevekpota is shallow with an impervious pan at about 60 cm depth. The soil in Djakakope is deeper (>200 cm), offering the crop the possibility to explore deeper soil layers to access water during drought. In Djakakope, LAI in the dry season (8 to 10 MAP) did not drop as strongly as in Sevekpota. At both sites, LAI rose between 10 and 11 MAP because rain resumed before harvest at 11 MAP. It is common practice in the Coastal Savanna zone of West Africa to perform the final harvest after rain has resumed ensuring the soil is sufficiently wet to harvest and preventing the storage roots from breaking.

Table 5.2. Soil physical and chemical characteristics before crop establishment on the fields in Sevekpota and Djakakope at 0-20, 20-40 and 40-60 cm depth.

	Sevekpota						Djakakope					
	2012, Field 1			2013, Field 2			2012, Field 1			2013, Field 2		
	0 - 20	20 – 40	40 - 60	0 - 20	20 - 40	40 - 60	0 - 20	20 – 40	40 - 60	0 - 20	20 - 40	40 - 60
SOC, g kg^{-1}	11.5	9.2	6.4	12.2	7.3	6.7	6.2	3.6	2.7	4.7	3.1	2.7
SON, g kg^{-1}	0.9	0.6	0.5	0.8	0.5	0.5	0.4	0.3	0.3	0.3	0.2	0.2
Na^+, mmol kg^{-1}	1.15	1.04	0.50	0.40	0.41	0.44	0.09	0.09	0.09	0.14	0.10	0.11
K^+, mmol kg^{-1}	3.52	2.19	1.12	1.35	0.98	1.43	0.38	0.28	0.26	0.66	0.21	0.15
Ca^{2+}, mmol kg^{-1}	18.1	14.5	16.0	13.6	14.3	15.7	18.2	13.6	14.4	17.3	14.9	15.7
Mg^{2+}, mmol kg^{-1}	5.32	3.51	5.43	4.47	5.84	4.86	7.1	6.8	7.7	7.0	4.8	6.5
Sand, g kg^{-1}	536	399	306	680	565	499	835	745	622	858	767	704
Silt, g kg^{-1}	163	147	152	150	101	95	52	46	43	45	37	32
Clay, g kg^{-1}	301	454	542	170	334	406	113	209	335	97	196	264
pH H_2O, 1:2.5	6.5	6.3	6.2	6.5	6.3	6.2	6.5	6.1	6.0	6.5	6.0	5.8
P-Bray-I, mg kg^{-1}	1.9	1.0	0.7	3.2	1.0	0.7	4.5	2.7	1.9	10.4	3.1	1.7
P-total, mg kg^{-1}	189	143	116	202	177	176	155	160	194	194	204	202

Table 5.3. Estimated cassava leaf angle distribution (x) values from 2 to 8 MAP (averages over years and treatments).

MAP	mean	STDEV
2	1.6	0.29
3	1.3	0.28
4	1.4	0.31
5	1.8	0.64
6	2.1	0.96
7	2.6	1.03
8	4.0	2.11
average 2-8 MAP	2.1	0.80
average 2-6 MAP	1.6	0.50

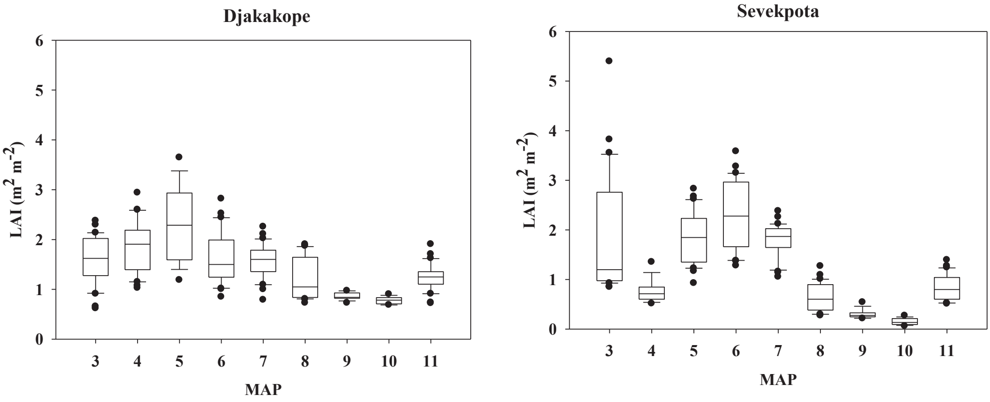

Fig. 5.2. Leaf Area Index (LAI) dynamics at Djakakope and Sevekpota (averages for years and for treatments). Whiskers indicate 10th and 90th percentiles. The black dots indicate outliers.

The responses of LAI to fertilizer applications were stronger with N than with K. Nitrogen applications significantly increased LAI at both sites (data not shown, P = 0.030 and <0.001 in Years 1 and 2 in Djakakope, and P = 0.010 and <0.001 in Years 1 and 2 in Sevekpota). Potassium also significantly increased LAI (data not shown), but only in Year 2 in Djakakope (P = 0.001). No significant effect of P on LAI was observed.

5.3.2. Effect of N, P and K on WUE, PTRAN and PET

Water use efficiency was estimated from the response of cassava biomass DM to cumulative PTRAN by the crop (Fig. 5.3a). This resulted in a WUE of 3.22 g biomass DM produced per kg water transpired over the cropping season, with a coefficient of determination (R^2) of 0.64. WUE was 3.58 and 2.99 g DM per kg water in Djakakope

(R^2 = 0.64) and Sevekpota (R^2 = 0.68), respectively. In Years 1 and 2, WUE values were 3.39 (R^2 = 0.56) and 3.71 (R^2 = 0.59) in Djakakope, and 2.20 (R^2 = 0.92) and 3.61 (R^2 = 0.86) g DM per kg water in Sevekpota (data not shown). Water use efficiency obtained at each harvest for individual treatments varied from 1.54 to 7.12 g DM per kg water transpired (Fig. 5.3a). The variability in WUE within sites can be ascribed to the effect of harvest time since WUE appeared to vary across the cropping season. Greater overall WUE was obtained (graphically) at Harvest 1, decreasing to smaller values at Harvests 2 and 3 (3.89, 3.31 and 3.11 g DM kg^{-1} water transpired at Harvest 1, 2 and 3 ($P < 0.001$) (data not shown). The decline in WUE was also observed between consecutive harvests (Table 5.4). Water use efficiency was larger between planting and Harvest 1, than between Harvests 1 and 2, and between Harvests 2 and 3 in Year 2 in Djakakope and Sevekpota. The opposite trend was observed from planting to Harvest 2 in Sevekpota during Year 1, whereas the lack of increase in biomass between Harvests 2 and 3 negatively affected WUE. The variability in WUE can also be attributed to the response of the crop to different fertilizer rates (Table 5.5).

Nitrogen applications did not significantly affect WUE in Year 1, but led to decreased WUE in Sevekpota in Year 2 (Table 5.5). In Year 2, PTRAN increased and PET declined in response to N applications. Phosphate fertilizer did not have any significant effect on WUE of cassava at either site. Phosphate fertilizer did not affect PTRAN and PET, except for Year 2 in Sevekpota, where 20 kg P ha^{-1} improved PTRAN and reduced PET in contrast to 0 and 40 kg P ha^{-1}. Potassium addition improved WUE over the cropping season in Djakakope in both years (Fig. 5.4a; Table 5.5). The slope of the WUE regression lines was larger at 50 and 100 kg K ha^{-1} than without K (K0). Potassium fertilizer application did not affect WUE in Sevekpota, and had no significant effect on PTRAN and PET.

There were no significant interactions of N, P and K on WUE, except between N, K and harvest time in Djakakope in Year 2 (Table 5.5, Fig. 5.5). Nitrogen application and harvest time influenced the effect of K on WUE. Without added N, the largest WUE was attained at 50 kg K ha^{-1}, irrespective of harvest time (Fig. 5.5). With the application of 50 kg N ha^{-1}, the largest WUE was observed at 100 kg K ha^{-1} at Harvests 1 and 2, and at 50 kg K ha^{-1} at Harvest 3. When 100 kg N ha^{-1} was applied, the largest WUE was obtained at 50 kg K ha^{-1}.

Table 5.4. Change in storage roots and total biomass produced (Mg DM ha^{-1}), accumulated potential transpiration (PTRAN, kg water, m^{-2}), potential evaporation (PEVAP, kg water, m^{-2}), water use efficiency (g biomass DM kg^{-1} water transpired), accumulated light (IPAR, MJ PAR intercepted m^{-2}) and radiation use efficiency (g biomass DM MJ^{-1} IPAR) between consecutive harvests and the overall cropping season. H1-3 stand for Harvest 1-3, PL indicates time of planting.

Site/Year	Period	Storage roots	Biomass	PTRAN	PEVAP	WUE	IPAR	RUE
Djakakope								
1	PL-H3	7.8	16.5	491	768	3.33	1518	1.07
2	PL-H1	4.4	7.9	149	332	5.36	450	1.77
2	H1-H2	3.2	5.0	175	205	2.80	524	0.94
2	H2-H3	0.6	2.2	127	246	1.67	384	0.55
2	PL-H3	8.2	15.1	451	783	3.32	1357	1.10
	P value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Sevekpota								
1	PL-H1	1.1	2.5	115	434	2.18	319	0.79
1	H1-H2	4.5	7.1	283	256	2.49	731	0.96
1	H2-H3	-1.2	-0.2	68	271	-0.27	187	-0.10
1	PL-H3	4.5	9.4	466	961	2.01	1237	0.76
	P value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
2	PL-H1	4.7	8.7	226	363	4.00	569	1.57
2	H1-H2	5.0	7.4	209	240	3.57	531	1.40
2	H2-H3	4.2	9.1	272	567	3.29	705	1.27
2	PL-H3	8.9	17.8	498	930	3.57	1274	1.39
	P value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*0.027*	*<0.001*	*0.009*

5.3.3. Effects of N, P and K on RUE, IPAR, biomass and storage roots production

A RUE of 1.16 g DM per MJ PAR intercepted was derived graphically for the cropping season on both sites (R^2 = 0.61) (Fig. 5.3b). Site-specific RUE values were 1.17 (R^2 = 0.63) in Djakakope and 1.15 g DM per MJ (R^2 = 0.64) in Sevekpota. RUEs for individual treatments were variable and ranged from 0.55 to 2.30 g DM per MJ IPAR (Fig. 5.3b). The small RUEs emanated from poor biomass production, especially in Sevekpota in Year 1, during the period of planting to Harvest 1 and from Harvest 2 to Harvest 3 (Table 5.4). Like in the case of WUE, RUE declined between consecutive harvests (Table 5.4). RUE declined from Harvests 1 to 3, respectively as: 1.47, 1.24 and 1.10 g DM biomass MJ^{-1} IPAR ($P < 0.000$, data not shown).

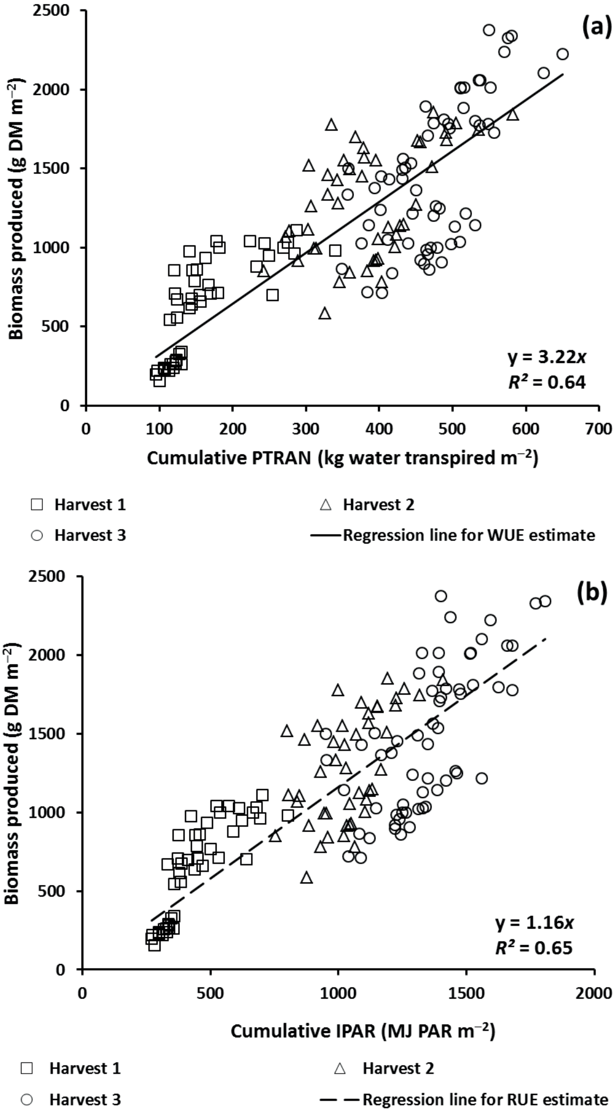

Fig. 5.3. Relationship between the cumulative cassava biomass produced and the cumulative amounts of (a) PTRAN and (b) IPAR for different harvest times, and the regression lines indicating WUE (slopes of the lines). Each point corresponds to the average of a treatment at a given site, harvest, time and year.

Table 5.5. Accumulated potential transpiration (PTRAN, kg water m^{-2}), potential evapotranspiration (PET, kg water m^{-2}) and WUE (g biomass DM kg^{-1} water transpired) as affected by N, P and K fertilizer applications and their significant interactions with harvest time in Djakakope and Sevekpota. For each fertilizer rate of a given nutrient, all rates of the two other nutrients are included.

Main effects /	Factor levels	Djakakope			Sevekpota		
Year		PTRAN	PET	WUE	PTRAN	PET	WUE
N effects							
1	0N	417	1271	3.26	297	1026	2.07
1	50N	529	1251	3.48	335	1021	2.15
1	100N	525	1252	3.31	347	1018	2. 37
	P value	*<0.001*	*<0.001*	*0.338*	*0.906*	*0.907*	*0.539*
2	0N	267	865	3.73	290	1033	3.99
2	50N	318	856	4.11	401	1016	3.70
2	100N	339	853	3.81	468	1005	3.44
	P value	*<0.001*	*<0.001*	*0.051*	*<0.001*	*<0.001*	*0.021*
P effects							
1	0P	477	1261	3. 44	331	1021	2.23
1	20P	524	1252	3.40	326	1022	2.13
1	40P	471	1262	3.22	323	1022	2.24
	P value	*0.479*	*0.492*	*0.823*	*0.193*	*0.281*	*0.577*
2	0P	300	859	3.73	391	1017	3.68
2	20P	308	858	4.13	403	1015	3.49
2	40P	315	857	3.83	365	1021	3.85
	P value	*0.788*	*0.813*	*0.296*	*0.029*	*0.020*	*0.277*
K effects							
1	0K	451	1266	2.66	323	1022	2.14
1	50K	517	1253	3.58	327	1022	2.18
1	100K	503	1256	3.76	330	1021	2.28
	P value	*0.181*	*0.156*	*<0.001*	*0.765*	*0.703*	*0.373*
2	0K	288	862	3.14	368	1021	3.74
2	50K	317	856	4.22	411	1014	3.77
2	100K	318	856	4.26	379	1019	3.51
	P value	*0.301*	*0.297*	*<0.001*	*0.730*	*0.822*	*0.162*
Significant interactions (*P* values)							
2	Harvest x N	*0.001*	*0.002*				*0.092*
2	Harvest x N x K			*0.024*			
2	P x K						*0.062*

Table 5.6. Storage roots and total biomass produced (Mg DM ha^{-1}), IPAR (MJ PAR intercepted m^{-2}) and RUE (g DM MJ^{-1} IPAR) as affected by N, P and K fertilizer applications and their significant interactions with harvest time in Djakakope and Sevekpota. For each fertilizer rate of a given nutrient, all rates of the two other nutrients are included.

Main effects / Year	Factor level	Djakakope Storage roots	Djakakope Biomass produced	Djakakope IPAR	Djakakope RUE	Sevekpota Storage roots	Sevekpota Biomass produced	Sevekpota IPAR	Sevekpota RUE
N effects									
1	0N	6.33	13.60	1308	1.04	3.24	6.16	799	0.77
1	50N	8.82	18.43	1628	1.13	3.85	7.19	889	0.81
1	100N	8.15	17.38	1617	1.07	4.18	8.21	916	0.90
	P value	*<0.001*	*0.004*	*<0.001*	*0.175*	*0.826*	*0.573*	*0.913*	*0.511*
2	0N	5.59	9.97	818	1.22	6.70	11.58	765	1.51
2	50N	7.45	13.08	954	1.37	8.23	14.84	1021	1.45
2	100N	7.28	12.90	1009	1.28	8.39	16.11	1157	1.39
	P value	*0.006*	*0.010*	*<0.001*	*0.030*	*<0.001*	*<0.001*	*<0.001*	*0.156*
P effects									
1	0P	7.57	16.40	1491	1.10	3.75	7.37	879	0.84
1	20P	8.28	17.84	1611	1.11	3.67	6.93	868	0.80
1	40P	7.44	15.17	1451	1.05	3.86	7.25	858	0.84
	P value	*0.899*	*0.495*	*0.467*	*0.881*	*0.354*	*0.473*	*0.173*	*0.565*
2	0P	6.30	11.18	906	1.23	7.63	14.40	994	1.45
2	20P	7.34	12.72	927	1.37	7.65	14.06	1018	1.38
2	40P	6.68	12.05	948	1.27	8.03	14.07	931	1.51
	P value	*0.089*	*0.101*	*0.715*	*0.319*	*0.094*	*0.372*	*0.043*	*0.271*
K effects									
1	0K	5.58	11.99	1382	0.87	3.60	6.92	860	0.80
1	50K	8.71	18.51	1598	1.16	3.75	7.13	870	0.82
1	100K	9.01	18.92	1573	1.20	3.92	7.51	875	0.86
	P value	*<0.001*	*<0.001*	*0.074*	*<0.001*	*0.033*	*0.030*	*0.780*	*0.297*
2	0K	4.87	9.04	877	1.03	7.71	13.76	939	1.47
2	50K	7.74	13.37	952	1.40	8.56	15.48	1038	1.49
2	100K	7.71	13.54	952	1.42	7.05	13.29	966	1.38
	P value	*<0.001*	*<0.001*	*0.301*	*<0.001*	*0.048*	*0.020*	*0.553*	*0.101*
Significant interactions (*P value*)									
2	P x K								*0.049*
2	Harvest x N		*0.007*	*<0.001*					
2	Harvest x K	*<0.001*	*<0.001*						
2	Harvest x N x K				*0.024*				

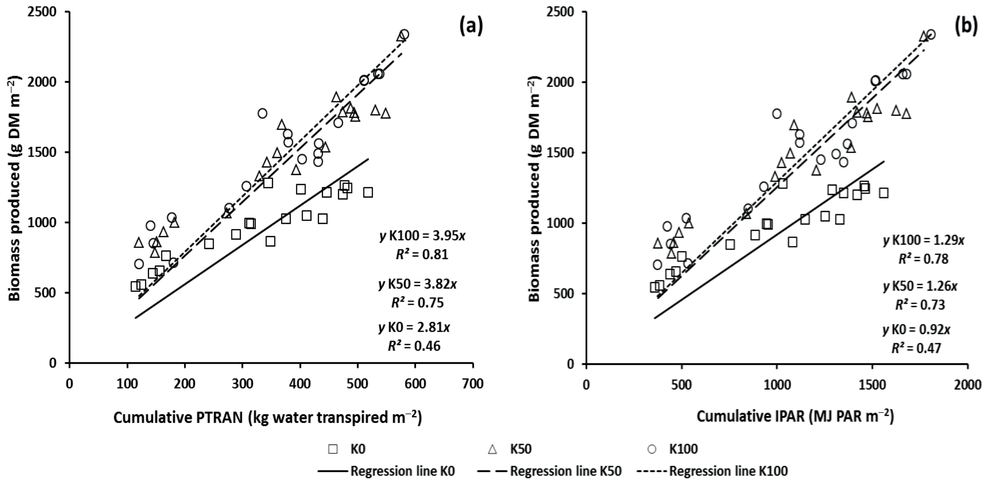

Fig. 5.4. Response of cassava biomass production to (a) PTRAN and (b) IPAR accumulation as affected by K rates in Djakakope, and the related (a) WUE and (b) RUE as indicated by the slopes of the regression lines. Each point corresponds to the average of a fertilizer treatment at a given harvest, time and year.

The effects of N fertilizer on RUE were not significant, except for Year 2 in Djakakope, where the largest RUE was attained with the application of 50 kg N ha^{-1} (Table 5.6). Nitrogen additions did increase storage roots DM, biomass DM and IPAR in both years in Djakakope and in Year 2 in Sevekpota. There was no significant effect of P fertilizer on RUE, or on storage roots DM, biomass DM and IPAR in Djakakope. This was also the case in Sevekpota, except for IPAR in Year 2, where the application of 20 kg P ha^{-1} generated the largest average IPAR. Potassium fertilizer increased RUE, as well as storage roots and biomass DM in Djakakope. The smallest values of RUE were found in treatments without fertilizer, especially in Djakakope, where RUE was 0.92 g DM MJ^{-1} IPAR without K application, and 1.26 and 1.29 with the application of 50 and 100 kg K ha^{-1}, respectively (Fig. 5.4b). However, K did not significantly affect IPAR at this site. Likewise, K applications did not influence IPAR and RUE in Sevekpota. K application did increase storage roots and biomass production at this site.

Most nutrient interaction effects on RUE were observed in Year 2. In Djakakope the interaction between K, N and harvest time on RUE was significant. The strongest responses of RUE to K were obtained at Harvest 1 at smaller N rates (0 and 50 kg ha^{-1}) (Data not shown since the trends were comparable to Fig. 5.5). At the same site, interaction effects between harvest time and N were significant for biomass production and IPAR, and so was the interaction between harvest time and K on storage roots and biomass production. In Sevekpota, the only significant interaction effect on RUE was observed between P and K.

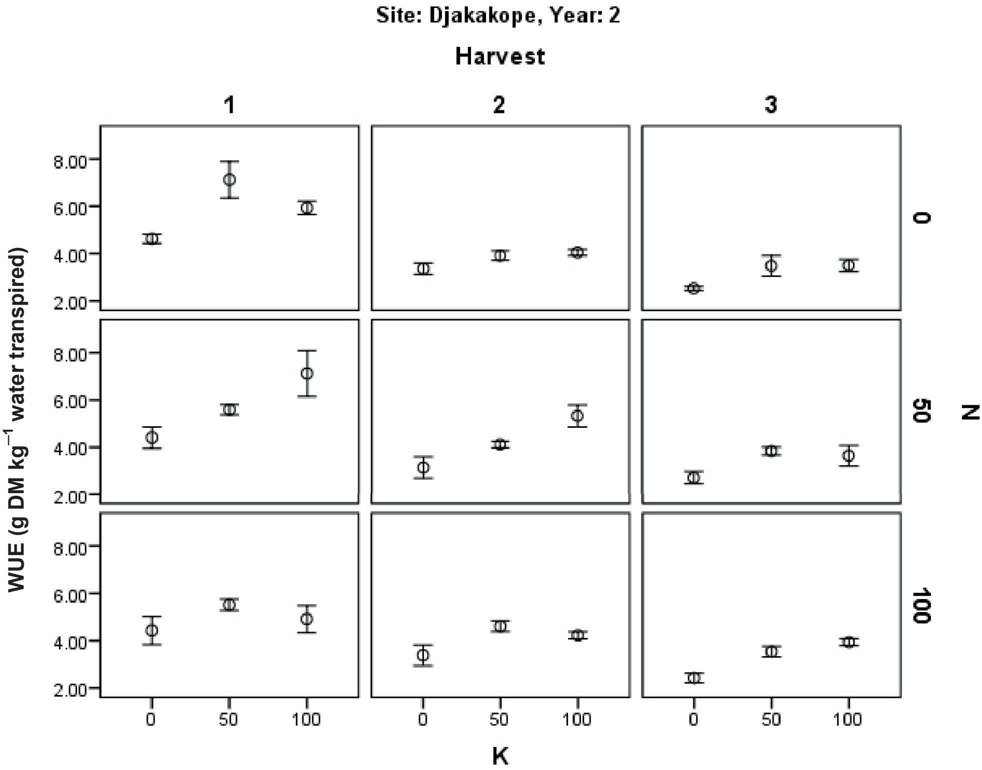

Fig. 5.5. WUE as affected by interactions between K and N rates (kg ha─1) and different harvest times in Djakakope in Year 2. Each point corresponds to the mean WUE value at a given K and N rate at a specific harvest time. The bars around the means represent the SEM.

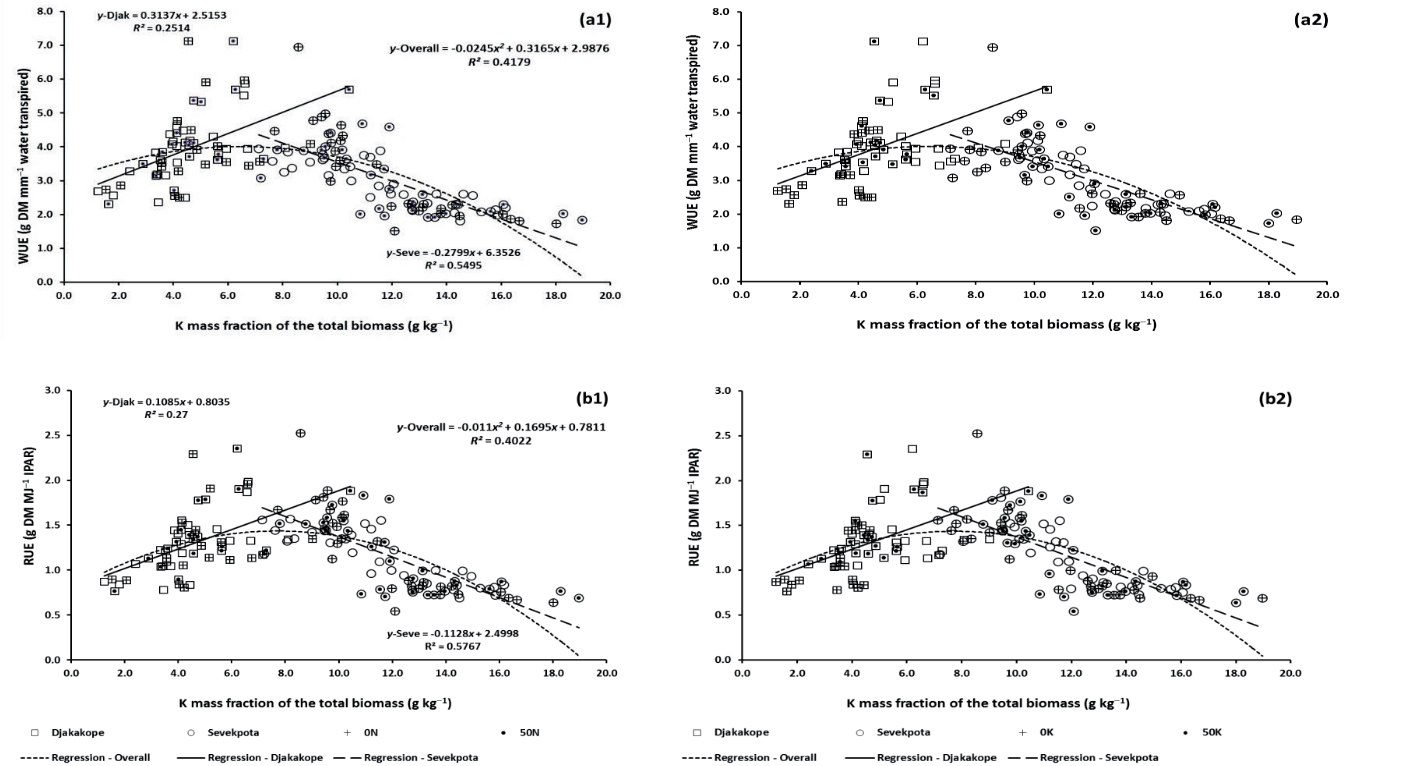

Fig. 5.6. Relationship between plant biomass K mass fraction and (a) WUE, and (b) RUE at two sites with highlight of applied N (a1, b1) and K (a2, b2) quantities in kg ha^{-1}. The blank symbols indicate 100 kg N ha^{-1} in a1 et b1, 100 kg K ha^{-1} in a2 et b2. Djak and Seve in the regression equations stand for the sites Djakakope and Sevekpota. A polynomial regression line was fitted for all data; linear lines were fitted for data from the individual sites.

Table 5.7. Pearson correlation analysis results between RUE and K mass fractions of the plant for different N and K fertilizer application rates at two sites.

Location	Treatment	*R*	*P*	*n**
Djakakope	0N	0.335	0.149	60
	50N	0.606	0.005	60
	100N	0.644	0.002	60
	0K	0.516	0.020	60
	50K	0.520	0.019	60
	100K	0.089	0.709	60
Sevekpota	0N	-0.827	0.000	90
	50N	-0.675	0.000	90
	100N	-0.846	0.000	90
	0K	-0.767	0.000	90
	50K	-0.705	0.000	90
	100K	-0.854	0.000	90

**n* represents the number of observations.

5.3.4. Relationship between cassava tissue K mass fractions and WUE and RUE

The relationship between cassava tissue K and WUE and RUE followed a polynomial curve (Fig. 5.6). Water use efficiency and RUE increased as plant tissue K increased, and reached their maximum values within a range of plant tissue K values, then declined beyond this range. The greatest values of WUE and RUE (above 75th percentile) were achieved within K mass fractions values of 3.9-11.9 g kg^{-1}. Increasing WUEs and RUEs with increasing K concentrations were mainly observed in Djakakope, where the soil was poor in K, whereas the reverse relationship was observed in Sevekpota. Pearson correlation analysis between RUE and K mass fractions (Table 5.7) indicated that without N application in Djakakope, there was no significant relationship between K mass fractions and RUE. When N fertilizer application was applied, RUE values rose with increasing K mass fractions. On this site, RUE and K mass fractions were positively correlated without K and with the application of 50 kg K ha^{-1}. No significant correlation was obtained when 100 kg K ha^{-1} was applied. In Sevekpota, RUE declined with increasing K mass fractions in the plant, regardless N application rates (0, 50 and 100 kg N ha^{-1}). The correlations between RUE and K mass fractions were also negative, irrespective of K application rates (0, 50 and 100 kg K ha^{-1}). The correlation analysis between WUE and K mass fractions indicated similar trends to those of RUE (not shown).

5.4. Discussion

The prime objective of this study was to assess how K availability interacting with N, P and harvest time affect cassava yield, WUE, transpiration, RUE and light interception under rain-fed conditions in West Africa. Differences in cassava performance between sites and seasons were clear. Stronger responses of WUE, water transpiration, RUE, light interception, biomass and storage root production to fertilizer applications were obtained at Djakakope, which had soils that were more deficient in N and K than Sevekpota. Water stress restricted crop growth at Sevekpota in Year 1 (Fig. 5.1), especially early in the vegetative stage. Water availability to cassava from 1 to 5 MAP is crucially important for determining yield of storage roots (Connor et al. 1981).

The effect of N applications on WUE was not significant in most cases, but N application increased PTRAN and reduced PET. The increase in PTRAN indicates a rise in plant photosynthetic activity (El-Sharkawy and Cock 1986) due to the positive effect of N on leaf area development (Section 3.2). By extending leaf area, N application accelerates and increases soil coverage by the plant canopy, which leads to reduced evaporation from the soil (Mihara 1961; Pellet and El-Sharkawy 1997). Unlike N, addition of K improved WUE in Djakakope (Fig. 5.4a), but not in Sevekpota. This shows that K fertilizer can increase WUE and cassava production on K deficient soils under rain-fed conditions. A similar influence of K availability on crop productivity under rain-fed conditions was found for banana production in Uganda (Taulya 2013). The positive effect of K on WUE could be associated with the ability of K to regulate stomatal aperture and closure (Chérel et al. 2014), given the high sensitivity of cassava to leaf-to-air vapour pressure deficit. This mechanism allows the crop to consume the limited amount of available water slowly during the dry season, resulting in greater dry matter gain over the stress period and larger WUE over the cropping season (El-Sharkawy 2004). However, in our study, K effects on WUE can be ascribed to the effect of K on the total biomass produced, since WUE was expressed relatively to the potential water transpiration, which likely masks the effect of stomata regulation by the crop on transpiration. Nevertheless, we assumed that the effects of stomata regulation on the cassava plant's performance are reflected in the total biomass measured in the field experiments.

The availability of K was not a major determinant of PTRAN and PET, for which N was more important. The effect of K on WUE was influenced by N application and harvest time (Fig. 5.5). Along with increasing rates of K, optimal N supply was required at different crop ages for greater WUE of cassava. The greatest responses were obtained at Harvest 1 around 4 MAP at 50 kg K ha^{-1} without N application, and at 100 kg K ha^{-1} with the application of 50 kg N ha^{-1}. These results suggest a need for a balanced nutrition by adjusting K application rates to match the availability of N. However, too much N appeared to impede the positive effect of K on WUE, since the value of WUE achieved at 50 kg N ha^{-1} was greater than that obtained at 100 kg N ha^{-1} with the application of 100 kg K ha^{-1} in Djakakope, especially at 4 MAP (Fig. 5.5). Too much N relative to K supply can induce an unbalanced nutrition (Ezui et al. 2016), which can reduce the WUE by the crop.

No significant effect of P application on WUE was observed. This implies that the P supplying capacity of the soil was sufficient to reach WUE values comparable with those obtained at P fertilizer rates of 20 and 40 kg ha^{-1}, even though soil available P concentrations were small, especially at Sevekpota (Table 5.2). Cassava forms strong mycorrhizal associations, which makes it efficient in extracting P from the soil (Sieverding and Leihner 1984).

It is noteworthy that the overall WUE was probably slightly overestimated, especially during drought periods for two main reasons. The effect of leaf litter on reducing evaporation and increasing the availability of water for transpiration was not accounted for in the estimation of potential evaporation and transpiration. Moreover, we did not consider the impact of a dry soil surface crust reducing evaporation. We did not have appropriate data to implement such corrections. However, the estimated range for WUE of 1.54-7.12 g DM per kg of water transpired, which corresponds to 0.5-2.5 g DM per kg water evapo-transpired for an average PTRAN/PET ratio of 0.35 obtained on the study sites, falls within the interval of 0.4-4.8 g DM per kg water evapo-transpired reported by Lemon (1969) as cited by Yao and Goué (1992). Furthermore, the overall WUE of 3.22 g biomass DM per kg water transpired is comparable to that reported by El-Sharkawy and Cock (1986) of 2.9 g total biomass DM per kg of water transpired for cassava. Our WUE is also comparable to 3.1 g total biomass DM per kg of water transpired reported for sorghum (El-Sharkawy and Cock 1986), and falls within the range obtained for wheat: 2.5–6.3 g biomass kg^{-1} water transpired (Siahpoosh and Dehghanian 2012; Zhang et al. 1998). The WUE we obtained for cassava is much larger than that of other C_3 plants such as bean with 1.7 g total biomass DM kg^{-1} water transpired (El-Sharkawy and Cock 1986), indicating a high drought tolerance of cassava.

A RUE of 1.16 g DM per MJ PAR intercepted across the cropping season (Fig. 5.3b) falls within the lower part of the range of 1.15–2.30 g DM per MJ IPAR obtained by Pellet and El-Sharkawy (1997). This could be attributed to the fact that the latter range was achieved under high rainfall regime amounting 1800 mm per year, whereas only 574 to 736 mm rain was recorded across the growing season on our study sites.

Radiation use efficiency and total biomass production were differently affected by fertilizer applications. Potassium applications increased RUE, storage roots and total biomass production in Djakakope, but did not significantly affect IPAR. The reported beneficial effects of K on plant growth include CO_2 assimilation for photosynthesis, enzyme activation or stimulation and protein synthesis (Chérel et al. 2014). Potassium application increases leaf K^+ concentration, especially cytosolic K^+ and chloroplast K^+, which enhances the photosynthetic rate of a specific leaf area (Marschner and Marschner 1995). Plant tissue K^+ concentration is related to soil K availability. Hence, the poor availability of soil K at Djakakope contributed to the response of cassava storage roots and biomass to K applications. The soil exchangeable K of 0.38 and 0.66 mmol kg^{-1} in Years 1 and 2 at this site were below the critical range of 0.8 to 1.8 mmol kg^{-1} soil exchangeable K for cassava production (Howeler 2002). The response to K in terms of cassava biomass and storage roots in Year 2 in Sevekpota with a soil exchangeable K value of 1.35 mmol kg^{-1}, implies that the critical K requirement for cassava production on this site is above 1.35 mmol kg^{-1}. However, the positive responses of biomass and storage roots to K in Year 1 in Sevekpota were unexpected since exchangeable K content of the soil was high (3.5 mmol kg^{-1}). This may be explained by the fact that under drought conditions, chloroplasts loose a large amount of their K^+, resulting in decreased photosynthesis, which can be overcome through external K supply (Marschner and Marschner 1995). It could also be explained by the large leaf K requirements under drought conditions to maintain high stomatal K^+ concentrations and thus optimal rates of photosynthesis (Marschner and Marschner 1995).

The improvement of RUE by K application without a substantial effect on IPAR in Djakakope suggests that K affects more the efficiency of converting light into photosynthates than the amount of light intercepted. This conversion of light energy into photosynthates is driven by the enhancement of photosynthesis by K applications (Marschner and Marschner 1995), involving the activation of many enzymes and the production of adenosine triphosphate (ATP).

The lack of increase of RUE in response to K applications in Sevekpota, especially in Year 2 when K concentration was small (1.35 mmol kg^{-1}) may be explained by the fact that RUE without K application at this site (1.47 g DM MJ^{-1} PAR) was close to optimum, since a comparable RUE was achieved with K applications in Djakakope (1.40–1.42 g DM MJ^{-1} PAR) in Year 2 (Table 5.6). This suggests that plant tissue K concentration is more limiting for RUE than soil exchangeable K. Under K deprived conditions, optimum crop growth can be maintained as long as the cytosolic K^+ concentration is above a critical value, despite the depletion of vacuolar K^+ concentrations (Chérel et al. 2014). However, excess K did not generate higher RUE

(Fig. 5.6b, Table 5.7). The largest RUEs were achieved with a total biomass K mass fraction range of 3.9 to 11.9 g K kg^{-1} biomass DM. Below and beyond this range, RUE of cassava was smaller. Weak RUEs with low K concentration were obtained in Djakakope (Fig. 5.6b), because soil K was highly deficient at this site, which likely caused a lower cytosol K^{+} concentration, leading to the poor RUE. By contrast, in Sevekpota poor RUE was observed with large concentrations of K (Fig. 5.6b), and RUE declined with increasing K concentrations, with or without K fertilizer application. This can result from the fact that the indigenous K supply on this site was generally above critical requirements for cassava response to K applications. However, this may also imply an overriding impact of another limiting factor, which may be drought as shown in Fig. 5.1. These findings suggest that the large RUE of cassava can be achieved under optimum plant tissue K concentrations.

Nitrogen applications did not significantly influence RUE, but led to increased production of storage roots and biomass, and improved light interception of cassava (Table 5.6). Thus, the fact that N applications increased light interception and biomass production did not imply increased RUE. In response to N applications, both biomass (numerator) and IPAR (denominator of RUE) changed in a similar way, without yielding any significant change in RUE. For this reason, one should look to both RUE (and WUE) and their component variables (biomass and IPAR for RUE; and biomass and PTRAN for WUE), for an enhanced understanding of the effect of nutrients on crop productivity. The positive response of IPAR and the lack of response of RUE to N applications together suggest that N is more important in determining radiation interception than in RUE of cassava. However, Sinclair and Horie (1989) showed that addition of N can increase RUE at low leaf N content for maize, rice and soybean. Possibly in our case, indigenous soil N supply provided sufficient leaf N for optimal RUE of cassava. However, N applications induced positive correlations between RUE and K concentrations in Djakakope (Table 5.7), where soil N and K were low (Table 5.2). Thus, N application can enhance K uptake, and therefore contribute to the increase of RUE on N and K deficient soils.

Both WUE and RUE were larger when estimated at 4 MAP (Harvest 1) than at 8 and 11 MAP (Harvest 2 and 3) in Djakakope and Sevekpota in Year 2 (Table 5.4). These results may be attributed to greater water and light energy demands during the first 6 MAP, which comprises a period of strong vegetative growth of cassava, generally from 3 to 6 MAP (Alves 2002). Beyond this period (7-10 MAP), the rate of shoot growth is reduced in favour of carbohydrate translocation to the roots (Alves 2002). Veltkamp (1985) also obtained higher RUE values of 1.34-1.40 g biomass DM MJ^{-1} IPAR during the first 6 MAP for four different cultivars and reported the decrease of RUE beyond 6 MAP. Since the variations in RUE and WUE seem to be physiologically imposed, it might be erroneous to use their values estimated at one specific stage of the crop alone to predict cassava productivity for the whole crop cycle.

Water-use efficiency and RUE explained the effect of K on cassava biomass and storage root production. Hence, improved K management can increase WUE and RUE of cassava. High WUE is important, especially in rain-fed production systems in SSA to optimise the use of water during droughts. High RUE increases the productivity of the crop. Cassava cultivars selection for K deficient soils should favour cultivars with high K use efficiency (El-Sharkawy and Cadavid 2000) that can optimise the use of available K and response to K fertilizers. Enhancing K management implies improving soil K supply, which involves applying the right rate of K when the plant needs it most on soils where K availability falls below the critical requirement for the plant. Potassium requirements of cassava varied from site to site, from harvest to harvest, and depended on N availability. Thus, improving K supply must be matched with a balanced supply of other nutrients, especially N. These findings demonstrate that the food insecurity threat of nutrient mining in smallholder farming systems in SSA is compounded by reductions in the efficiency of water use. This study also provides quantitative values of RUE for water-limited yield predictions, and values of WUE that can be indicative in irrigation planning to estimate cassava water needs and distributions over the season for a given target yield.

5.5. Conclusion

We showed that the effect of K on the productivity of cassava was largely due to the positive effect of K on RUE and WUE rather than on light interception and water transpiration. Light interception and water transpiration of cassava were more influenced by the availability of N than of K, stressing the leading role of N in photosynthesis. These results highlight the important and complementary roles of N and K in achieving high RUE and WUE of cassava under rain-fed conditions in West Africa. Cassava response to K is mainly noticeable when soil K is below the required critical level. The best responses of cassava to K applications were observed during the vegetative stage of the crop, suggesting a timely application of required nutrients and timely planting to make the best use of the rainfall to achieve high yields. Enhanced K management is key to improving WUE and RUE for increased cassava production under rain-fed conditions in West Africa.

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CHAPTER SIX

6.0. Understanding water-limited yield of cassava in Southern Togo

Abstract

The present study aimed to improve our understanding of water-limited yields of cassava under rain-fed systems in Southern Togo using a modelling approach based on light interception and use efficiency. Data collected in four different fields in two locations, Sevekpota and Djakakope, during two consecutive growing seasons from 2012 to 2014 helped to achieve this goal. Data from Sevekpota in Year 2, which received a larger amount of rainfall than Year 1 were used for model parameterisation and calibration. The model was evaluated with data from Year 1 in Sevekpota and Years 1 and 2 in Djakakope. The model calibration and testing results indicated an overall good agreement between simulated and observed leaf area index, storage roots and total biomass dry matter. The decline of LAI towards the end of the cropping season and the regrowth at the onset of the new rainy season matched well with the simulated dormancy and recovery from the dormancy phase. The model also captured the decline in yield of storage roots due to leaf regrowth at the recovery from dormancy as observed in Sevekpota. Best harvest periods to minimise storage roots losses can be identified on that basis. The assessment of the effect of drought as the difference between simulated potential yields, assuming water content at field capacity, and water-limited yields indicated that drought can cause 9-60% loss of yield. The largest yield loss was recorded in Sevekpota in Year 1, and was mainly due to water stress occurring from 79 to 125 days after planting. The best planting period simulated was around mid-February, which is earlier than the usual planting time in Southern Togo. Further experimental studies are required to confirm this finding and assess how this can practically fit into existing cropping systems. These findings enhance our understanding of water-limited yield of cassava and unveil possibilities of improving it in the region.

Keywords: *Dormancy, drought, rain-fed, planting date, leaf area index, LINTUL.*

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6.1. Introduction

Drought stress can cause serious yield reductions in cassava production despite its drought tolerance. Yield losses ranging from 32-60% have been reported under prolonged drought as compared with irrigated cassava crops (Alves 2002; Connor et al. 1981). Cassava is particularly sensitive to drought stress occurring between 1 and 5 months after planting. Prolonged water stress towards the end of the first 12-month cycle of the crop's growth period can result in entering the dormancy phase (Alves 2002). Dormancy is characterised by decreased leaf production, increased leaf shedding (to an extent that almost all leaves fall) and termination of shoot vegetative growth (Alves 2002). Dormancy is generally broken by rainfall, but little is known about which soil moisture suction suffices to trigger the recovery from dormancy. It has been reported that the recovery from drought is characterised by a rapid production of new leaves, which temporarily occurs at the expense of carbohydrate reserves in the stem and storage roots (El-Sharkawy and Cock 1987). To our knowledge, the extent to which this process affects stems and storage roots yields is not well understood. A better understanding of this process could guide decisions on harvest time for increased cassava yield. These knowledge gaps unveil the need for understanding drought stress impacts on yields in sub-Saharan Africa where most cassava is produced under rain-fed conditions.

Process-oriented models are used for assessing water-limited yields. The most recommended process-oriented model for cassava growth is the GUMCAS (meaning "simulate" in Tagalog, the national language of the Philippines) model by Matthews and Hunt (1994). The GUMCAS model, also referred to as CROPSIM-Cassava in the framework of the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al. 2003; Singh et al. 1998), was designed to simulate potential, water-limited and nitrogen-limited growth of cassava as affected by environmental variables (temperature, solar radiation, drought stress, photoperiod, vapour pressure deficit) and crop-genetic characteristics. In this model, the potential biomass growth is determined as a function of the leaf area index and the maximum canopy photosynthesis rate of a given cultivar, and the leaf and stem growth are modelled independently to the total assimilate supply. The accurate assessment of these variables is required to ensure a good estimate of storage roots dry matter yield. The growth of leaf, stem and fibrous roots are modelled in great detail and involve many variables. Leaf growth is modelled as a function of leaf appearance and expansion rates, the latter depending on the number of active growing apices, individual leaf area of newly produced leaves and on the specific leaf area. The modelling of leaf appearance rate involves cultivar-specific parameters like the leaf appearance rate at emergence and the developmental time from emergence to the stage at which leaf production effectively ceases. Stem growth is described in relation to the leaf growth rate and the stem/shoot fraction. Root growth is quantified in relation to leaf and stem growth rates and to the crop developmental age since emergence. The unavailability of data to assess these model input parameters could decrease the accuracy of simulation results for cassava in West Africa. Another characteristic of GUMCAS is the ability to assess the effects of recovery from drought, which are modelled via a compensatory increase of individual leaf size (Connor and Cock 1981). However, the contribution of storage roots as source of assimilates for this compensatory leaf size increase has not been indicated. Storage roots dry matter reduction and leaf dry matter increase at the recovery from drought has been observed in previous studies (Howeler and Cadavid 1983).

The Light INTerception and UtiLisation (LINTUL) model (Spitters 1990) provides an alternative modelling approach. The first version of the model (LINTUL 1), developed for simulating potential growth, aimed to assess potato growth from daily intercepted photosynthetically active radiation (PAR) and light use efficiency under optimal growth conditions. It was thereafter extended to simulate crop growth under water-limited conditions (LINTUL 2) (Spitters and Schapendonk 1990). The model has been adapted for crops such as maize (Farré et al. 2000), winter oilseed rape (Habekotté 1997), rice (Shibu et al. 2010) and banana (Nyombi 2010; Taulya 2015). In the model, biomass growth rate is assumed linearly correlated with the amount of light intercepted with a constant light or radiation use efficiency, following Monteith (1977). Unlike in GUMCAS, the partitioning of the dry matter among different plant organs is modelled in LINTUL using partitioning factors defined as a function of the physiological age of the crop. It has been reported that fibrous root, stem and leaf growth have priority on storage root growth in the juvenile vegetative stage of the crop, and that translocation of dry matter to storage roots increases in the reproductive stage (Alves 2002). The LINTUL model had not yet been adapted for cassava.

This study aims at adapting LINTUL for cassava in order to assess water-limited yields as affected by drought stress and planting date in rain-fed systems in West Africa. In separate field experiments in Southern Togo data were collected for model parameterisation and testing, followed by the application of the model to assess the contribution of planting date on mitigating the impact of drought on the performance of the crop.

6.2. Materials and methods

6.2.1. Description of LINTUL-Cassava

6.2.1.1. Cassava development simulation

The original LINTUL2 model to simulate water-limited production was modified to incorporate the development and growth of cassava under water-limited conditions. The model assumes three development phases as in CROPSIM-Cassava: i) planting to emergence, ii) emergence to first branching, iii) first branching to maturity or harvest. The functioning of the model is summarized in the relational diagram in Fig. 6.1, which depicts relationships between key parameters as described in the sections below. Temperature is the key environmental factor driving these phases. The duration of each phase is measured using the temperature sum (TSUM). The TSUM is determined as a function of the daily effective temperature (DTEFF) and of the planting date (DOYPL) (Eq. 6.1). The DTEFF is calculated as the difference between the daily average temperature (DAVTMP) and the base temperature (TBASE) (Eq. 6.2).

$$TSUM = DTEFF \times f\,(TIME, DOYPL) \qquad \text{(Eq. 6.1)}$$

$$DTEFF = MAX\,(\,0., DAVTMP - TBASE\,) \qquad \text{(Eq. 6.2)}$$

DTEFF: [^{o}C] is the daily effective temperature.

DAVTMP: [^{o}C] is the actual average daily temperature approximated by (TMAX+TMIN)/2.

TBASE [^{o}C] is the base temperature below which the crop no longer develops; DOYPL is the planting date (day of the year on which planting occurred).

a. Emergence

The model assumes that the emergence (EMERG) occurs when soil water content (WC) is above wilting point (WCWP) and that TSUM accumulation from the time of planting has reached OPTEMERGTSUM. The OPTEMERGTSUM defines the optimal amount of TSUM accumulated from planting to emergence. The emergence occurs within two weeks after planting (Alves 2002). We used a default OPTEMERGTSUM value of 180^{o}C under an optimum temperature of 27^{o}C (optimum cassava growth is achieved between 25 and 29^{o}C) and a TBASE of 15^{o}C (Alves 2002). The list of model parameters and their default values are presented in Table 6.1. As soon as EMERG is activated (EMERG = 1), it remains ON for the rest of the growth process.

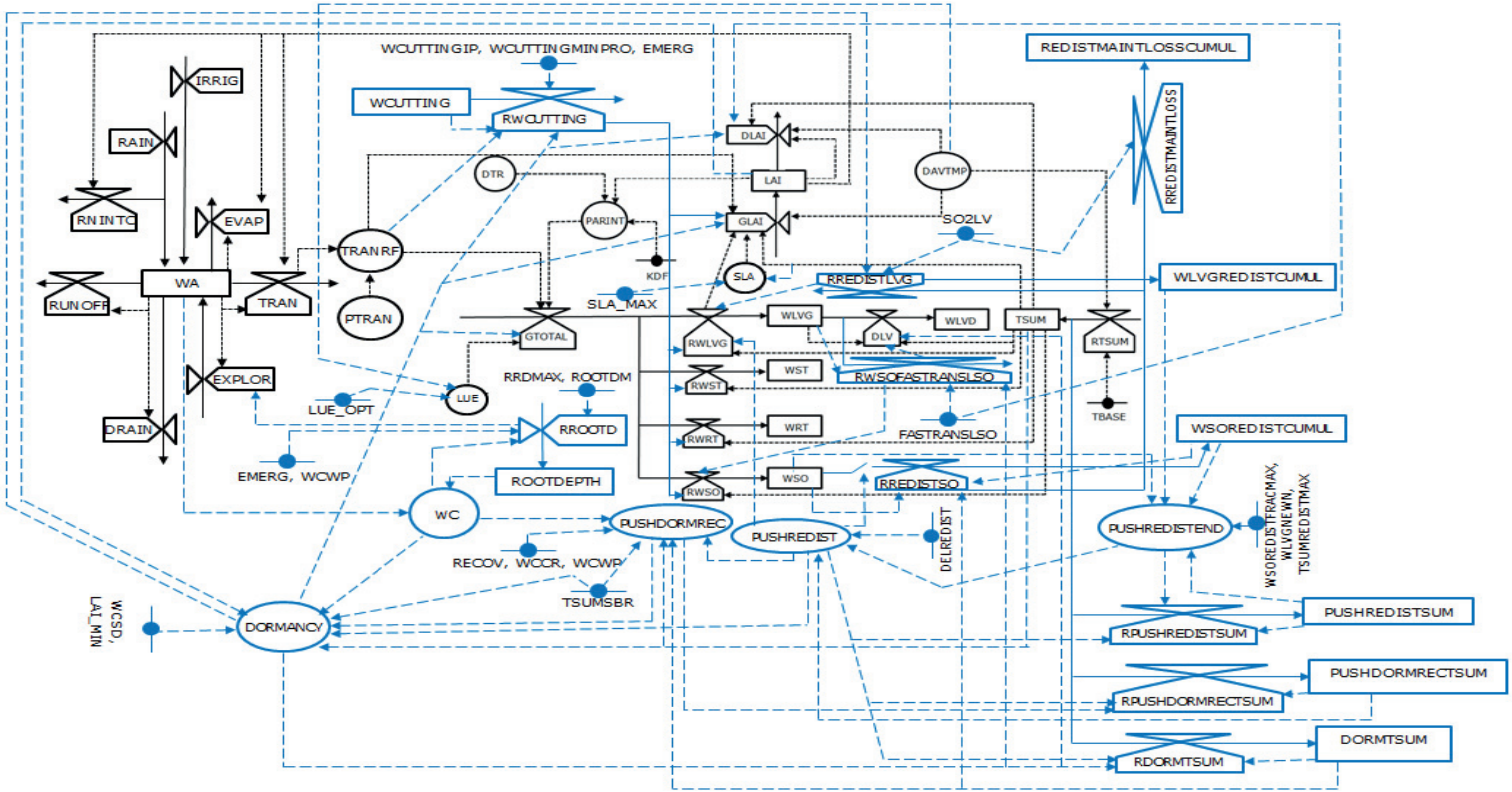


Fig. 6.1. Relational diagram of LINTUL-Cassava for water-limited production. In black the original LINTUL2 with the crop growth part (right part in black) and the water balance part (left part in black). In blue the representation of the modification we made including the cutting growth (middle of the upper part in blue), the dormancy part (lower left corner in blue), and the redistribution part (lower middle and right part in blue).

Table 6.1. Model parameters and default values.

	Parameters codes	Signification	Unit	Default value	Source
	Crop parameters				
1.	SLA_MAX	Maximum specific leaf area	$m^2\ g^{-1}$	0.03	Measured
2.	WCUTTINGUNIT	Average weight per cutting	G	14	van Heemst (1988)
3.	TBASE	Base temperature	^oC	15	Alves (2002)
4.	RGRL	Relative growth rate of leaf area	$(^oC\ d)^{-1}$	0.003	Estimated
5.	LAIEXPOEND	Maximum leaf area index for exponential growth phase	$m^2\ m^{-2}$	0.75	Estimated
6.	TSUMSOBULKINIT	Temperature sum accumulation to the start of storage roots bulking	^oC d	529	El-Sharkawy (2003)
7.	TSUMSBR	Temperature sum accumulation to first branching	^oC d	776	Gutierrez et al. (1988)
8.	LAICR	Critical leaf area index	$m^2\ m^{-2}$	5	Keating et al. (1982)
9.	LAI_MIN	Minimum leaf area index	$m^2\ m^{-2}$	0.09	Measured
10.	RDRSHM	Relative death rate of leaves due to shade	d^{-1}	0.09	Estimated
11.	RDRB	Base relative death rate of leaves	d^{-1}	0.09	Estimated
12.	FRACTLLFENHSH	Fraction of leaf life at which enhanced shedding can be induced		0.85	Estimated
13.	FASTRANSLSO	Proportion of senesced leaf weight translocated to storage roots before the shedding of the leaf		0.5	Estimated
14.	OPTEMERGTSUM	Optimal temperature sum for emergence	^oC d	170	Alves (2002)
15.	DELREDIST	Delay for redistribution of dry matter	^oC d	12	Estimated
16.	TSUMLA_MIN	Temperature sum accumulation for minimum leaf area	^oC d	180	Alves (2002)
17.	WSOREDISTFRACMAX	Maximum proportion of dry matter redistribution from storage roots for the formation of new leaves		0.05	Estimated
18.	WLVGNEWN	Minimum amount of new leaves weight produced in the redistribution phase	g DM m^{-2}	10	Estimated
19.	SO2LV	Conversion rate of storage organs dry matter to leaf dry matter	g leaves DM g^{-1} storage roots DM	0.8	Estimated

20.	RRREDISTSO	Relative rate of redistribution of dry matter from storage roots to leaves	d^{-1}	0.01	Estimated
21.	RECOV	Proportion of critical soil water content above which the crop recovers from drought		0.7	Estimated
22.	TSUMLLIFE	Temperature sum accumulation to leaf life	^{o}C d	1500	Alves (2002)
23.	TSUMREDISTMAX	Maximum temperature sum accumulation to indicate the duration of dry matter redistribution	^{o}C d	144	Estimated
24.	WCUTTINGMINPRO	Minimum proportion of the stem cutting weight that remains unchanged		0.15	Estimated
25.	RDRWCUTTING	Relative decrease rate of cutting weight	d^{-1}	0.017	Alves (2002)
26.	LUE_OPT	Light use efficiency at optimum growing conditions	g MJ PAR^{-1}	1.5	Measured
27.	K_ext	Light extinction coefficient		0.7	Measured
28.	RRDMAX	Maximum rate of increase in rooting depth	m d^{-1}	0.022	Matthew and Hunt, 1994
	Soil parameters for the Ferruginous soil at Sevekpota in Year 2				
29.	WCI	Initial water content (at start of the simulation run)	$m^3\ m^{-3}$	0.41	Estimated as identic to WCFC at planting
30.	WCAD	Water content at air dry	$m^3\ m^{-3}$	0.01	Estimated
31.	WCWP	Water content at wilting point	$m^3\ m^{-3}$	0.12	Estimated
32.	WCFC	Water content at field capacity	$m^3\ m^{-3}$	0.41	Aina and Periaswamy (1985)
33.	WCWET	Water content at wet	$m^3\ m^{-3}$	0.46	Estimated
34.	WCST	Water content at saturation	$m^3\ m^{-3}$	0.52	Estimated
35.	TWCSD	Proportion of WCWP at which water content at severe drought (WCSD) is assumed to be reached (unitless, default value set at 5% above WCWP)		1.05	Estimated
36.	TRANCO	Transpiration constant	mm d^{-1}	8	Estimated
37.	DRATE	Drainage rate	mm d^{-1}	50	Estimated

b. Simulation of first branching

Two types of branches characterise a cassava plant: the main branches emerging from the planted stem cutting and the lateral branches arising from the main branches where an apex evolves into an inflorescence. The appearance of the first lateral branch marks the start of the reproductive stage (Matthews and Hunt 1994). This phase is temperature and photoperiod dependent, and cultivar specific. However, the current model does not include photoperiod effects not only due to a lack of data, but also to the fact it is reported that photoperiod may not limit storage roots production in the tropics because of the small variation in day length very 10 and 12 hours (Alves 2002). The period from emergence to first branching, denoted as TSUMSBR in LINTUL-Cassava, has been reported in the literature to occur between 15 and 65 developmental days (Veltkamp (1985); Keating et al. (1982) and Gutierrez et al. (1988)) depending on whether the cultivar grown was branching early or late. This period corresponded to a TSUM range of 180 to 780^{o}Cd for an optimum temperature of 27^{o}C and TBASE of 15^{o}C (Hillocks et al. 2002). Since the cultivar used in this study was late branching type (TME 419 or "Gbazekoute" as local name in Togo), 780^{o}Cd was considered as default value for TSUMSBR in our simulations.

c. Simulation of maturity and harvest

As a perennial shrub, the cassava plant is an indeterminate crop. It can grow for more than a 12-months cycle and can be harvested from 8 to 24 months after planting (MAP). The current version of the model simulates only the first 12-month cycle since most farmers in Southern Togo and in most land constrained areas commonly harvest cassava before 12 MAP because the land needs to be prepared for other crops in the subsequent growing season. Thus, the simulation stops when a TSUM of 4320^{o}Cd, corresponding to 360 days under optimal temperature of 27^{o}C and TBASE of 15^{o}C, is reached, or when a predefined end of simulation time or harvest time is attained.

6.2.1.2. Cassava growth processes simulation

The model describes nine main processes: the growth of i) stem cuttings, ii) leaf area index, iii) biomass, iv) leaf, stem, fibrous root and storage roots, v) senescence, vi) dry matter partitioning, vii) dormancy; viii) biomass production upon the recovery from dormancy and ix) the growth of rooting depth. Temperature is the key environmental factor affecting the growth processes. Cassava growth is inhibited below 15^{o}C and beyond 40^{o}C (Alves 2002). Considering the optimal temperature range of cassava growth between 25 and 29^{o}C, four cardinal temperatures were used: TBASE, optimum temperatures 1 and 2 (TOPT1 and TOPT2) and high temperature (THIGH).

d. Stem cutting growth

The planted stem cutting is the initial source of dry matter for shoot and root growth at emergence (Alves 2002). Hence, we initialised the weight per square meter of the stem cuttings (WCUTTING), stems (WST), leaves (WLV), storage roots (WSO) and of fibrous roots (WRT) at emergence using the following equations:

$WST = WCUTTINGIP \times FST\_CUTT$ (Eq. 6.3)

$WRT = WCUTTINGIP \times FRT\_CUTT$ (Eq. 6.4)

$WLVG = WCUTTINGIP \times FLV\_CUTT$ (Eq. 6.5)

$WSO = WCUTTINGIP \times FSO\_CUTT$ (Eq. 6.6)

WCUTTING, WST, WRT, WLVG and WSO are expressed in [g m^{-2}]. WLVG is the weight of green leaves per square meter of soil. WCUTTINGIP [g m^{-2}] is the stem cutting weight at planting. FST_CUTT, FRT_CUTT, FLV_CUTT and FSO_CUTT are the respective proportions of WCUTTINGIP allocated to the production of stem, adventitious roots, leaves and storage root at emergence and have units as e.g. g stem g^{-1} cutting for the stems. FSO_CUTT is null at emergence since there is no storage roots production at emergence.

From emergence, WCUTTING declines exponentially to a minimum cutting weight (WCUTTINGMIN) (Alves 2002). The relative rate of decline of WCUTTING (RDRWCUTTING) derived following Alves (2002) is about 0.017 day^{-1}.

$WCUTTING = INTGRL(WCUTTINGIP, RWCUTTING)$ (Eq. 6.7)

$RWCUTTING = -RDRWCUTTING \times WCUTTING$ if $WCUTTING > WCUTTINGMIN$ (Eq. 6.8)

RWCUTTING = 0 if WCUTTING ≤ $WCUTTINGMIN$

$WCUTTINGMIN = WCUTTINGMINPRO \times WCUTTINGIP$ (Eq. 6.9)

WCUTTINGMINPRO is the fraction of WCUTTINGIP at which the exponential decline of the stem cutting is expected to stop.

e. Leaf area index growth

According to Alves (2002), in the first 30 days after planting (DAP), period corresponding approximately to 15 days after emergence (DAE), the growth of shoot and roots mainly depends on the reserves of the stem cutting. However, the exact timing of the start of photosynthetic activity of the leaves is not well known. We assume that the photosynthetic activity of the leaves starts from emergence, and that leaf area growth (GLAI) is exponential during 15 DAE (Eq. 6.10). This 15-days period corresponds to a TSUM of 180°Cd under an optimal temperature of 27°C and TBASE of 15^{o}C. We referred to this period as TSUMLA_MIN, which stands for TSUM accumulation for minimum leaf area.

$$GLAI = dLAI/dt = (RGRL \times DTEFF) \times LAI + |RWCUTTING| \times FLV \times SLA \quad \text{(Eq. 6.10)}$$

GLAI is expressed in [m^2 leaf m^{-2} ground area d^{-1}]; *RGRL* [°Cd^{-1}] is the relative growth rate of leaf area; LAI [m^2 leaf m^{-2} ground area] is the leaf area index; FLV [g leaf g^{-1} DM produced (or present in the stem cutting)] is the fraction of the biomass DM allocated to the leaves. As a first approximation, we assume that the fraction of the stem cutting weight used for leaf production during TSUMLA_MIN is similar to the fraction of the total biomass allocated to leaves. SLA [m^2 leaf g^{-1} leaf] is the specific leaf area.

At later development stage, leaf expansion is restricted by assimilate supply.

$$GLAI = dLAI / dt = dWLV / dt \times SLA \quad \text{(Eq. 6.11)}$$

WLV [g leaf m^{-2}] is the total leaf weight per ground area.

Leaf area is affected by leaf death, DLAI. Thus, the net rate of leaf area growth is defined as follows:

$$LAI = \int_0^t (GLAI - DLAI)\, dt \quad \text{(Eq. 6.12)}$$

f. Total biomass growth

The potential biomass growth (GTOTAL) is modelled as a function of light use efficiency (LUE) and light interception (PARINT) (Eqs. 6.13 & 6.14). Under water-limited conditions, GTOTAL is limited by drought stress expressed by the transpiration reduction factor (TRANRF), which is the ratio of the actual transpiration over the potential transpiration.

$$\mathrm{GTOTAL = LUE \times PARINT \times TRANRF} \quad \text{(Eq. 6.13)}$$

$$\mathrm{PARINT = 0.5 \times DTR \times (1. - EXP(-K\_ext \times LAI))} \quad \text{(Eq. 6.14)}$$

$$\mathrm{LUE = LUE\_OPT} \times f\mathrm{(TBASE, TOPT1, TOPT2, THIGH, DAVTMP)} \quad \text{(Eq. 6.15)}$$

GTOTAL [g m^{-2} ground d^{-1}]; PARINT [MJ PAR m^{-2} ground d^{-1}] is defined as the amount of light intercepted by the canopy per day and per m^2, assuming an exponential light profile in the plant canopy from its top towards the soil; LUE [g MJ PAR^{-1}] is expressed as a function of LUE_OPT (LUE under optimal condition) that is a parameter, which value is null below TBASE and beyond THIGH, maximum between TOPT1 and TOPT2, and linearly increasing between TBASE and TOPT1, and decreasing between TOPT2 and THIGH; we approximated LUE_OPT as 75th percentile of the ratio between the total biomass and the accumulated PAR measured on fertilized plots on the model calibration site (Sevekpota in Year 2); K_ext is the light extinction coefficient; DTR [MJ m^{-2} d^{-1}] is the daily total radiation; 0.5: is the conversion factor from MJ DTR to MJ PAR.

g. Leaf, stem, fibrous root and storage root growth

Biomass production is calculated on the basis that the total biomass is comprised of dry matter (DM) produced from photosynthesis as well as dry matter provided by the stem cutting. Hence, the rate of weight increase (g DM m^{-2} day^{-1}) of the stem (RWST), the green leaves (RWLVG), the fibrous roots (RWRT) and the storage organs (RWSO) are calculated as follows:

$$RWST = (GTOTAL + |RWCUTTING|) \times FST \quad \text{(Eq. 6.16)}$$

$$RWLVG = (GTOTAL + |RWCUTTING|) \times FLV - DLV + RREDISTLVG \times PUSHREDIST \quad \text{(Eq. 6.17)}$$

$$RWRT = (GTOTAL + |RWCUTTING|) \times FRT \quad \text{(Eq. 6.18)}$$

$$RWSO = (GTOTAL + |RWCUTTING|) \times FSO + RWSOFASTRANSLSO - RREDISTSO \quad \text{(Eq. 6.19)}$$

FST, FLV, FRT and *FSO* are the proportions of the produced dry matter allocated to the stems, the leaves, the fibrous roots and the storage organs, respectively. As a first approximation, we assume that these proportions are identical for both the DM from the stem cutting and from photosynthesis. *DLV* is the rate of leaf death. *RREDISTLVG* [g leaves DM m^{-2} day^{-1}] is the growth rate of new leaves with DM provided by storage roots during the dry matter redistribution process (see Section 6.2.1.2k) at the recovery from dormancy (see Section 6.2.1.2j). This production of new leaves occurs only when the redistribution process is active after a dormancy event. *PUSHREDIST*, described under Section 6.2.1.2j, is a switch on the redistribution process. *RREDISTSO* [g storage roots DM m^{-2} day^{-1}] is the rate of redistribution of storage roots dry matter to leaves (see Section 6.2.1.2k). *RWSOFASTRANSLSO* [g storage roots DM m^{-2} day^{-1}] is the rate of storage roots DM production with DM supplied by the leaves before abscission (see Section 6.2.1.2h). The integration of *RWST*, *RWLVG*, *RWRT* and *RWSO* over time leads to the amount of dry matter accumulated (g DM m^{-2}) for stem (*WST*), green leaves (*WLVG*), fibrous roots (*WRT*) and storage organs (WSO). The total biomass (*WGTOTAL*, Eq.22) is the sum of the weights of all plant organs. The WLV is the total amount of leaves produced, including the green leaves (not yet dropped from the plant, WLVG) and the dead leaves (WLVD, Eq. 6.21).

$$W\gamma = \int_0^t R\gamma \, dt \quad \text{(Eq. 6.20)}$$

γ stands for plant organs (green leaf, stem, fibrous roots and storage roots); Wγ stands for the weight of each plant organ, Rγ is the growth rate of each plant organ.

$$WLVD = \int_0^t DLV\ dt \qquad \text{(Eq. 6.21)}$$

$$WGTOTAL = WLV + WST + WCUTTING + WSO + WRT \qquad \text{(Eq. 6.22)}$$

h. Senescence

Leaf area death (DLAI) and leaf weight death (DLV) are modelled as a function of the relative death rate (RDR) as follows:

DLAI = LAI x RDR x (1. − FASTRANSLSO) x (1. − DORMANCY) (Eq. 6.23)

DLV = WLVG x RDR x (1. − FASTRANSLSO) x (1. − DORMANCY) (Eq. 6.24)

FASTRANSLSO [-] is the fraction of leaf dry matter allocated to storage roots before the shedding of the leaf. We did not measure this in our experiment, but this approach was also used in the simulation of potato growth in SUBSTOR-Potato following Johnson et al. (1986). As a first approximation, we assume no LAI death (DLAI = 0.) nor leaf weight death (DLV = 0.) to occur during the dormancy phase. Similarly, the model assumes that biomass growth is completely inhibited (GTOTAL = 0.) with no leaf area growth (GLAI = 0.). RDR [d^{-1}] can be caused by leaf age (RDRDV), shade (RDRSH) or soil water content at severe drought (RDRSD) (Eq. 6.25). The RDRDV is defined as a function of temperature and of the cultivar specific leaf age parameter TSUMLLIFE, which is the developmental time from leaf appearance to leaf senescence (Eq. 6.26). The RDRSH is triggered by LAI reaching LAICR, the critical LAI value beyond which leaf shedding is stimulated (Eq. 6.27). The model assumes that severe drought accelerates leaf shedding and that this acceleration of leaf shedding occurs only after a certain leaf age has been reached (Eqs. 6.28 and 6.29).

RDR = MAX (RDRDV, RDRSH, RDRSD) (Eq. 6.25)

RDRDV = f(TSUMLLIFE, TSUM, DAVTMP) (Eq. 6.26)

RDRSH = f(RDRSHM, LAICR, LAI) (Eq. 6.27)

RDRSD = RDRB x ENHSHED (Eq. 6.28)

ENHSHED = f(WC, TSUM, TSUMLLIFE) (Eq. 6.29)

In line with Johnson et al. (1986), we assume that leaf shedding due to RDRSH, RDRSD as well as to RDRDV, is preceded by the allocation of part of the leaf dry matter to storage roots. The rate at which leaf dry matter is reallocated to storage roots before abscission is denoted as RWSOFASTRANSLSO (Eq. 6.30). This phenomenon is assumed not active under dormancy.

RWSOFASTRANSLSO = WLVG x RDR x FASTRANSLSO x (1.0−DORMANCY) (Eq. 6.30)

i. Dry matter partitioning

Dry matter proportions of cassava plant organs relative to the total biomass at specific periods of the crop growth and development (Table 6.2) are used to simulate daily dry matter partitioning. These proportions were either found in literature or empirically determined during our field experiments. Before the start of storage roots bulking, dry matter is mainly allocated to the shoot (stems and leaves) and fibrous roots. It has been reported that starch deposition starts 25-40 days after planting for many cultivars (Cock 1984), but that root bulking is noticeable only between 60-120 days after planting (El-Sharkawy 2003). A default storage bulking initiation (TSUMSOBULKINIT) value of 540^{o}Cd corresponding to 45 days after emergence (60 days after planting) is considered in the simulations. Thereafter, dry matter allocation to storage roots reaches a maximum around 1980^{o}Cd after emergence or 2160^{o}Cd after planting, which corresponds to 6 MAP (Alves 2002). After 6 MAP, priority is given to dry matter allocation to storage roots at the expense of stems and leaves until the end of the 12-month cycle. Based on these data points in time (Table 6.2), DM partition is linearly interpolated on a daily basis between consecutive points.

Table 6.2. Dry matter partitioning in fibrous roots, stems, leaves and storage roots at different development stages and some specific measuring points.

Development stage/harvest	TSUM (^{o}Cd)	FRT	FLV	FST	FSO	Source
Emergence	0	0.110	0.710	0.180	0.000	Estimated (Fukai and Hammer 1987; Gutierrez et al. 1988)
Start of storage roots bulking	540	0.100	0.515	0.385	0.000	Interpolation between 0 and 720 ^{o}Cd
Partitioning at 60 developmental days after emergence	720	0.094	0.393	0.393	0.120	Estimated (Alves 2002; Gutierrez et al. 1988)
Harvest 1 in Sevekpota Year 2	1488	0.010	0.210	0.260	0.520	Measured
Maximum translocation to storage roots	1980	0.010	0.180	0.190	0.620	Estimated (Alves 2002)
Harvest 2 in Sevekpota Year 2	2676	0.010	0.130	0.290	0.570	Measured
Harvest 3 in Sevekpota Year 2	3684	0.010	0.210	0.290	0.490	Measured

Dry matter partitioning is modified under water stress conditions (Eq. 6.31-6.35). Under water stress conditions, TRANRF is set to be inferior to 1, and dry matter allocation to fibrous roots is enhanced. This mechanism has been reported to enable the cassava crop to invest in root development under water stress conditions in order to explore more soil volume to access water (El-Sharkawy 2003). The modification of FRT affects the proportion of dry matter allocated to the shoot (stems and leaves) and the storage roots. Otherwise, no modification of dry matter allocation to roots is considered.

$$\text{FRTWET} = f(\text{TSUM}) \qquad \text{(Eq. 6.31)}$$

$$\text{FRTMOD} = \text{MAX}(\,1.,\ 1./(\text{TRANRF} + 0.5)) \qquad \text{(Eq. 6.32)}$$

$$\text{FRT} = \text{FRTWET} \times \text{FRTMOD} \qquad \text{(Eq. 6.33)}$$

$$\text{FSHMOD} = (1. - \text{FRT}) \,/\, (1. - \text{FRT}/\text{FRTMOD}) \qquad \text{(Eq. 6.34)}$$

$$\text{FLV, FST, FSO} = f(\text{TSUM}) \times \text{FSHMOD} \qquad \text{(Eq. 6.35)}$$

FRTWET is FRT at optimal water supply, FRTMOD the relative modification of FRTWET by drought, and FSHMOD the relative modification of allocation to shoot by drought.

j. Dormancy and recovery from dormancy

The model assumes that dormancy is triggered by soil water content (WC), leaf area and temperature. It assumes that dormancy begins when LAI attains a minimum critical value (LAI_MIN) under water shortage (drought). Water shortage is defined by a WC below the critical water content (WCCR, Fig. 6.2). The WCCR varies between the wilting point (WCWP) and the field capacity (WCFC): 2.0 < pF < 4.2. The WCCR was the lowest soil water content at which the crop does not suffer from water shortage. The WCCR depends on a crop's drought tolerance (TRANCO) and on the actual potential transpiration (PTRAN) (Eq. 6.36).

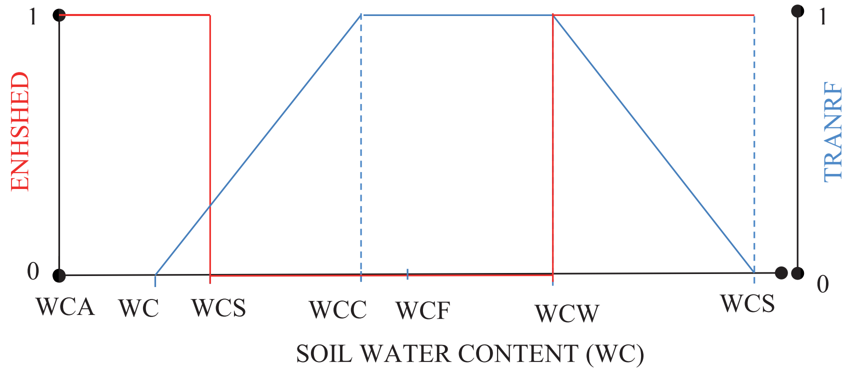


Fig. 6.2. Transpiration reduction factor (TRANRF, blue line) and shedding enhancement factor (ENHSHED, red line) with soil water content at air dry (WCAD), wilting point (WCWP), severe drought (WCSD), critical water content (WCCR), field capacity (WCFC), wet water content (WCWET) and at saturation (WCST). *WCCR* is *WC* below which *TRANRF* reduction occurs. *WCWET* is *WC* above which there is reduction in transpiration due to shortage of oxygen.

Between WCCR and WCWP, WC can reach severe drought water content (WCSD, Fig. 6.2) from which leaf shedding is taking place exponentially towards reaching LAI_MIN, marking the start of the dormancy phase.

$$\text{WCCR} = \text{WCWP} + \text{MAX}(\text{WCSD} - \text{WCWP}, \text{PTRAN}/(\text{PTRAN}+\text{TRANCO}) \times (\text{WCFC} - \text{WCWP})) \quad \text{(Eq. 6.36)}$$

The WCCR varies daily based on PTRAN values in response to the crop's growth (leaf area growth) and its influence on the soil water dynamics. It can be seen from Eq. 6.36 that WCCR (see also Fig. 6.2) can be close to WCFC (pF 2) for drought sensitive crops (small TRANCO) and close to WCWP (pF 4.2) for drought tolerant crops (large TRANCO). Below WCCR (WCWP≤WC<WCCR), the crop suffers from drought and the biomass growth rate is linearly reduced by a transpiration reduction factor (TRANRF).

The occurrence of dormancy, the recovery from dormancy and afterwards the redistribution of storage roots DM to produce new leaves are governed by environmental and physiological conditions. Such conditions set ON or set OFF the corresponding developmental reaction of the plant. To this purpose, we use a so-called push function that takes a value 1 (set ON) or 0 (set OFF). Three push functions comprising *PUSHDORMREC, PUSHREDIST* and *PUSHREDISTEND* are used. Their functioning and enabling conditions at different development stages are described in Table 6.3.

DORMANCY = f (WC, LAI, PUSHDORMREC, PUSHREDIST, TSUM, TSUMSBR) (Eq. 6.37)

DORMANCY: is not active (*DORMANCY* = 0) as long as *LAI* > *LAI_MIN* or *WC*>*WCSD*. It is activated (*DORMANCY* = 1) when *WC*≤*WCSD* and leaf area ≤ *LAI_MIN*. The model assumes that dormancy occurs only in the reproductive phase (after first branching, *TSUMSBR*). The dormancy then remains active as long as *PUSHDORMREC* is active. *PUSHDORMREC* is the push function defined to indicate when WC is increased towards *WCCR,* and is deactivated when another push denoted as *PUSHREDIST* is switched ON. *PUSHREDIST* indicates the recovery from dormancy and the redistribution of dry matter from storage roots to leaves. This push is activated after a delay period in order to avoid oscillations of *DORMANCY* status when WC is fluctuating around WCCR.

After a long period of drought and dormancy, we assume that the plant requires some adaptation period (corresponding to the above mentioned delay) before growth resumes.

PUSHREDIST is deactivated (PUSHREDIST=0) when PUSHREDISTEND is activated (PUSHREDISTEND=1). PUSHREDISTEND is the trigger of the end of redistribution of DM from storage roots to new leaves. The PUSHREDISTEND is determined either by reaching the maximum proportion of redistribution of storage roots DM (WSOREDISTFRACMAX), or when a minimum amount of new photosynthetic assimilates or dry matter is produced (WLVGNEWN) or when a maximum TSUM for DM redistribution is achieved (TSUMREDISTMAX). PUSHREDISTEND is not activated (PUSHREDISTEND=0) as long as WSOREDISTFRACMAX, WLVGNEWN or TSUMREDISTMAX are not yet reached. The main hypotheses for simulation drought and dormancy are summarised in Fig. 6.3.

Table 6.3. Summarising the PUSH functions at different development and growth phases of cassava.

Development phases, conditions and assumptions	EMERG	DORMANCY	PUSHDORMREC	PUSHREDIST	PUSHREDISTEND
1. Planting to emergence					
TSUM<OPTEMERGTSUM or WC<WCWP	OFF	OFF	OFF	OFF	OFF
TSUM≥OPTEMERGTSUM and WC>WCWP	ON	OFF	OFF	OFF	OFF
2. Emergence to the start of storage roots bulking: juvenile vegetative growth phase					
- Plant growth DM is provided by stem cutting and photosynthesis	ON	OFF	OFF	OFF	OFF
- DM contribution of stem cutting to plant growth stops when a minimum cutting weight (WCUTTINGMIN) is reached					
- DM allocation to shoot (leaves and stems) and fine roots only					
- No DM allocation to storage roots					
3. Start of storage roots bulking to first branching					
- The vegetative stage is still ON	ON	OFF	OFF	OFF	OFF
- DM allocation to storage organs starts					
- DM allocation to the other organs continues					
4. First branching: start of the reproductive phase					
- The reproductive stage starts, while the vegetative stage is still ON	ON	ON/OFF	ON/OFF	ON/OFF	ON/OFF
- DM allocation to storage organs continues					
- DM allocations to the other organs continue but with decreasing proportions in favour of storage roots					
- Dormancy and the related push functions can be activated during this reproductive phase depending on the fact that the required conditions as described below are met (ON) or not (OFF)					

Development phases, conditions and assumptions	EMERG	DORMANCY	PUSHDORMREC	PUSHREDIST	PUSHREDISTEND
5. Dormancy phase					
WC≤WCSD indicates a severe drought. This triggers enhanced leaf shedding by the crop to reduce transpiration during the drought period. This is simulated using “ENHSHED” function.	ON	OFF	OFF	OFF	OFF
WC>WCSD and LAI< or >LAI_MIN	ON	OFF	OFF	OFF	OFF
WC≤WCSD and LAI>LAI_MIN	ON	OFF	OFF	OFF	OFF
WC≤WCSD and LAI≤LAI_MIN	ON	ON	OFF	OFF	OFF
WC≥ RECOV*WCCR & WC>WCSD & PUSHDORMRECTSUM<DELREDIST	ON	ON	ON	OFF	OFF
6. Recovery from dormancy & DM redistribution: the activation of PUSHREDIST ends the dormancy phase, the activation of PUSHREDISTEND ends the redistribution					
WC≥ RECOV*WCCR & WC>WCWP & PUSHDORMRECTSUM>DELREDIST (& WSOREDISTFRACMAX or WLVGNEWN or TSUMREDISTMAX are not yet reached) DM redistribution follows the activation of PUSHREDIST.	ON	OFF	OFF	ON	OFF
DM redistribution continues until the following condition is met: WSOREDISTFRACMAX or WLVGNEWN or TSUMREDISTMAX are reached	ON	OFF	OFF	OFF	ON
PUSHREDISTEND is deactivated with the condition that PUSHREDISTSUM = 0	ON	OFF	OFF	OFF	OFF

Note: switch EMERG cannot switch back to OFF, once emergence has taken place.

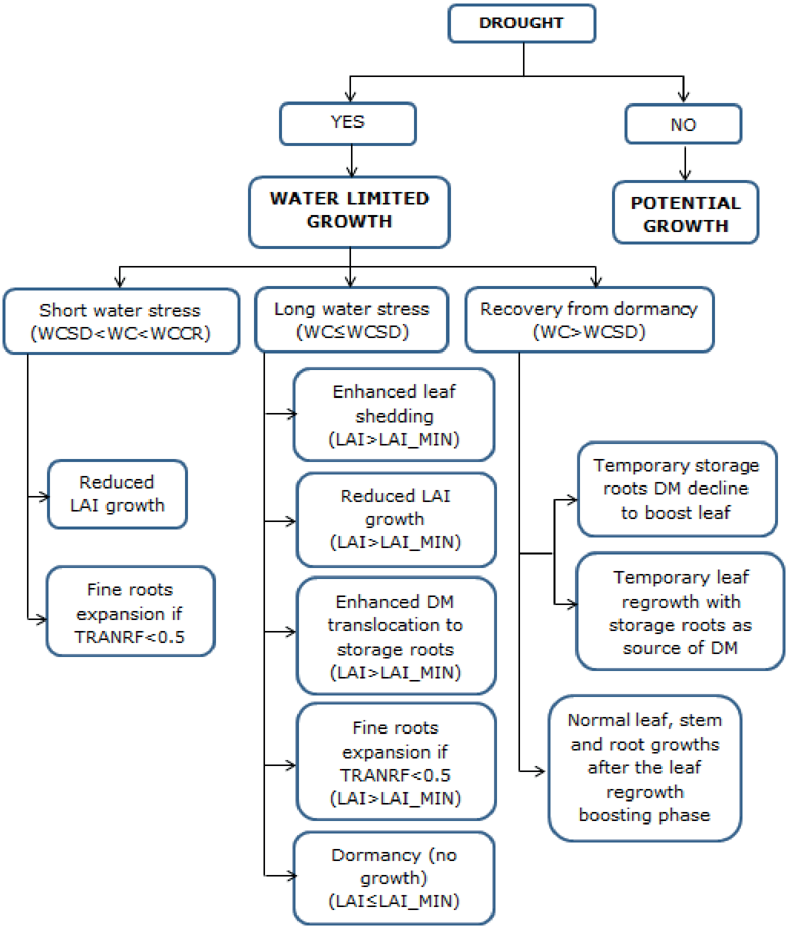


Fig. 6.3. Summary of drought stress simulation assumptions applied in the model.

k. Biomass production upon the recovery from dormancy

Upon the recovery from dormancy, *RREDISTSO* and RREDISTLVG become active to influence leaf growth and storage roots rates (Eqs. 6.17 and 6.19). They are approximated as follows:

RREDISTSO = *RRREDISTSO* x *WSO* x *PUSHREDIST* (Eq. 6.38)

RREDISTLVG = *SO2LV* x *RREDISTSO* (Eq. 6.39)

RRREDISTSO: [day^{-1}] is the relative rate of redistribution of DM from storage roots to leaves; WSO: [g storage roots DM m^{-2}]. RREDISTLVG [g leaves DM m^{-2} day^{-1}] is the growth rate of new leaves with DM provided by storage roots. SO2LV [g leaves DM g^{-1} storage roots DM] is the parameter for converting storage root dry matter to leaf dry matter; RREDISTSO [g storage roots DM m^{-2} day^{-1}] is the rate of redistribution of storage roots dry matter to leaves.

l. Rooting depth growth

The rooting depth determines the volume of water available in the soil. The rate of growth of the rooting depth was thus modelled as a function of WC and of the maximum rate of increase in rooting depth (RRDMAX) and the maximum rooting depth (ROOTDM). The latter is soil type specific.

$$ROOTD = \int_0^t RROOTD\, dt \qquad \text{(Eq. 6.40)}$$

ROOTD: [m]; at time t=0, ROOTD = ROOTDI. ROOTDI [m] is the initial rooting depth at emergence; RROOTD: [m day^{-1}] is the rate of increase in rooting depth.

$$RROOTD = f\,(WC,\ WCWP,\ RRDMAX,\ ROOTDM) \qquad \text{(Eq. 6.41)}$$

The WC is modelled as a function of ROOTD, as well as of the cumulative amount of available water in the root zone (WA) (Eq. 6.42).

$$WC = 0.001 \times WA\ /\ ROOTD \qquad \text{(Eq. 6.42)}$$

WC [m^3 m^{-3}]; WA [mm] results from the difference between water addition to and water loss from the soil profile.

The equation for RROOTD assumes that rooting depth increases at a maximum rate when WC ≥ WCWP until a maximum rooting depth (ROOTDM). Otherwise (WC < WCWP), there is no increase in rooting depth.

6.2.2. Model parameterisation

A dataset collected during a field experiment in Sevekpota (6.437°N, 0.959°E, 121 m above sea level – masl) in southern Togo was used for model parameterisation. The location has a bimodal rainfall regime with two growing seasons annually: from mid-March to July and from September to mid-November. The experiment was carried out on a ferruginous soil with a hard pan at about 40-80 cm depth. Healthy stem cuttings of the disease resistant and drought tolerant cultivar Gbazekoute (TME 419) grown across West Africa were planted on April 23, 2013. The experiment was laid out following a randomised complete block design with three replicates of 15 NPK combinations with applications of 0, 50 and 100 kg N and K ha^{-1}, and 0, 20 and 40 kg P ha^{-1}. In order to ensure no nutrient limitations and since the optimal fertilizer requirements were not known on the study sites, only data from treatments with N and K applications of 50 kg ha^{-1} and above, and with P applications of 20 kg ha^{-1} and above, were used for model crop parameter determinations between 75th to 95th percentiles of the dataset. Crop parameters derived as a function of time (different measurement periods) included: specific leaf area (SLA), light extinction coefficient

(K_ext) and radiation or light use efficiency (LUE). Cassava was harvested at 4, 8 and 11 months after planting (MAP). At each harvest, storage roots, leaves and stem weights were measured, as well as SLA. To measure SLA, small circular pieces of leaves with known area size were cut in a set of leaf limbs (collected at different positions on the stem), counted, dried and weighted. The value of SLA (cm^2 leaf g^{-1} leaf) was calculated by dividing the total area size of all leaf pieces by their dry weight. The light extinction coefficient was determined following Campbell (1986), based on an ellipsoidal leaf angle distribution parameter, derived from canopy dimensions (average value of canopy width on the horizontal plane divided by canopy thickness on the vertical plane) measured in this experiment, and on the zenith angle of the sun estimated by AccuPAR equipment (Decagon Devices 2004). Leaf area index values were obtained on a monthly basis from 3 to 11 MAP. These were used to assess the cumulative amount of light intercepted by the crop at each sequential harvest (at 4, 8 and 11 MAP). The LUE was obtained as the slope of the regression line between the cumulative light interception and the total biomass produced at each sequential harvest (Pellet and El-Sharkawy 1997; Sinclair and Muchow 1999). Moreover, soil hydraulic parameters were derived using pedo-transfer functions for field capacity (WCFC) and wilting point (WCWP). Rainfall data were measured *in situ* with a rain gauge; solar radiation data was supplied by NASA Power (http://power.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi?email=agroclim@larc.nasa.gov) on the site, while minimum and maximum temperatures, air humidity, and wind speed data were provided by the nearest weather station at Lomé (6.167°N, 1.250°E, 19.6 masl). The same field experiment used for parameterisation was used for model calibration after the sensitivity analysis.

6.2.3. Model sensitivity analysis

The sensitivity analysis was conducted to identify input parameters for which the model is highly sensitive and to subsequently do an appropriate model calibration. All parameters in Table 6.1 were assessed in the sensitivity analysis. Default values of these parameters were either measured or estimated from literature. They were used to first run the simulation and assess the outputs of state variables including LAI, yields of total biomass produced and storage roots, as well as the cumulative soil water evaporated (EVAP) and the cumulative water transpired (TRAN). Then the simulation was re-run with a given default parameter value incremented by 1%, followed by another run with the default parameter value reduced by 1%. The sensitivity of the model to these parameters was assessed by measuring the elasticity of the state variable based on the following formula:

$$E_{s,p,t} = \frac{(S_{t,p_{max}} - S_{t,p_{min}})/S_{t,p_{default}}}{(p_{max} - p_{min})/p_{default}} \qquad \text{(Eq. 6.43)}$$

$E_{s,p,t}$ is the elasticity of state variable S to parameter p at time t. p_{max}, p_{min} and $p_{default}$ are respectively the maximum, minimum and default values of p. $S_{t,pmax}$ is the state variable at time t with p_{max}. $S_{t,pmin}$ is the state variable at time t with p_{min}. $S_{t,pdefault}$ is the state variable at time t with $p_{default}$.

The model was considered insensitive to a given parameter if $-10\% < E_{s,p,t} < +10\%$; otherwise, it was deemed to be sensitive. The following scale, in which $E_{s,p,t}$ is expressed as a percentage, was used to assess the sensitivity of the model to a change by ±1% of each parameter value:

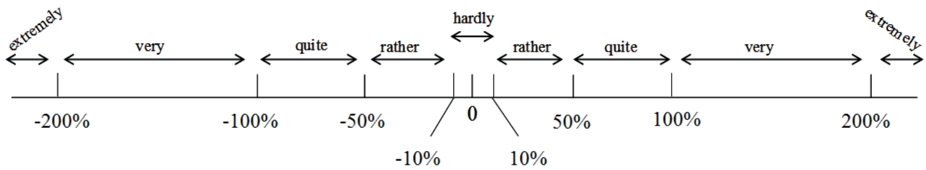


Fig. 6.4. Scale of the degree of sensitivity of the model to ±1% change of a given parameter.

6.2.4. Model testing

Field experiment data collected in Djakakope (6.464°N, 1.597°E, 86 masl) between 2012 and 2014 (Year 1 from 2012 to 2013, Year 2 from 2013 to 2014), and in Sevekpota in Year 1 were used for model testing. These experiments followed the same design and data collection schemes as the experiment in Sevekpota in Year 2, and were located on different fields in Years 1 and 2 at each site. Similarly to the model parameterisation experiments, rainfall was measured *in situ* using rain gauges, and solar radiation data were supplied by NASA Power.

Minimum and maximum temperatures, air humidity, and wind speed data were provided by Lomé weather station for Sevekpota and by Tabligbo weather station (6.583°N, 1.500°E, 40 masl) for Djakakope. The model simulations were run using site specific parameters presented in Table 6.4.

Table 6.4. Site-specific parameters used during the model testing.

Parameter	Sevekpota Year 1		Djakakope Years 1 & 2	
	Value	Source	Value	Source
ROOTDM (m)	0.35	Estimated	2.00	Estimated
WCWP (m^3 m^{-3})	0.12	Estimated (Idem as Year 1)	0.08	Estimated
WCFC (m^3 m^{-3})	0.41	Idem as Year 1 (Aina and Periaswamy 1985)	0.23	(Minasny and Hartemink 2011)

Simulation results and field observations were compared to assess the robustness of the model using the Normalised Root Mean Squared Error (*NRMSE*) (Loague and Green 1991), the slope of the regression line between measured and simulated values, and the coefficient of determination R^2.

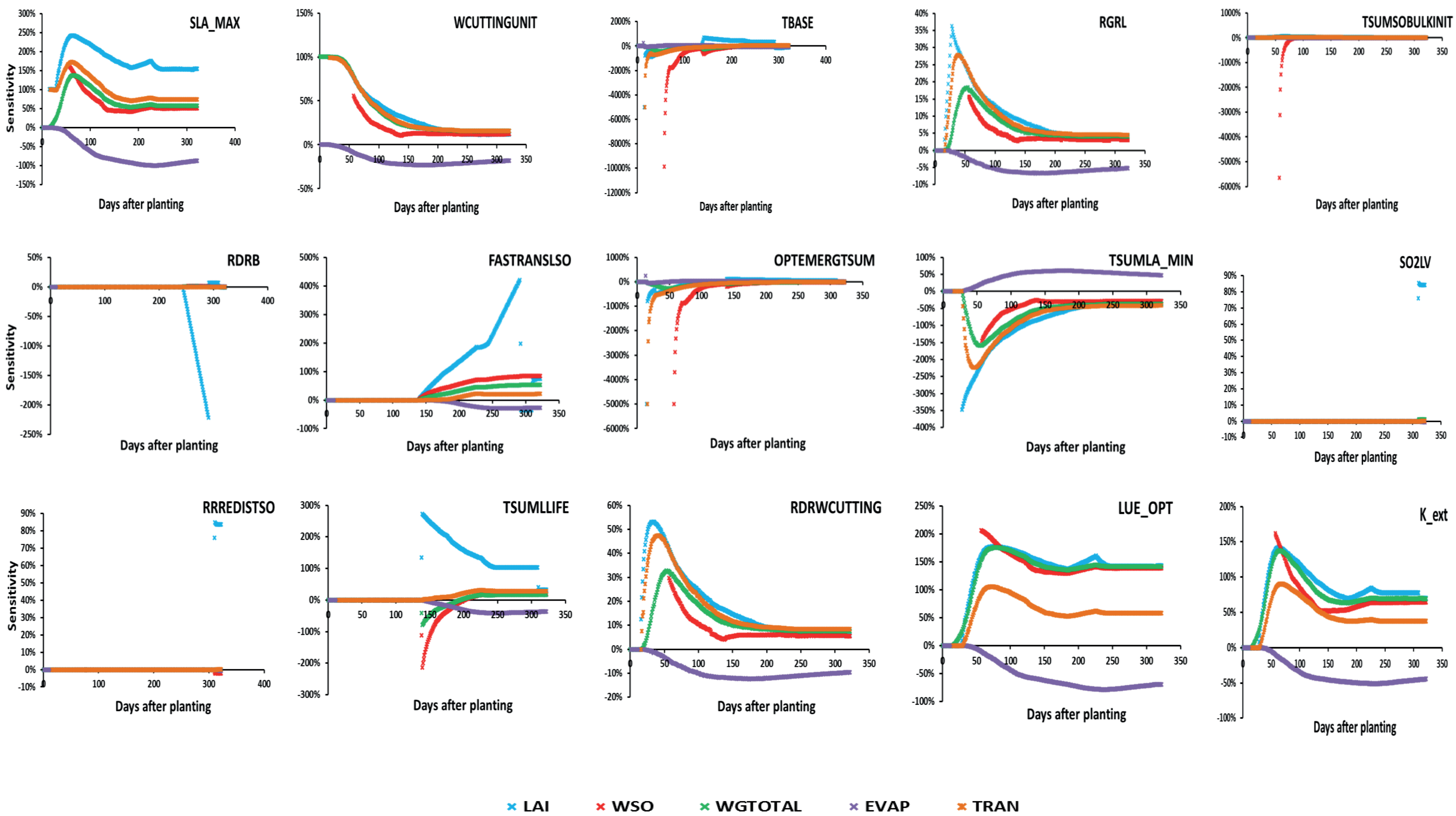
6.2.5. Model application

The tested model was used to assess the potential and water-limited yields of cassava, and the difference between these two yields was considered as the yield gap caused by drought. Subsequently the best planting window was assessed for the study sites using daily measured rainfall and satellite data (solar radiation, minimum and maximum temperature, wind speed and vapour pressure) over the period of 2001 through 2011. Storage roots yields were simulated by planting every 30 days from January 16 to July 15 of each year. The harvest in the simulations occurred 330 days after planting (11 MAP). The planting dates giving the largest storage roots DM are chosen as proxy of the best planting periods.

6.3. Results

6.3.1. Model parameters sensitivity

The model was sensitive ($E_{s,p,t}$ <-10% and $E_{s,p,t}$ > 10%) to 20 out of the 37 parameters studied (Table 6.1). This model sensitivity was variable across the crop life cycle with respect to at least one of the state variables considered in the sensitivity analysis, namely LAI, dry matter yields of storage roots (WSO), total biomass produced (WGTOTAL), the cumulative amount of soil water evaporation (EVAP) and plant water transpiration (TRAN) (Fig. 6.5). The model remained sensitive throughout the crop life cycle to some crop parameters, viz. SLA_MAX, WCUTTINGUNIT, TBASE, TSUMLA_MIN, LUE_OPT and K_ext. To some crop parameters, the model was mainly sensitive in the first half of the crop life cycle: OPTEMERGTSUM, RDRWCUTTING, TSUMSOBULKINIT and RGRL. To some other crop parameters, the model was primary sensitive in the second half of the crop life: RDRB, SO2LV, RRREDISTSO, FASTRANSLSO, TSUMLLIFE, ROOTDM and RRDMAX. The most sensitive state variable to changes in parameters values was LAI. The latter provided $E_{s,p,t}$ values that classified these parameters from rather sensitive to extremely sensitive (See Fig. 6.4 for the scale). Among the extremely sensitive parameters, we can feature TSUM accumulation related parameters such as TBASE, OPTEMERGTSUM and TSUMSOBULKINIT, which affect the duration of the development stages, hence of the whole crop life cycle. Changes in TSUMSOBULKINIT affected mainly storage roots production (WSO) during part of the crop life cycle.


SLA_MAX
WCUTTINGUNIT
TBASE
RGRL
TSUMSOBULKINIT
RDRB
FASTRANSLSO
OPTEMERGTSUM
TSUMLA_MIN
SO2LV
RRREDISTSO
TSUMLLIFE
RDRWCUTTING
LUE_OPT
K_ext
Sensitivity
Days after planting
LAI
WSO
WGTOTAL
EVAP
TRAN

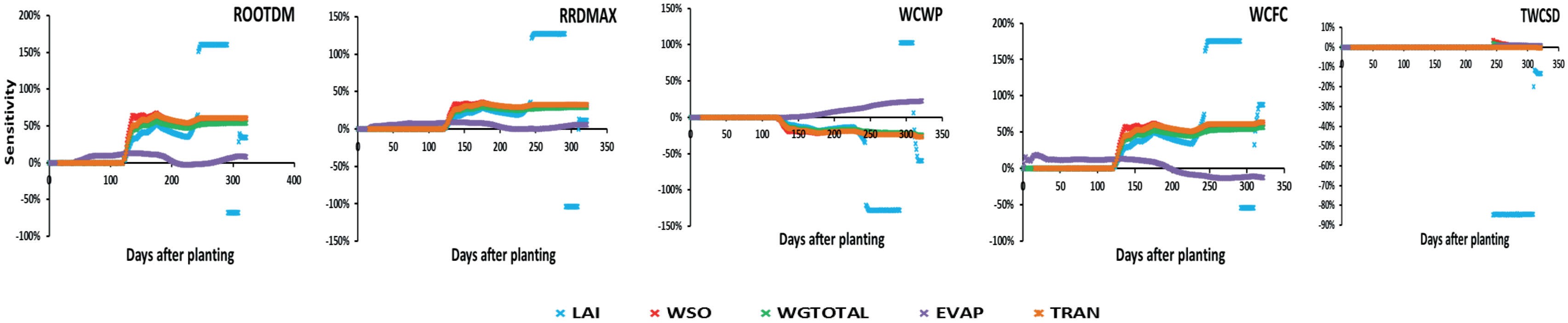


Fig. 6.5. Sensitivity of LAI, WSO, WGTOTAL, EVAP and TRAN to ±1% change of the parameters across the first growth cycle of the crop in Year 2 in Sevekpota. Only parameters inducing sensitive responses (sensitivity <-10% and >10%) of at least one of the variables (*LAI, WSO, WGTOTAL, EVAP* and *TRAN*) are presented here. See Fig. 6.4 for the scale of the degree of sensitivity of each variable. Note the differences in the scales of the y-axes of the different figures.

Soil parameters inducing most model sensitivity comprised WCWP, WCFC and TWCSD (Fig. 6.5), with WCFC inducing sensitive responses of the model across the crop life cycle, while WCWP and TWCSD were found to generate sensitive model response mainly towards the second half of the crop life cycle. The model was not sensitive to any of the remaining parameters.

6.3.2. Model calibration

The model performance of simulating cassava growth was improved with the parameters presented in Table 6.5 (Figs. 6.6 and 6.7) compared to the model with default values of these parameters. These parameters were found sensitive according to the sensitivity analysis, except LAICR. Although LAICR was not sensitive, we found the LAICR value of 5 $m^2\ m^{-2}$ reported by Keating et al. (1982) too high compared to the LAI values we observed, which were in general below 4 $m^2\ m^{-2}$. For this reason, we revised the LAICR value to 3.5 $m^2\ m^{-2}$ as presented in Table 6.5. There was a good match between simulated and observed yields with regression line slopes near 1 and R^2 values also close to 1, and *NRMSE* of 5.8% for the observed storage roots yields, and also 5.8% for the total biomass produced (Fig. 6.6). However, LAI values were slightly underestimated by the model (Fig. 6.7). The measurement of LAI in the field did not cover the first three months of the crop growth (Fig. 6.7a). Comparing observed LAI values with simulated values on the dates measurements were taken gave an NRMSE of 17% (Fig. 6.7b).

Table 6.5. Calibrated parameters.

Parameters codes	Unit	Default value	New value
LAICR	$m^2\ m^{-2}$	5	3.5
TSUMLLIFE	^oC d	1500	1200
FASTRANSLSO		0.50	0.45
K_ext		0.70	0.67
RRDMAX	$m\ d^{-1}$	0.022	0.012

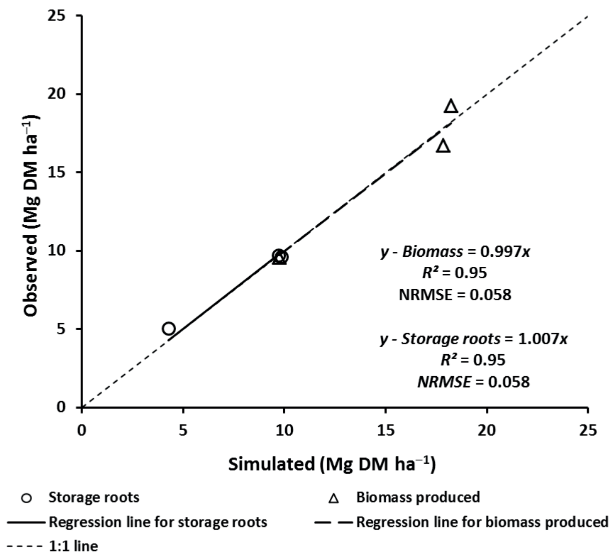


Fig. 6.6. Simulated and observed storage roots and total biomass yields in Year 2 in Sevekpota.

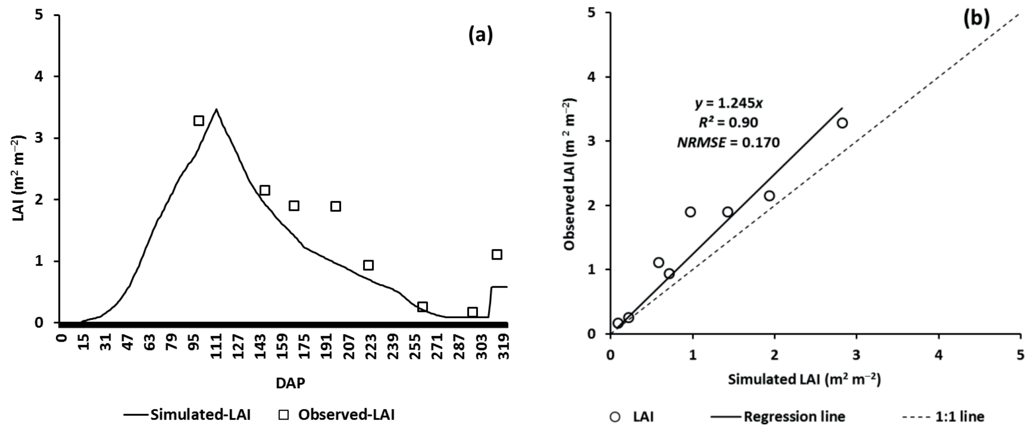


Fig. 6.7. Simulated and observed LAI along the crop growth cycle (a) and on the measuring date of the observed LAI (b).

6.3.3. Model functioning

6.3.3.1. Leaf area index growth, water stress and dormancy simulation

The LAI curves presented in Fig. 6.8 were simulated in a good rainfall year (Year 2, Fig. 6.8a) and in a low rainfall year (Year 1, Fig. 6.8b) in Sevekpota. The LAI curve for Year 2 showed a slow leaf area growth the first 30 days after planting (DAP) followed by a fast growth to reach a maximum value of 3.5 m^2 m^{-2} at 112 DAP (Fig. 6.8a). A lower maximum LAI value of 2.5 m^2 m^{-2} was achieved at 119 DAP in Year

1, where LAI growth slowed down around 79 DAP (Fig. 6.8b). From this peak value, LAI declined progressively and reached very low values towards the end of the crop growth, before rising again a few days before harvest. This last phase of LAI decline and rising before harvest was also observed in the measured LAI (Fig. 6.7a). The low LAI growth occurred under water stress conditions when the transpiration reduction factor (TRANRF) was less than 1, and even zero towards the end of the crop growth period (Fig. 6.8). Water stress was caused by soil water content falling below the critical water content (WCCR) (Fig. 6.8). The TRANRF became zero when water content reached the severe drought condition (WCSD), which was defined in the model as 5% above the wilting point (WCWP). It can be noticed that the period during which TRANRF = 0, the model showed that the dormancy was active (DORMANCY = 1) only when LAI was very low (Fig. 6.8). During this dormancy period, soil water content was below WCSD, and the simulated LAI was 0.086 m^2 m^{-2} in Year 2 and 0.087 m^2 m^{-2} in Year 1. These LAI values were just below the value of parameter LAI_MIN of 0.09 m^2 m^{-2} set as minimum LAI to trigger the dormancy phase. The recovery from dormancy was triggered by the improvement of soil water content (Fig. 6.8) caused by rain.

6.3.3.2. Dry matter fractions in plant organs

Dry matter fractions as presented in Fig. 6.9 show how dry matter allocation was initialised few days after planting, marking the start of the partitioning to different organs. The partitioning started at emergence. From that moment onwards, the stem cutting proportion declined exponentially towards a minimum value. The proportion of dry matter allocation was larger in the leaves, stems and fibrous roots in the early stages of the crop growth. Dry matter proportions of these organs declined as storage roots dry matter accumulation increased. Storage roots dry matter accumulation started about 57 DAP in Year 2, and its proportion represented 54.0% of the total biomass dry matter produced at harvest against 22.3% for the stems, 21.4% for the leaves, 2.1% for the fibrous roots and 0.2% for the stem cuttings. In Year 1 in Sevekpota, storage roots DM accumulation began 62 DAP in Year 1 in Sevekpota, and constituted 49.6% of the total biomass DM produced against 22.4%, 24.6%, 3.1% and 0.3% for the stems, the leaves, the fibrous roots and the stem cuttings, respectively.

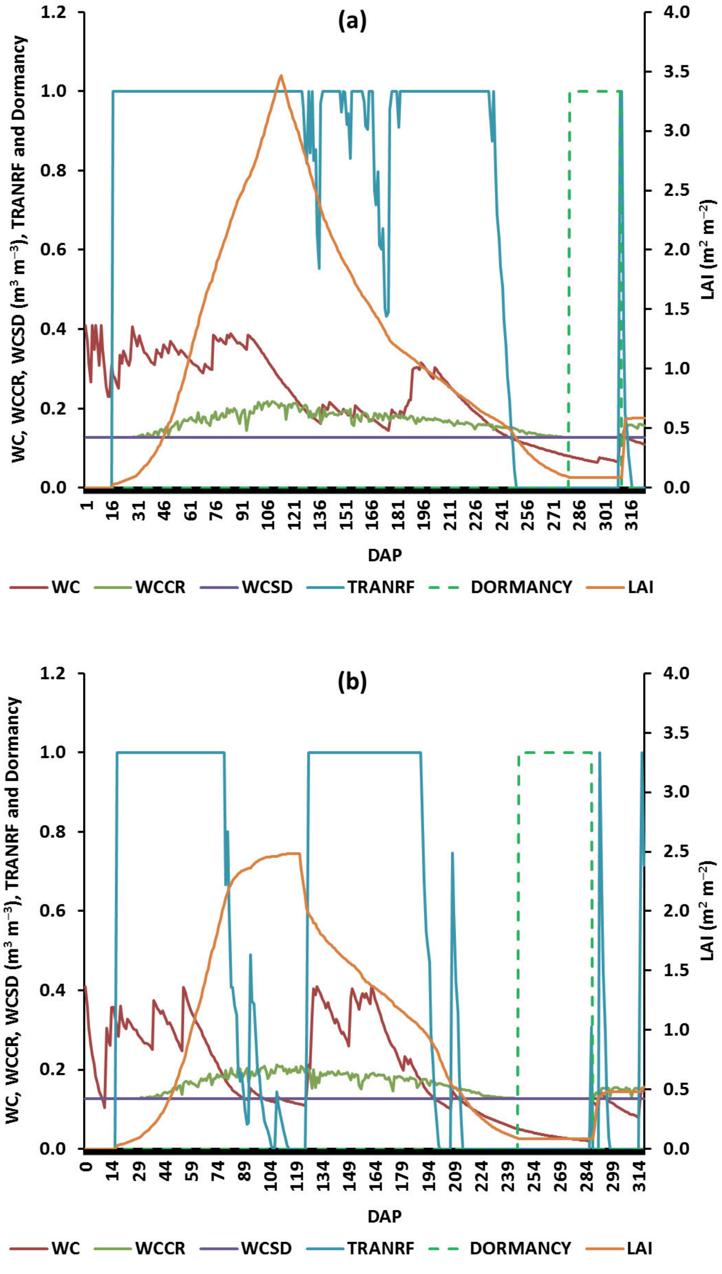


Fig. 6.8. Simulated dormancy, WC, WCCR, WCSD, TRANRF relatively to simulated LAI during cassava growth in Sevekpota in Year 2 (a) and in Year 1 (b).

6.3.3.3. Stem cutting, fibrous roots, stems, leaves and storage roots growth

The model initialised the stem cutting dry matter from a value of 22 g m^{-2} (0.22 Mg ha^{-1}) at planting to 19 g m^{-2} (0.19 Mg ha^{-1}) at emergence. Subsequently, this latter value declined exponentially to a minimum value of 3.2 g m^{-2} (0.032 Mg ha^{-1}) at 118 DAP in Year 2, and 3.3 g m^{-2} (0.033 Mg ha^{-1}) at 159 DAP in Year 1, which remained stable till the harvest (Figs. 6.10a1 and 6.10b1). The reduced dry matter of stem cutting at planting was mainly used to initialise fibrous roots, stem and leaf dry matter. The storage roots dry matter was logically nil at emergence. The increase in fibrous roots dry matter was fast the first 3 MAP, then slow from 3 to 7-8 MAP before levelling off to reach its final value towards the end of the crop life cycle (Figs. 6.10a1 and 6.10b1).

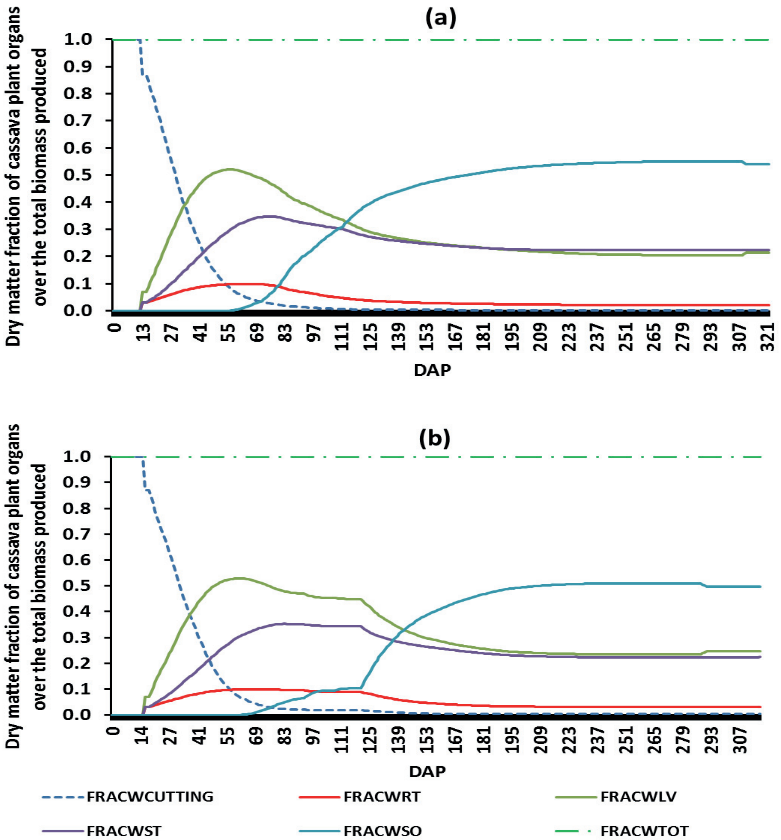


Fig. 6.9. Simulated dry matter proportions of cassava plant organs relatively to the total biomass produced during the plant growth in Year 2 (a) and Year 1 (b) in Sevekpota. *FRACWCUTTING, FRACWRT, FRACTWLV, FRACWST* and *FRACWSO* are the dry matter fractions of stem cuttings, fibrous roots, leaves, stems, storage roots relatively to the total biomass. *FRACWTOT* is the sum of all the fractions.

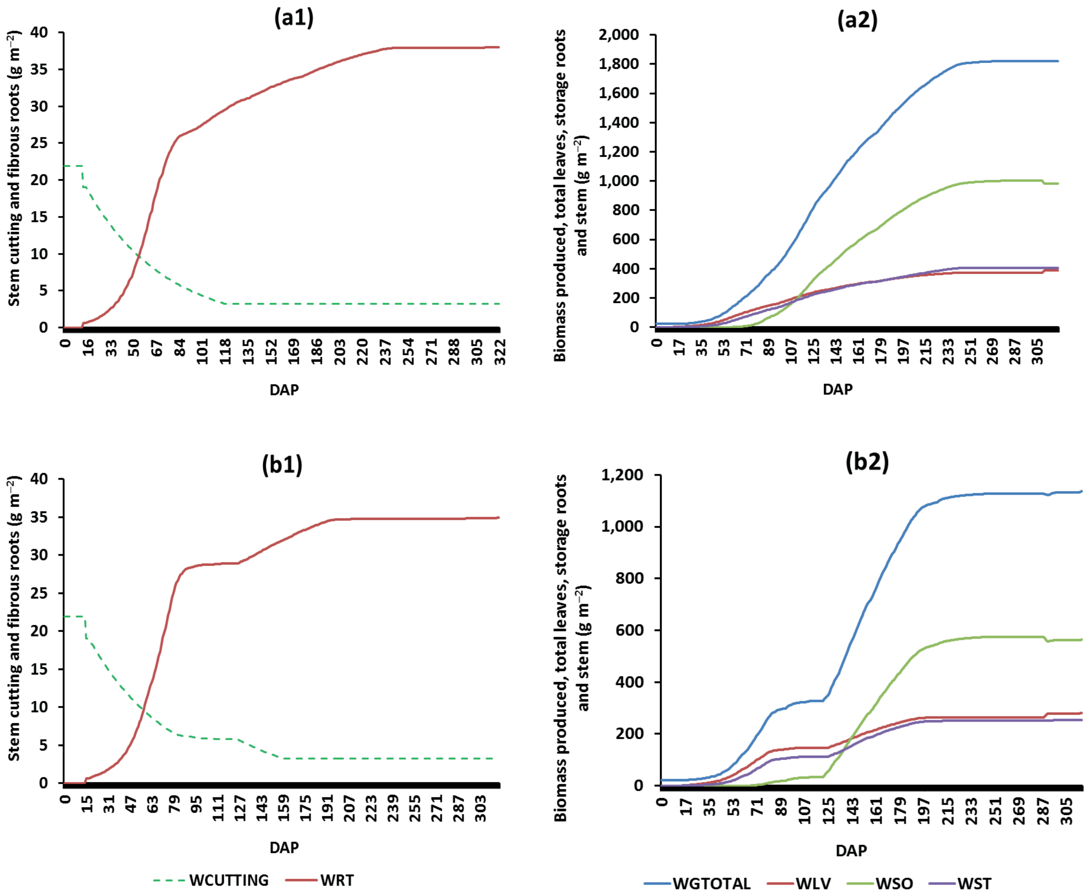


Fig. 6.10. Simulated cassava dry matter growth of stem cutting (*WCUTTING*) and fibrous roots (*WRT*) (a1, b1) and of total biomass produced (*WGTOTAL*), leaf (*WLV*), storage roots (*WSO*) and stems (*WST*) (a2, b2) during Year 2 (a) and Year 1 (b) in Sevekpota.

It is noteworthy that the simulated DM yield of fibrous roots seems small, but we did not found any reported values for comparison purposes. Stem and leaf growth rates had priority on storage roots growth during the first 2 MAP, occasioning higher stem and leaf DM than the storage roots DM during the first 3-4 MAP. Storage roots DM was larger at later stages of the crop's life (Figs. 6.10a2 and 6.10b2). Storage roots growth started at 57 DAP in Year 2, and at 62 DAP in Year 1, then increased to reach it maximum value around 279 DAP in Year 2, and 249 DAP in Year 1 in Sevekpota, which coincided respectively with the day dormancy was initialised. There was no dry matter growth during the dormancy phase. Storage roots dry matter decreased before harvest, while leaf dry matter increased slightly (Figs. 6.10a2 and 6.10b2). The reduction in storage roots dry matter and the rise in leaf dry matter corresponded to the period between deactivation of the dormancy phase (DORMANCY = 0), and harvest.

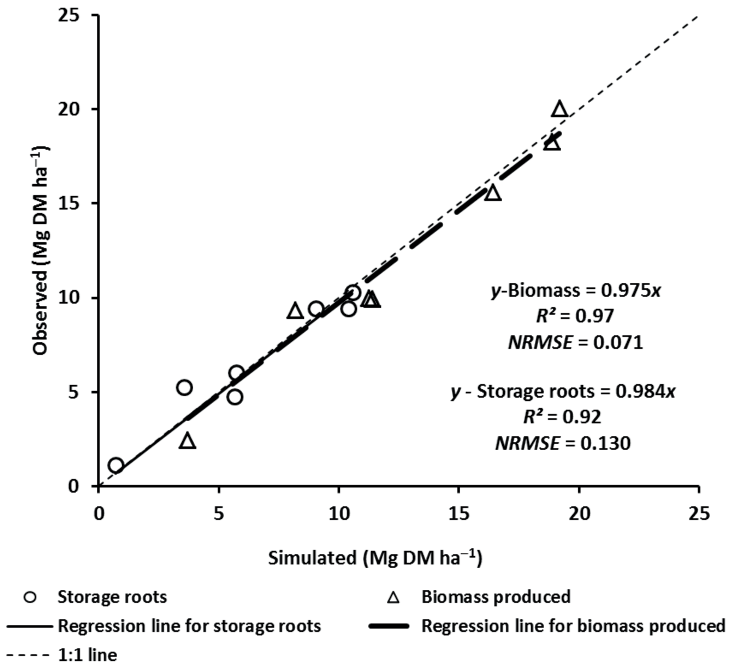


Fig. 6.11. Model performance in simulating storage roots and biomass produced yields in fields different from the model development field. The model testing fields were comprised of Sevekpota Year 1 and Djakakope Years 1 and 2, and the observed yield data were measured in the sequential harvests.

The total biomass grew from its initial cutting weight at planting, and levelled off from 279 DAP until the final harvest in Year 2 (Fig. 6.10a2). The total biomass followed the same trend in Year 1, but levelled off earlier around 249 DAP and slightly dropped for a short period around the dormancy deactivation phase before reaching its final value at harvest (Fig. 6.10b2).

6.3.4. Model testing

The evaluation of the calibrated model indicated a good agreement between simulated and observed total biomass (Fig. 6.11). The NRMSE obtained between simulated and observed yields was about 7% of the average observed total biomass; R^2 value and the slope of the regression line were close to 1. The simulation of the storage roots dry matter was achieved with a difference of 13% (NRMSE) of the observed value, with an R^2 value of 0.92 and slope of the regression line close to 1. The Pearson correlation coefficients between observed and simulated yields were 0.986 for total biomass and 0.972 for storage roots, with a *P* value <0.001 in either case (data not shown). However, it is noteworthy that the simulated yields were overestimated compared to observed yields in Year 1 in Sevekpota (data not shown), and that the reduction of ROOTDM from 0.7 m to 0.35 m (Table 6.4) helped to achieve yields closer to the observations. Although ROOTDM is crop and cultivar specific, its small value in Sevekpota soils can be attributed to the hard pan being likely closer to the soil surface (thus closer to the lower end of the 0.4-0.8m range indicated in Section 6.2.2) in the Year 1 site, and implies a lower water availability in the experimental field in Year 1 in Sevekpota compared to Year 2.

6.3.5. Effect of drought on cassava yields

The difference between potential and water-limited yields is an indicator of the impact of drought or water stress (Table 6.6, Fig. 6.12). The simulations suggest that drought stress caused 9 to 55% total biomass yield reduction and 9 to 60% storage roots yield decline (Table 6.6). The largest yield losses were obtained in Year 1 in Sevekpota (Fig. 6.12a1). In Sevekpota, the cumulative rain curve (Fig. 6.12a) shows drought stress effects occurred earlier in the development of the plant in Year 1 (Fig. 6.12a1, Fig. 6.8b) than in Year 2 (Fig. 6.12a2, Fig. 6.8a). Water stress (TRANRF <1) occurred for 46 days between 79 and 125 days after planting in Year 1 in Sevekpota (data not shown). Simulated potential yields ranged from 11.6 to 14.1 Mg storage roots DM ha^{-1} and 20.7 to 25.5 Mg total biomass DM ha^{-1} across sites during the two cropping years according to the model.

Table 6.6. Simulated potential and water-limited yield gaps as proxy for drought effects on cassava biomass and storage root yields.

Site	Year	Biomass produced (Mg ha^{-1})		Drought effect	Storage roots (Mg ha^{-1})		Drought effect
		Water-limited	Potential		Water-limited	Potential	
Sevekpota	1	11.4	25.5	55%	5.6	14.1	60%
	2	18.2	22.5	19%	9.8	12.5	21%
Djakakope	1	19.2	23.3	18%	10.4	12.9	20%
	2	18.9	20.7	9%	10.6	11.6	9%

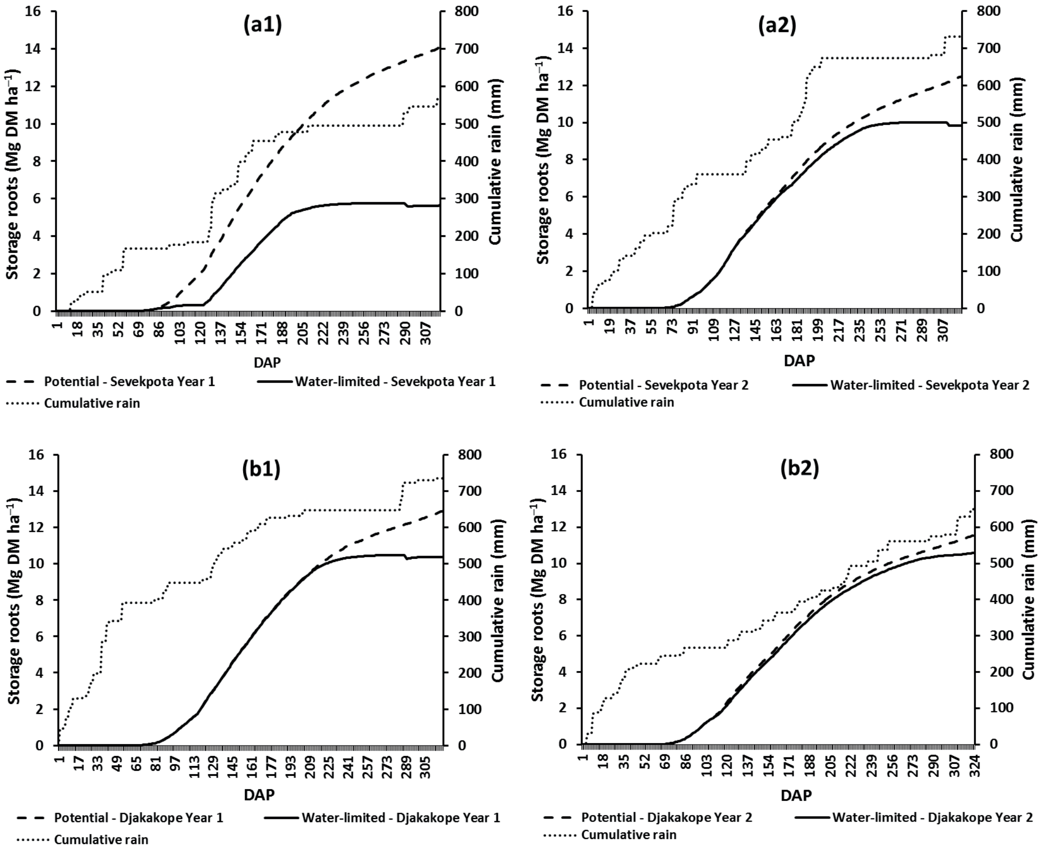


Fig. 6.12. Potential and water-limited yields as simulated by the model in Years 1 and 2 for Sevekpota (a1 and a2) and Djakakope (b1 and b2) and the respective measured cumulative rain per location and year.

6.3.6. Cassava water-limited yields as affected by planting dates

The largest storage roots yields were achieved with planting early in the year: around mid-February in Djakakope, and mid-January to mid-February in Sevekpota (Fig. 6.13). Those were followed by mid-March planting. Beyond these periods, storage roots yield declined and reached their smallest value with mid-July planting.

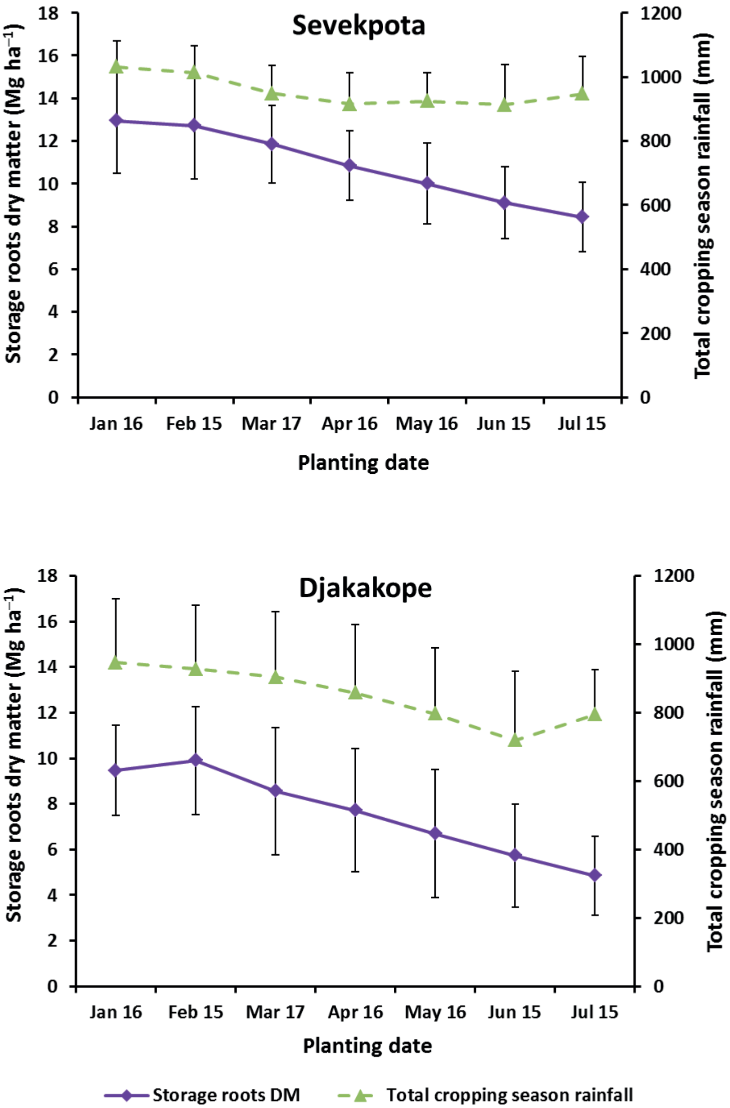


Fig. 6.13. Effect of planting dates on simulated water-limited yields of storage roots and total rainfall amount measured per cropping season. Error bars are standard deviations per planting date over 10 cropping seasons.

Larger amounts of rainfall were also accumulated from planting to harvest with January to March planting, compared with the other planting dates. There were positive correlations between the simulated water limited storage roots yields and the measured total rainfall amounts in both sites (with Pearson correlation coefficient of 0.723 in Djakakope and 0.478 in Sevekpota, $P < 0.001$). Drought related yield losses decreased with the early planting than the latter planting (Fig. 6.14). There were negative correlations between water-limited yields and drought related yield losses on both sites (Pearson correlation coefficient of -0.989 in Djakakope and -0.973 in Sevekpota, $P < 0.001$). Unlike the water-limited yields, the simulated potential yields indicated that later planting, viz. June and July were the best for cassava production under irrigated system.

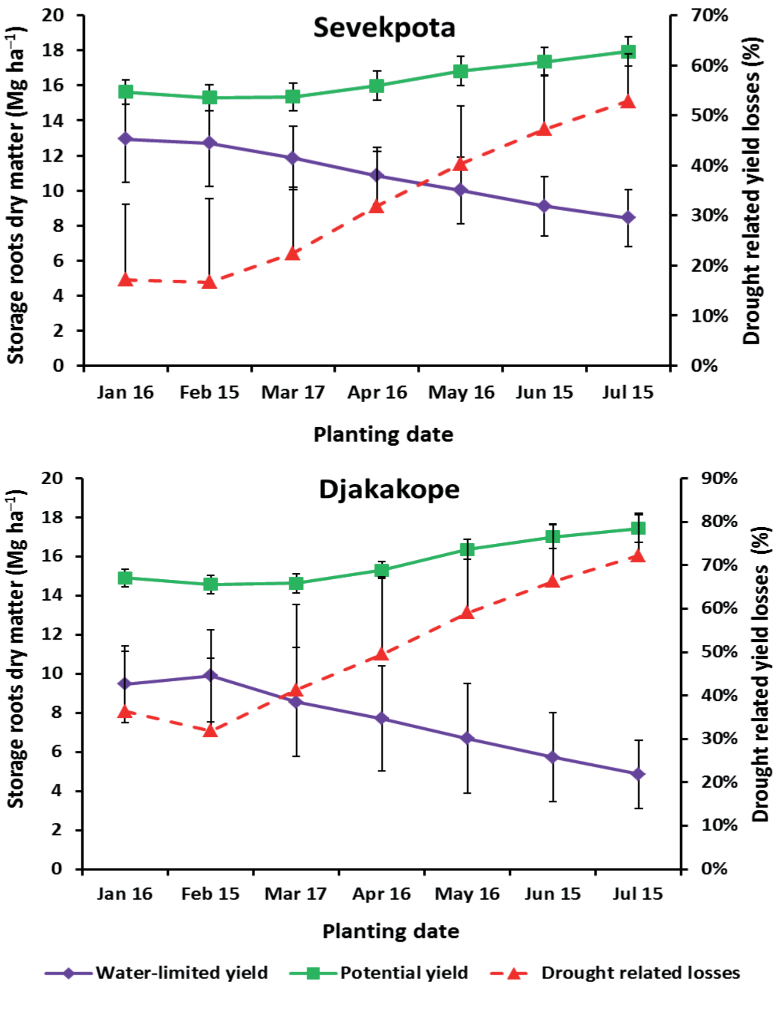


Fig. 6.14. Simulated potential yield, water-limited yield and drought related yield losses as affected by planting dates. Error bars are standard deviations per planting date over 10 cropping seasons.

6.4. Discussion

The process-oriented LINTUL-Cassava model successfully simulated cassava growth and assessed the effects of drought on yields. The model simulated well the trend in leaf area growth beyond 3 MAP (Fig. 6.7), but slightly under-estimated the values of LAI. Future studies should measure LAI earlier than 3 MAP to better appreciate model performance during the whole period of crop growth. The model simulated well the decline in LAI and the regrowth of LAI after dormancy. This phenomenon of leaf regrowth after dormancy has also been observed in other studies (Keating et al. 1982). This leaf regrowth was associated with increased leaf dry matter production and decreased storage roots dry matter (Figs. 6.9a2 and 6.9b2). Howeler and Cadavid (1983) reported similar responses of leaf and storage roots dry matter to soil water availability for M Mex 59 and M Col 22 cultivars in Columbia. Although LINTUL-Cassava assumed that this reduction in storage roots does not exceed 5% of the yield at the recovery from dormancy, this reduction is quite important for farmers given that storage roots are the main commercial product. To prevent a reduction in storage roots yields due to leaf regrowth, cassava harvest time should be appropriately chosen. However, this comes with the challenge of harvesting during the dry season, when the soil is hard and can break the storage roots. Unfortunately, these soil physical considerations at harvest are not considered in the model. In our study, leaf regrowth was preceded by drought periods of 30 days in Year 2 and of 42 days in Year 1 in Sevekpota, which stopped with new rains that improved soil water content. In the model, the recovery from dormancy occurred only when water content was improved to at least 70% of the critical water content (WCCR) and above wilting point. Model outcomes were not sensitive to changes in the RECOV parameter referring to this proportion (70%) of WCCR. The soil parameters mostly affecting yield were WCFC and WCWP. They have been reported as important soil parameters in determining yields also in highland banana production in East Africa (Taulya 2015). These parameters should be accurately assessed to guarantee sound simulation results. The model was also sensitive to TWCSD, a parameter set to indicate soil water content has reached the severe drought condition, which triggers dormancy at a low LAI (<LAI_MIN). TWCSD defined as the proportion of WCWP at which WCSD is reached, justifies the need to ensure sound assessment of WCWP and other soil hydraulic parameters in order to achieve realistic model outputs. Other key parameters that induced model output sensitivity during most part of the crop life cycle were SLA_MAX, LUE_OPT, K_ext, TBASE, WCUTTINGUNIT and TSUMLA_MIN. The first three were measured in our field experiments. The other parameters were estimated from literature (Table 6.1), but it is important to assess these in future studies, given their relevance for simulations of LAI and biomass growth. Other key

parameters induced model output sensitivity during the first half of the cropping season (TSUMSOBULKINIT, OPTEMERGTSUM, RDRWCUTTING and RGRL), whereas others were more effective towards the second half of the cropping system (RDRB, FASTRANSLSO, TSUMLLIFE, SO2LV, RRREDISTSO, ROOTDM and RRDMAX). Knowing which parameter most strongly affects which growth or development phase is of a paramount importance, and can guide future calibration of the model. Among the model sensitivity parameters, TSUMSOBULKINIT, related to the physiological time from emergence to the start of storage roots bulking, was assumed to be cultivar-specific. Changing the value of this parameter in the sensitivity analysis affected mainly the storage roots, with negative $E_{s,p,t}$ values. This indicates that reducing the default value of this parameter, which implies earlier bulking initiation, may generate larger yields. Breeding or promoting cultivars with early bulking of storage roots are highly recommended, since late bulking has been found as a key reason of abandoning cassava cultivars in sub-Saharan Africa (Hillocks 2002). The TSUMLLIFE defined as the developmental time from leaf appearance to leaf senescence, is also a sensitive cultivar-specific parameter. A TSUMLLIFE value of 1200^{o}Cd, equivalent to 100 days leaf life (assuming optimal temperature of 27^{o}C and a TBASE of 15^{o}C), has been obtained after calibration. This falls in the reported range of 60 to 120 days by Cock (1984). The right TSUMLLIFE of a given cultivar should be used in LINTUL-Cassava, since this parameter had a strong effect on LAI and storage roots yields. The OPTEMERGTSUM defining the TSUM accumulation from planting to emergence is cultivar specific and its value should be appropriately defined because of its strong effects on the model responses. In the current version of the model, OPTEMERGTSUM is mainly affected by the daily average temperature and soil water content. Future versions of the model should also consider the effects of planting method on the emergence of the plant, since planting vertically proved to provide greater storage roots yields than planting horizontally (Leihner 2002). Vertical planting leads to deeper rooting allowing better access to water and nutrients. In our experiments, we planted at 45^{o} inclination of the stem cutting, which is intermediate between vertical and horizontal planting. Another important cultivar-specific parameter is TSUMSBR, which refers to the period of the first branching of the cultivar. However, TSUMSBR did not appear as a sensitive parameter in this version of the model. Since the current study focused only on a late branching cultivar, further studies involving a range of cultivars including early branching types are recommended in order to extrapolate the results to a wider range of agro-ecological zones.

The simulations for Sevekpota in Year 1 indicated drought can cause yield reductions up to 55% and 60% of the total biomass and storage roots. Comparable yield losses due to drought have been reported in other studies (Alves 2002; Connor et al. 1981). The low rainfall recorded in that year in Sevekpota (574 mm compared to 731 mm in Year 2) and the occurrence of a long period of drought (46 days water stress caused between 79 and 125 days after planting) during the vegetative phase of the crop as shown in Figs. 6.12a1 and 6.8b are likely the cause of the low yield obtained. The occurrence of long periods of drought between 1-5 MAP can cause significant yield losses (Alves 2002; Connor et al. 1981). The assessment of planting dates using historical data of the respective sites indicated that the best planting window of cassava is between mid-January and mid-March, as this resulted in lower yield losses due to drought. The January and February plantings are quite unexpected since these periods are generally considered dry. Moreover, the most recommended cropping period in Southern Togo is at the onset of the rainy season, which is around mid-March and mid-April. However, the simulation results are supported by the fact that the largest amounts of cumulative rainfall were also achieved with mid-January and mid-February plantings. This means there has been rain in January and February across the simulation period of 2001 to 2011. One can expect low sprouting of the cutting during this period if water supply is not sufficient, but the model assumes the emergence occurs only when water content is above wilting point; otherwise, the emergence is delayed. Some farmers do prepare their land early and plant with the first rains. However, this is often a risky planting period for crops like maize because rain is not reliable during this period in which cassava can still thrive. Hence, planting in January and February may not be applicable for maize-cassava intercropping systems since the recommended period for planting maize is around April in Southern Togo according to Dzotsi et al. (2003) who did not test earlier planting dates that seemed not relevant for maize. In such systems, cassava is generally planted either at the same time or 1-2 weeks after maize. Another practical issue is that rains generally cease around mid-November in Southern Togo, and soils are hard from December to February. This makes land preparation difficult in January and February. These aspects related to soil physics dynamics should be considered in further model improvement. Simulated potential yields were highest with planting in June-July (Fig. 6.14). Thus, higher yields could be achieved in Southern Togo under irrigation conditions. However, irrigating cassava is not a common practice because of its cost implications. This could be considered in areas where water for irrigation is easily available, for instance nearby rivers. Setting up an experiment in which cassava will be planted every two weeks from January to December for at least two years and harvested at 11MAP under rain-fed and irrigated conditions will help have better understanding of the best planting period of cassava to verify the simulation results. Nethertheless, these results have already improved our understanding of water-limited yield of cassava, and suggest that there is room for increasing cassava yields in West Africa.

6.5. Concluding remarks

The calibrated LINTUL-Cassava model successfully assessed water-limited yields and improved our understanding of cassava growth and development, and of the effects of drought stress on cassava yields in the study sites. We found that drought stress can considerably undermine yields in rain-fed cassava production systems in Southern Togo, and that yields could be improved through early planting of cassava. Further improvement of the model may help build a decision support system to capture adequate planting windows and harvest period to minimise storage roots losses and achieve higher yields of cassava in West Africa.

Acknowledgements

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CHAPTER SEVEN

7.0. General Discussion

7.1. Introduction

The research presented in this thesis aimed to understand cassava productivity, farm incomes and food self-sufficiency in rain-fed cassava production systems in West Africa. The long-term goal is to contribute to a decision support tool for site-specific nutrient management. The implementation of activities towards achieving this goal led to some key lessons discussed below. Besides these lessons, we reflected on the applicability of the findings for intercropping systems, on the potential for extrapolating the results beyond the study zones, and on the perspectives for completing the development of a decision support tool for site-specific fertilizer recommendation for cassava production in West Africa.

7.2. Lessons learnt

7.2.1. The confounded effect of the low agricultural potential of the area and the closeness to urban market motivates the adoption of cassava production intensification options in West Africa

Poor soil fertility and erratic rainfall were perceived by farmers as major constraints to cassava production within the study zones (Chapter 2). However, the agricultural potential of the area for cassava production was a major determinant of farmers' use of intensification options. The Plateaux Zone in Togo was more suitable for cassava production from an agro-ecological perspective than the Maritime Zone that had lower rainfall, poorer soils and generally lower yields. Within the zones, there was no significant difference between resource endowment groups in soil fertility management, neither in cassava yields. However, the closeness of the Maritime study sites to urban markets (Vogan and Afagnan markets within 9 km) has likely motivated, irrespective of the resource endowment group, i) the diversification of crop and livestock production, and ii) the application of crop production intensification options with the use of mineral fertilizers and organic resources including manure and household wastes, and the cultivation of legumes as intercrops in cassava fields. Although crop intensification options were mostly directed to maize, cassava can benefit from these as an intercrop. Improving nutrient management in maize can be an entry point towards enhancing fertilizer use for cassava production in maize-cassava systems in southern Togo. Despite this tendency to intensify crop production in the Maritime zone, yields were still low. This implies that either the current amounts of fertilizer applied were not enough, or other factors are limiting. Moreover, our study revealed that all households live below the poverty line of US$ 1.25 per day in the

Maritime zone. Our study areas in the Maritime were also identified as zones vulnerable to poverty by the Government of Togo for the implementation of an IFAD funded project (PADAT: “Projet d’Appui au Développement Agricole du Togo”) for improving agricultural development within the area (FIDA 2010).

7.2.2. Indigenous soil nutrient supplies and plant needs for a given target yield explain the response of cassava to mineral fertilizers

The calibrated QUEFTS model for cassava helped to assess nutrient uptake, physiological use efficiency and yield responses of cassava to fertilizer applications in the study zones of Ghana and Togo (Chapter 3). We found that cassava response to fertilizer depended on the indigenous fertility of the soil. If the indigenous supply of a given nutrient was below the plant’s need to achieve a given target yield within a location, the uptake of that nutrient and the yield of cassava increased in response to fertilizer application. However, the assessment of the indigenous soil nutrient supply did not yield any strong relationship between soil properties and plant uptakes. Conducting more multi-locational nutrient omission trials, analysing soil samples in each location, and measuring plant uptakes and yields in these locations will help improve QUEFTS equations relating total nutrient supply to soil physical and chemical properties. It is noteworthy that QUEFTS modelling assumes good management practices, resulting in an overestimation of yields on control plots in farmers’ fields (Chapter 3). This implies that farmers could considerably improve cassava yield through enhanced management practices, even without fertilizer application. The model provides realistic estimates of yields in good rainy years but overestimates yield under severe drought conditions, like in the case of Nyankpala (Chapter 3). This is because the model is static and does not simulate water dynamics. Coupling QUEFTS with a dynamic model that simulates water-limited yields may adjust target yields to seasonal variabilities within a given location for enhanced fertilizer recommendations.

7.2.3. Balanced nutrition increases cassava yields and benefit-cost ratio of fertilizer use

The balanced nutrition approach provided higher nutrient use efficiency and benefit-cost ratio compared to blanket fertilizer applications (Chapter 4). Site-specific fertilizer recommendation based on the balanced nutrition approach is crucial to optimize nutrient use and achieve high yields and profits in cassava production systems in West Africa. However, due to the generally high costs of single fertilizers and the difficulty to blend site-specific fertilizer mixes for cassava for each location of West Africa, major soil type or agro-ecology specific recommendations will be a step forwards towards improving fertilizer use efficiencies in West Africa. With major soil types or agro-ecology specific recommendations, which expand across countries, fertilizer companies will have larger markets, and this can contribute to reducing the fertilizer price for the farmer's benefit. A fertilizer blend with larger K content than the existing NPK complexes found in West Africa (N-P_2O_5-K_2O: 15-15-15, 20-10-10, etc.) will be a good start, given the strong demand of cassava for K. The key challenge is to increase the use of fertilizers by farmers in cassava production systems. We found a greater intensity of fertilizer use in the Maritime compared to the Plateaux Zone irrespective of the farmer resource endowment groups. The former zone has a high need of intensification due to its closeness to urban markets as well as its lower agricultural potential for cassava production compared to the latter. The intensity of fertilizer use could have been limited to resource endowed households only in the Maritime Zone in case of lack of access to close urban markets since resource-constrained farmers are generally less inclined to use fertilizers due to financial limitations (Franke et al. 2014). Beyond the use of fertilizer, emphasis should be placed on the promotion of site-specific balanced fertilizer rates, which should go along with the promotion of good management practices (recommended planting density, planting periods, weeding, disease control, etc.) and improved cultivar cultivation in order to optimize returns on investment in fertilizer use.

7.2.4. Potassium increases water and radiation use efficiencies of cassava

We found that the effect of potassium (K) on cassava productivity was mainly explained by the impact of K on radiation use efficiency and water use efficiency (Chapter 5). Potassium showed a leading role in improving radiation use efficiency and water use efficiency, whereas nitrogen (N) was the leading nutrient affecting light interception and water transpiration in cassava. These findings show that K and N play complementary roles in improving cassava productivity. The improvement of water-use efficiency by K supply is of paramount importance in climate-smart agriculture in the context of rain-fed cassava production systems, and indicates the need for enhanced K management in such systems to achieve high yields. The use of computer models like QUEFTS can help to estimate K need within a given location when water-limited yields of this location are known.

7.2.5. Inappropriate planting periods can cause considerable drought-related yield losses in cassava production systems in Southern Togo

Development of the cassava model has been a challenging experience. Unlike other crops like cereals, cassava is a perennial crop cultivated as an annual crop, which still remains longer in the field beyond 6-10 months after planting. This has consequence on the duration and costs of field experiments and data collection. Moreover, there is no distinct separation between the vegetative stage and the production of storage roots as main commercial product (which is not a fruit), unlike cereals for instance, for which the grain is the main commercial product. These characteristics added to other specific attributes of the crop including its tolerance to drought versus its response to water dynamics make the development of the cassava model quite complex.

The newly developed version of LINTUL-Cassava estimates water-limited yields of cassava, assesses the impacts of drought stress on cassava yields and simulates dormancy and the effect of recovery from dormancy on yields. The comparison of simulated water-limited yields and potential yields shows the prevalence of drought stress impacts on yield formation within the study sites with 9-60% yield reduction. The largest yield loss due to drought was obtained when drought occurred early in the crop life cycle, as reported by Alves (2002). The model showed that drought related yield losses can be reduced and storage roots yields could be increased with planting earlier than April. Although planting before April may be practically challenging in the current cropping systems which lack proper mechanization like planters, irrigation systems and harvesters, this result calls for attention to the possibility to improve cassava storage roots yields by adjusting planting dates. However, confirmation of this result and further improvement of the model are required. The lack of data to estimate some soil and crop parameters constrained further advances of this model. Among the key soil parameters, soil hydraulic properties such as water content at field capacity and wilting point are major determinants of the model's behaviour. Their accurate estimate in experimental fields is required for proper model development. Field experiments for model improvement should be established near a synoptic weather station to obtain daily weather inputs. After the improvement of the water-limited production version of LINTUL-Cassava, a nutrient limited production version can be developed. Further studies to develop the nutrient limited production of this model requires a strong consideration of the effects of nutrient availability, especially K, on stomata regulation. Conducting research on the physiological impacts of K deficiency on water use efficiency of cassava may unveil the main mechanisms involved in this process relatively to K effects on stomata regulation.

7.3. Applicability of the results for cassava-based intercropping systems

It is important to understand water-limited yields and nutrient requirements of cassava in sole crops before assessing those for cassava-based intercropping systems. Some key elements are important to consider in terms of applicability of the experimental findings to intercrops. Firstly, water-limited yield of cassava will be larger in the sole system than in the intercropping system. Cassava yields in an intercropping system are generally less than in sole crops due to competition for light, water and nutrients with the intercrop (Mason and Leihner 1988; Mason et al. 1986). Secondly, larger amounts of nutrients will be needed to achieve the same yields for the intercropped cassava, as for the sole cassava, assuming identical planting density of the cassava in both systems. For a precise estimate of the fertilizer requirements for cassava in intercropping systems, the relative contribution of different nutrients to yield formation of each intercrop should be investigated. However, the intercropping system might have an advantage over the sole system in terms of soil coverage, which may reduce soil evaporation, and increase water supply to each intercrop. Furthermore, a greater overall productivity can be achieved in intercropping systems due to larger use efficiency of resources such as water, light and nutrients than in the sole system. These aspects can be considered when upgrading LINTUL-Cassava with intercropping simulations.

7.4. Applicability of the results beyond the study zones

The research activities of this thesis were conducted in agro-ecological zones (AEZ) that cut across several countries in West Africa. These AEZs include the Coastal Savannah zone, the Forest zone and the Southern Guinean Savanna zone, which demarcate the cassava belt of West Africa across Nigeria, Benin, Togo, Ghana, Côte d'Ivoire, Liberia, Sierra Leone and Guinea. This will facilitate the extrapolation of the results beyond the study sites and within the same AEZs. The extrapolation of the results beyond the study AEZs might require further validation trials on a larger range of soils, climatic conditions, and cassava cultivars. The dynamic modelling approach with LINTUL facilitates an extrapolation based on weather data within and across AEZs. Improving the estimate of potential soil nutrient supplies based on soil properties also facilitates this extrapolation.

7.5. Towards an enhanced decision support tool for site-specific fertilizer recommendation in West Africa

The QUEFTS modelling deployed in this project with the balanced nutrition approach yielded a decision support system that can be used to develop site-specific fertilizer recommendation for cassava production in West Africa. However, this model was limited in its capacity to simulate drought impact, for which the LINTUL modelling was more suitable. Coupling both models as proposed in Fig. 7.1, will strengthen their individual capacities and can contribute to robust fertilizer recommendations. It will help to select areas suitable for good yields under rain-fed conditions, to identify the best periods of cassava planting for reduced impacts of drought stress and facilitate the extrapolation of the simulation results to larger areas across West Africa. This decision support system framework presented in Fig. 7.1 comprises many phases, starting from water-limited yield simulation, to deriving optimal fertilizer rates, to validation trials, to economic analysis before deriving the fertilizer rates to be recommended. The water-limited yield simulation requires some sites information, daily weather data, and crop parameters and management information. The simulated water-limited yield should be used as a boundary constraint for deriving the optimal fertilizer rates. The latter requires also information about the indigenous soil fertility and locally available organic resources, the physiological nutrient use efficiency, the target yield, and the maximum recovery fraction. Depending on data availability, three options of assessing the indigenous soil fertility were proposed: the first option is based on the original QUEFTS approach (Janssen et al. 1990), which requires soil chemical properties to assess the indigenous soil fertility; the second option is based on the approach by Dobermann and White (1998); Witt et al. (1999), which uses plant uptake from nutrient omission plots as a proxy for the indigenous soil N, P and K; the third option is based on the common situation whereby no data is available on soil chemical properties, nor on plant uptakes from nutrient omission trials. In this case, yields from well-managed fields without fertilizer application are used as proxy for the indigenous soil fertility. The emphasis is put on management in the latter case, because without good crop and nutrient management, yields do not express the potential capacity of the soil to supply a given nutrient. Hence, yields from control plots on researcher-managed fields will generally be more appropriate than on farmer's fields. After determining the optimal fertilizer rates, which are mainly nutrient requirements to achieve a given target yield, it is important to test them in farmers' fields through multi-locational validation trials. These trials should be a set of 3-4 treatments at most (including a farmer's practice, a blanket rate and a recommended rate plots for instance) per field, conducted in both areas similar to where the model has been calibrated, as well as in other areas to assess the capacity of the model to capture spatial soil fertility and weather variabilities. The validation trials will help improve the calculated fertilizer rates. They should be conducted along with economic analyses to assess the profitability of the new fertilizer rates compared with farmer's practice and blanket recommendations if they exist. A minimum value-cost ratio (VCR) of 2 is required for a profitable fertilizer investment, but a VCR of 4 is preferred to minimize risks induced by fluctuations in input and output prices (Koffi Tessio 1998). Conducting this validation trial on hundreds of fields widely distributed per AEZ will allow not only to assess the variability in response to fertilizer, but also to determine the proportion of fields where the new rate gives a profitable response. After the validation of the most profitable fertilizer rates, the recommendations are ready for up-scaling. Given the low fertilizer use for cassava production and the risk averse attitude of smallholder farmers in sub-Saharan Africa, the validation trials should be accompanied with field observations and participatory learning to attract farmers' attention to the effects of fertilizer on cassava, and on the role of each nutrient. Thus, such validation trials will also serve to demonstrate the benefits of fertilizer use to many farmers. In this validation process, in addition to the farmers, the extension service providers and the national research institutes, it is crucial to involve other stakeholders such as input dealers, agricultural finance institutes and policy makers in farmers field days and other appropriate fora in order to stimulate the development of enabling policies for access to credit, to inputs and to markets.

Our study built the empirical and theoretical foundations of cassava growth modelling based on light interception and utilization approach under rain-fed systems. However, LINTUL-Cassava requires further improvement since it was based on many assumptions that have not yet been tested. Fortunately, there are several research initiatives within the region that can be used to improve the model. In particular the new funded Bill & Melinda Gates Foundation project, the African Cassava Agronomy Initiative (ACAI) that is led by the International Institute of Tropical Agriculture (IITA) provides a good platform to improve LINTUL-Cassava. A key feature of this project focuses on improving farmers' livelihood through the delivery of *à la carte* fertilizer recommendations for cassava production using smartphone, tablet-based decision support tool and any other relevant tools requested by development partners in Nigeria and Tanzania. The LINTUL and QUEFTS based framework will be useful in the development of this decision support tool.

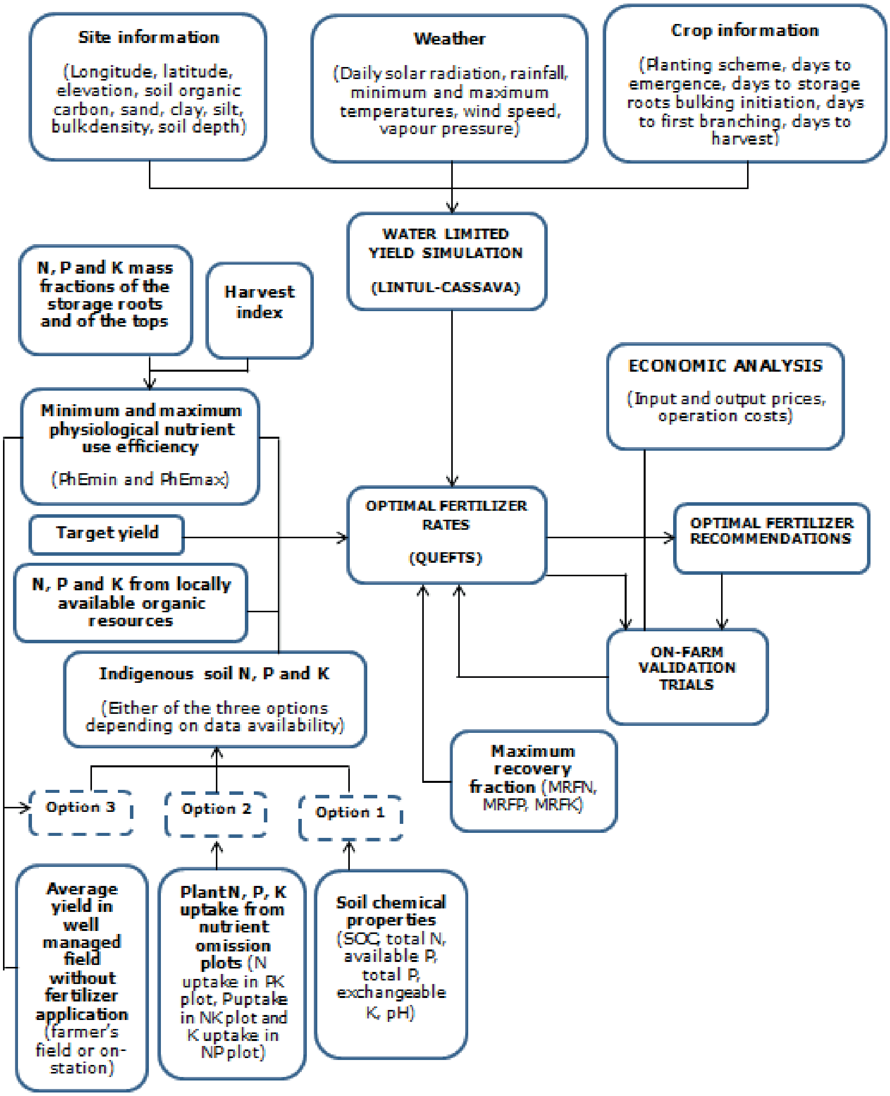

Fig. 7.1. Framework for developing site-specific fertilizer recommendation for cassava production.

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APPENDICES

APPENDIX 5.1: FORMULAS FOR CALCULATING PTRAN, PEVAP AND PET BASED ON PENMAN EQUATIONS AS USED IN THE LINTUL MODEL.

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PEVAP  =     EXP(-0.5*LAI)  * (PENMRS + PENMD) / LHVAP
PTRAN  = (1.-EXP(-0.5*LAI)) * (PENMRC + PENMD) / LHVAP
PTRAN  = MAX( 0., PTRAN-0.5*RNINTC )

DTRJM2 = DTR * 1.E6
BOLTZM = 5.668E-8
LHVAP  = 2.4E6
PSYCH  = 0.067
BBRAD  = BOLTZM * (DAVTMP+273.)**4 * 86400.
SVP    = 0.611 * EXP(17.4 * DAVTMP / (DAVTMP + 239.))
SLOPE  = 4158.6 * SVP / (DAVTMP + 239.)**2
RLWN   = BBRAD * MAX(0.,0.55*(1.-VP/SVP))
NRADS  = DTRJM2 * (1.-0.15) - RLWN
NRADC  = DTRJM2 * (1.-0.25) - RLWN
PENMRS = NRADS * SLOPE/(SLOPE+PSYCH)
PENMRC = NRADC * SLOPE/(SLOPE+PSYCH)
WDF    = 2.63 * (1.0 + 0.54 * WN)
PENMD  = LHVAP * WDF * (SVP-VP) * PSYCH/(SLOPE+PSYCH)
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Where:

PEVAP [mm d^{-1}]: Potential rate of evaporation from the soil; *PTRAN* [mm d^{-1}]: Potential transpiration rate; *LAI* [$m^2 m^{-2}$]: Leaf area index; *PENMRS* [J m^{-2} d^{-1}]: Radiation term of the Penman equation for evaporation from the soil; *PENMRC* [J m^{-2} d^{-1}]: Radiation term of the Penman equation for transpiration from the canopy; *PENMD* [J m^{-2} d^{-1}]: Drying power term of the Penman equation; *LHVAP* [J kg^{-1}]: Latent heat of vaporization; *RNINTC* [mm d^{-1}]: Interception of rain by the canopy; *DTRJM2* [J m^{-2} d^{-1}]: Daily global radiation; *DTR* [MJ m^{-2} d^{-1}]: Daily global radiation; *BOLTZM* [J m^{-2} s^{-1} K^{-4}]: Stefan-Boltzmann constant; *PSYCH* [kPa $°C^{-1}$]: Psychrometric constant; *BBRAD* [J m^{-2} d^{-1}]: Black body radiation; *DAVTMP* [°C]: Daily average temperature; *SVP* [kPa]: Saturation vapour pressure; *SLOPE* [kPa $°C^{-1}$]: Change of saturation vapour pressure per °C; *RLWN* [J m^{-2} d^{-1}]: Net outgoing long-wave radiation; *VP* [kPa]: Vapour pressure of the air; *NRADS* [J m^{-2} d^{-1}]: Net radiation absorption rate by the soil; *NRADC* [J m^{-2} d^{-1}]: Net radiation absorption rate by the crop; *WDF* [kg m^{-2} d^{-1} kPa^{-1}]: Wind function in the Penman equation; *WN* [m s^{-1}]: Wind speed.

SUMMARY (English)

The productivity of cassava in sub-Saharan Africa is poor, despite increases in yields over recent decades. Given the rapid human population growth and the increasingly limited land resources, soil fertility is at stake in the context of rain-fed cropping systems and nutrient mining agricultural practices in West Africa. In these conditions, drought stress is also a major yield limiting factor. In order to improve yields in the region, we analysed cassava production systems by investigating the socio-economic and biophysical factors determining cassava productivity and exploring opportunities to increase cassava yield in West Africa. Furthermore, we translated existing knowledge and experimental data on cassava growth into two models: QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) and LINTUL (Light Interception and Utilization), in order to improve our understanding of water-limited yield and drought effects on yields, and to derive site-specific fertilizer requirements for cassava production in West Africa.

A baseline farm survey was used to assess drivers of diversity among households. It was followed by a detailed farm characterization to assess yield, farm incomes and food security as affected by current farming practices, and to evaluate the suitability of resource endowment groups to the intensification of cassava production in the Maritime and the Plateaux zones in Southern Togo. The agricultural potential of the area and the proximity to regional markets were major drivers for the adoption of crop intensification options including the use of mineral and organic fertilizers. Most farmers in the lower agricultural potential zone (Maritime) use fertilizers to remediate the low fertility of their soils. Their proximity to the regional market provided them with the opportunity to access inputs and to sell their produce. Farmers perveived erractic rainfall and poor soil fertility to be prime constraints for cassava production in the Maritime Zone due to the low rainfall amount in this zone compared with the Plateaux Zone where the main constraint evoked by farmers was poor soil fertility. Although mineral and organic fertilizer use was common in the Maritime Zone, yields of storage roots were below the national average of 2.2 Mg dry matter per hectare, and average incomes per capita per day of 0.62, 0.46 and 0.46 US$ for the high, medium and low resource groups (REGs – HRE, MRE and LRE, respectively) were below the poverty line of 1.25 US$. In the Plateaux Zone, HRE and MRE households rose above this poverty line by earning 2.58 and 2.59 US$ per capita per day, respectively, unlike the LRE households with 0.89 US$ per capita per day.

As soil fertility was perceived a major constraint to cassava production across the study zones, we further studied the effects of mineral fertilizer on nutrient uptake, nutrient physiological use efficiency and storage roots yields of cassava. Nutrient omission trials conducted across Togo and Ghana in three different agro-ecological zones for two

consecutive years provided the dataset to successfully adapt QUEFTS model for cassava. Other fertilizer response experiments carried out in other locations across these two countries were used to test the performance of the model. We found out that this model was most appropriate to assess cassava responses to N, P and K applications in years with good rainfall. Under excessive drought conditions, the model overestimated yields.

Fertilizer rates used by farmers in the Maritime Zone were about 70% of the blanket NPK rate recommended by the National Research System, according to the detailed farm characterization survey. But this did not translate into high yields. For this reason, we assessed the impact of balanced nutrition on nutrient use efficiency, yield and return on investment compared to blanket fertilizer use in cassava production systems in Southern Togo, and in Southern and Northern Ghana. The balanced nutrition approach using the QUEFTS model aims at maximizing simultaneously the use efficiency of N, P and K in accordance with the plant's needs. Larger nutrient use efficiencies of 20.5 to 23.9 kg storage roots dry matter (DM) per kilo crop nutrient equivalent (CNE: unit to define the quantity of a nutrient that has the same effect on yield as 1 kg of N under conditions of balanced nutrition) were achieved at balanced nutrition at harvest index (*HI*) values of 0.50 compared to 20.0 to 20.5 kg storage root DM per kilo CNE for the blanket rates recommended by national research services for cassava production. Blanket fertilizer rates gave average benefit:cost ratios of 2.4±0.9, which are less attractive to farmers compared with 3.8±1.1 for the balanced fertilizer rates. Fertilizer recommendations for cassava production should be based on balanced nutrition in order to increase yield and returns on investment. Our study also revealed that potassium (K) was a major yield limiting factor for cassava production, especially on Ferralsols in Southern Togo.

Another field experiment conducted in Southern Togo on K deficient and K rich soils investigated the effect of K and its interaction with N, P and the timing of harvest on the productivity of cassava in relation to the effects of K on radiation use efficiency (RUE), light interception, water use efficiency (WUE) and water transpiration. This study unveiled the leading role of K in determining RUE and WUE of cassava, versus the leading role of N in light interception and water transpiration. Potassium application increased RUE and WUE, but K effects depended on the availability of N and harvest time. Larger RUE and WUE were achieved at harvests taken 4 and 8 months after planting (MAP) than at 11 MAP for 50 kg N and 100 kg K ha^{-1}. Values of RUE and WUE declined with harvest from 4, 8 to 11 months after planting. These results suggest enhanced K management with sufficient supply of N during the early stage of development of cassava in order to maximize RUE and WUE, and consequently attain larger storage roots yields.

Although the QUEFTS model could be used to improve N and K management, it failed to appropriately assess the impacts of drought stress on yields, whereas drought was perceived as a major constraint to cassava production. In order to quantify drought impacts on yields and explore strategies to improve yields, another modelling approach based on light interception and utilization (LINTUL) was studied. Part of the dataset generated by the study on K effects on RUE and WUE was used to parameterize and adapt LINTUL for cassava, and another part of this dataset was used for the model testing. The evaluation of the model indicated good agreement of the simulations with the observations of leaf area index, storage roots yields and total biomass yield. The model showed how drought stress affected growth, and resulted in low yields on the study sites. Simulated yield losses due to drought ranged from 9-60% of the water-limited yields. The evaluation of planting dates from mid-January to mid-July indicated that the best planting window is around mid-February. Larger amounts of total season rainfall were achieved with early planting. These results contradict current practices of planting at the onset of the rainy season around mid-March to mid-April, and appear practically challenging because soils are likely to be hard to cultivate in January and February, given the rudimentary cropping practices in Southern Togo. However, the results call for our attention to the possibility to increase cassava yields with earlier planting, which lead to reducing yield losses due to drought. Unlike the rain-fed condition, the best planting periods of cassava with irrigation in Southern Togo appeared to be around June-July compared to earlier planting periods. This shows that appropriate water control and planting periods can contribute to attaining larger yields in Southern Togo. The LINTUL model was very sensitive to soil hydraulic parameters, stressing the importance of the use of good soil data to ensure reliable results. Further improvement of the model is required towards using it in combination with QUEFTS to assess water-limited yields and derive site-specific fertilizer requirements for enhanced cassava yield and return on investments in West Africa.

RESUME (Summary in French)

La productivité du manioc est faible en Afrique sub-Saharienne, malgré l'augmentation du rendement au cours des récentes décennies. Avec une croissance démographique gallopante et des ressources en terres arables de plus en plus limitées, la fertilité du sol est mise en jeu dans un contexte d'agriculture pluviale et de pratiques agricoles épuisantes pour les nutrients du sol en Afrique Occidentale. Dans ces conditions, le stress hydrique est également un facteur limitant majeur du rendement de manioc. En vue d'améliorer les rendements dans la sous-région, nous avons analysé les systèmes de production du manioc en étudiant les facteurs socio-ecomomiques et bio-physiques qui déterminent la productivité du manioc, et en explorant les opportunités d'augmentation du rendement du manioc en Afrique de l'Ouest. Par ailleurs, nous avons traduit des connaissances existantes et des données expérimentales sur la croissance du manioc en deux modèles de cultures: QUEFTS ('Quantitative Evaluation of the Fertility of Tropical Soils') et LINTUL ('Light Interception and Utilization') en vue d'améliorer notre compréhension des rendements limités par l'eau et des effets du stress hydrique sur les rendements, et de déterminer les besoins par site-spécifique en engrais pour la production du manioc en Afrique de l'Ouest.

Une étude de référence des exploitations agricoles a été conduite pour évaluer les facteurs déterminant la diversité des ménages. Par la suite, une étude de caractérisation détaillée des exploitations agricoles a été menée d'une part pour évaluer les rendements, les revenus et la sécurité alimentaire de l'exploitation agricole tels qu'affectés par les pratiques agricoles actuelles du producteur, et d'autre part pour analyser la conformité des classes de dotation en ressources à l'intensification de la production du manioc dans les régions Maritime et des Plateaux au Sud du Togo. Le potentiel agricole de la zone et la proximité des exploitations agricoles des marchés régionaux ont constitués des facteurs déterminants pour l'adoption des options d'intensification agricole comprenant l'utilisation d'engrais minéraux et organiques. La plupart des producteurs de la zone à potentiel agricole relativement plus faible (région Maritime) utilisaient les engrais pour remédier à la faible fertilité de leurs sols. Leur proximité des marchés régionaux leur avait permis d'avoir accès aux intrants et de vendre leurs produits. Les producteurs percevaient l'irrégularité des pluies et la faible fertilité des sols comme étant des contraintes majeures pour la production du manioc en région Maritime à cause du faible niveau des pluies comparé à la région des Plateaux où la principale contrainte évoquée par les producteurs était la faible fertilité des sols. Bien que les engrais minéraux et organiques soient utilisés dans la région Maritime, les rendements en racines de manioc étaient en dessous du rendement national de 2.2 Mg de matière sèche par hectare, et les revenus par capita par jour de 0.62, 0.46 et 0.46 US$ respectivement pour les producteurs à dotation en ressources forte, moyenne et faible (HRE, MRE et LRE, respectivement) étaient en dessous du seuil de pauvreté de 1.25 US$

par capita par jour. Dans la région des Plateaux, les ménages HRE et MRE étaient au-dessus de ce seuil de pauvreté en gagnant respectivement 2.58 et 2.59 US$ par capita par jour, contrairement au ménage LRE gagnant 0.89 US$ par capita par jour.

Comme la fertilité du sol était perçu comme une contrainte majeure à la production du manioc à travers les zones études, nous avons étudié l'effet des engrais minéraux sur l'absorption des nutriments, sur l'efficience d'utilisation physiologique des nutriments et sur les rendements en racines de manioc. Des essais soustractifs conduits à travers le Togo et le Ghana dans trois zones agro-écologiques pendant deux années consécutives ont fourni les données qui ont servi à adapter avec succès le modèle QUEFTS pour le manioc. Des données d'autres essais de réponses à l'engrais menés dans d'autres localités à travers ces deux pays ont été utilisées pour tester la performance du modèle. Les résultats ont montré que ce modèle est plus approprié pour l'évaluation de la réponse du manioc aux apports de l'azote (N), du phosphore (P) et du potassium (K) durant les années de bonne pluviosité. Dans des conditions à fort stress en eau, le modèle avait sur-estimé les rendements.

Les doses d'engrais utilisées par les producteurs en région Maritime étaient autour de 70% de la dose générale recommandée par le système national de recherche, d'après les résultats de l'étude de caractérisation détaillée. Mais, cela ne s'est pas traduit en rendements élevés en racines de manioc. Pour cela, nous avons étudié l'impact de la nutrition équilibrée sur l'efficience d'utilisation des nutriments, sur le rendement et sur le retour sur investissement en engrais comparés à l'utilisation de recommendations générales (sans distinction de zone agro-écologique ni de type de sol) pour la production du manioc au Sud Togo, et au Sud et au Nord du Ghana. L'approche de nutrition équilibrée utilize par le modèle QUEFTS vise à maximiser de façon simultanée l'efficience d'utilisation de N, P et K avec les besoins en nutriments de la plante. Des efficiences d'utilisation de nutriments plus élevées de 20.5 – 23.9 kg de matière sèche de racine de manioc par kilo de 'crop nutrient equivalent' (1 kCNE, unité de conversion désignant la quantité d'un nutriment qui produit le même effet sur le rendement qu'un kg d'azote) ont été atteintes en nutrition équilibrée à un indice de récolte de 0.50, comparées à 20.0 – 20.5 kg de matière sèche de racine de manioc par kilo de CNE pour les doses générales recommandées par les services nationaux de recherche pour la production du manioc. Ces doses générales d'engrais ont donné en moyenne des ratios bénéfice-coût de 2.4±0.9, qui sont moins attractifs pour les producteurs comparés à 3.8±1.1 pour les doses d'engrais équilibrées. Les recommandations d'engrais pour la production du manioc devraient être basées sur l'approche de nutrition équilibrée en vue d'accroitre le rendement et de rentabiliser les investissements en engrais. Notre étude a aussi révélé que le potassium (K) est un facteur limitant majeur de la production du manioc, surtout sur les Ferralsols au Sud du Togo.

Un autre essai conduit au Sud Togo sur les sols déficients en K et sur des sols riches en K ont permis d'étudier l'effet de K et ses interactions avec N, P and avec la période de récolte sur la productivité du manioc en relation avec les effets de K sur l'efficience d'utilisation de la radiation (RUE), sur l'interception de la lumière, sur l'efficience d'utilisation de l'eau (WUE) et sur la transpiration. Cette étude a révelé le rôle primordial de K dans la détermination de RUE et WUE, et le rôle principal de N dans les mécanismes d'interception de la lumière et de la transpiration. L'application de K a augmenté RUE et WUE, mais les effets de K dépendaient de la disponibilité de N et de la période de récolte. Des valeurs plus élevées de RUE et WUE ont été atteintes pour les récoltes à 4 et 8 mois après la plantation (MAP) du manioc que pour la récolte à 11 MAP pour 50 kg N et 100 kg K ha^{-1}. Les valeurs de RUE et WUE ont chuté avec les récoltes de 4, 8 à 11MAP. Ces résultats suggèrent une meilleure gestion du K avec l'approvisionnement suffisant de N durant le stade de développement juvenile du manioc en vue de maximiser RUE et WUE, puis d'atteindre de grand rendements de racines de manioc.

Bien que le modèle QUEFTS pourrait être utilisé pour améliorer la gestion de N et K, il n'a pas pu estimer efficacement les impacts du stress hydrique sur les rendements, alors que ce stress hydrique est perçu comme une contrainte majeure à la production du manioc. En vue de quantifier les impacts du stress hydrique sur les rendements et d'explorer les stratégies d'amélioration des rendements, une autre approche de modélisation basée sur l'interception et l'utilisation de la lumière (LINTUL) a été utilisée. Une partie des données générées par l'essai sur l'effet de K sur RUE et WUE a été exploitée pour paramétrer et adapter ce modèle pour le manioc, et une autre partie de ces données a été utilisée pour tester le modèle. L'évaluation du modèle a indiqué une concordance des résultats de simulation avec les données mesurées relatives à l'indice de la surface foliaire, aux rendements en racines et en biomasse totale de manioc. Le modèle a montré comment le stress hydrique a influencé la croissance, et engendré des rendements faibles sur les sites d'essai. Les réductions simulées de rendements dues au stress hydrique ont varié de 9 à 60% par rapport aux rendements limités par l'eau. L'évaluation de dates de plantation de manioc de mi-janvier à mi-juillet a indiqué que la meilleure période de plantation est autour de mi-février. Les plus grandes quantités totales de pluie enrégistrées de la plantation à la récolte ont été aussi atteintes avec les plantations précoces. Ces résultats sont contradictoires vis à vis des pratiques courantes de semis au début de la saison pluvieuse de mi-mars à mi-avril, et parait difficile à réaliser parce que les sols sont probablement durs à travailler en janvier et en février, vu les pratiques culturales rudimentaires au Sud Togo. Toutefois, ces résultats attirent notre attention sur la possibilité d'acccroître le rendement du manioc avec des plantations précoces, qui amènent à réduire les pertes de rendements dues au stress hydrique. Contrairement aux conditions pluviales, la meilleure période de plantation du manioc sous irrigation au Sud Togo parait être autour de juin-juillet. Cela démontre qu'une bonne gestion de l'eau et un choix judicieux de la période de plantation peuvent contribuer à la réalisation de rendements élevés de manioc au Sud Togo. Le modèle LINTUL a été très sensible aux paramètres hydrauliques du sol, soulignant ainsi l'importance d'utilisation de bonnes données de sol en vue d'assurer des résultats de simulation fiables. La poursuite des travaux d'amélioration de ce modèle est requise pour son utilisation en combination avec QUEFTS pour estimer le rendement limité par l'eau et déterminer les besoins par site-spécifiques d'engrais pour un meilleur rendement en racine et un investissement en engrais plus rentable pour la production du manioc en Afrique de l'Ouest.

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LIST OF PUBLICATIONS

PEER-REVIEWED PUBLICATIONS

1. **Ezui KS**, Franke AC, Leffelaar PA, Mando A, van Heerwaarden J, Sanabria J, Sogbedji J, Giller KE (2017) Water and radiation use efficiencies explain the effect of potassium on the productivity of cassava. European Journal of Agronomy 83: 28–39. doi: http://dx.doi.org/10.1016/j.eja.2016.11.005.
2. **Ezui KS**, Franke AC, Mando A, Ahiabor BDK, Tetteh FM, Sogbedji J, Janssen BH, Giller KE (2016) Fertilizer requirements for balanced nutrition of cassava across eight locations in West Africa. Field Crops Research 185: 69-78. doi: http://dx.doi.org/10.1016/j.fcr.2015.10.005.
3. Amouzou KA, **Ezui KS** and Sogbedji JM (2013) Impacts of Climate Variability and Soil Fertility Management Strategies on Maize Grain Yield on Ferrralsols in Coastal Western Africa. Journal of Renewable Agriculture 1(3): 44-52. doi: 10.12966/jra.06.04.2013.

CONFERENCE PROCEEDINGS, BOOK CHAPTERS AND INVITED PAPERS

1. **Ezui KS,** Mando A, Franke AC, Sogbedji J, Ahiabor BDK, Tetteh FM, Janssen BH, Giller KE (2012) Improving fertilizer use efficiency in cassava production systems of West Africa. 8th International Symposium Agro Environ 2012, Wageningen, the Netherlands.
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BOOKS EDITED

1. Fofana B, Zida Z, **Ezui G** (2012) Promoting sustainable crop-livestock integration through farmer's participation and integrated soil fertility management in the Sahel of West Africa. In: Whalen, J. (Ed.) Soil fertility improvement and integrated nutrient management - a global perspective. InTech, Open Access book publisher, Rijeka, Croatia and Shanghai, China, pp. 273-292. doi: 10.5772/29172. http://www.intechopen.com/books/soil-fertility-improvement-and-integrated-nutrient-management-a-global-perspective/promoting-sustainable-crop-livestock-integration-through-farmer-s-participation-and-integrated-soil-

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)
- Resource use and soil fertility management for sustained cassava production in west Africa (2012)

Writing of project proposal (4.5 ECTS)
- Resource use and soil fertility management for sustained cassava production in west Africa

Post-graduate courses (13.7 ECTS)
- Sampling in space and time for survey and monitoring of natural resources; PE&RC (2012)
- Sense PhD course; Eijkelkamp (2012)
- Farming systems and rural livelihood: vulnerability and adaptation; PE&RC, WASS, WIAS (2013)
- Modelling climate effects on crops and cropping systems; Aarhus University (2013)
- Statistics, generalized linear models, multivariate analysis, introduction to R; PE&RC (2013)
- Companion modelling; PE&RC (2014)

Deficiency, refresh, brush-up courses (7.5 ECTS)
- Systems analysis, simulation and systems management; PPS (2011)
- Basic statistics; PE&RC (2013)

Competence strengthening / skills courses (7.4 ECTS)
- Techniques for writing and presenting a scientific paper; WGS, WU (2011)
- Career orientation; WGS, WU (2014)
- Entrepreneurship in and outside science; Startlife (2015)
- Scientific writing; WUR (2014)
- Writing grant proposals; WUR (2015)

PE&RC Annual meetings, seminars and the PE&RC weekend (2.4 ECTS)
- First years PE&RC weekend (2011)
- Middle and last years PE&RC weekends (2014)
- PhD Carousel (2015)

Discussion groups / local seminars / other scientific meetings (6.7 ECTS)
- Modelling and statistics network (2012-2013)
- R-users discussion group (2014-2015)
- African Cassava Agronomy Initiative workshops (2016)

International symposia, workshops and conferences (6.9 ECTS)
- 8th International symposium Agro Environ (2012)
- International training program on decision support tools for agricultural production, fertilizer recommendations and climate variability (2012)
- ECOWAS-USAID regional workshop on fertilizer recommendations (2016)

Lecturing / supervision of practicals / tutorials (6 ECTS)
- The applications of crop models in agriculture; University of Lomé, Togo (2012, 2016)

Supervision of MSc students
- Effects of fertilizer on the use efficiency of light, water and nutrients for cassava production on a ferruginous soil at Sevekpota in Togo
- Effects of potassium on the use efficiency of light, water and nutrients for cassava production on "terres de barre" in southern Togo
- Farm typology and identification of niches for the intensification of cassava based cropping systems in the maritime region of Togo.

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Kodjovi Senam Ezui, alias Guillaume, was born on 10th January 1977 in Lomé, Togo. He pursued his primary and secondary educations in Lomé before joining the "Ecole Supérieure d'Agronomie" of the University of Lomé in September 1995. He graduated from this school with BSc. Agronomy, option Crop production, in November 2001. He joined the International Fertilizer Development Centre (IFDC) in January 2002, and was involved in many research and development projects implemented across West Africa and beyond. In March 2007, he enrolled on a part time basis in a MSc. programme on agricultural resources and environmental engineering, and graduated in February 2009. He continued working for IFDC until he started his PhD programme at Wageningen University in October 2011, in collaboration with IFDC.

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