EVALUATING WATER-USE EFFICIENCY IN SORGHUM-PIGEONPEA (SORGHUM BICOLOR L. MOENCH-CAJANUS CAJAN [L] MILLSP.) DIVERSIFIED CROPPING SYSTEMS IN MARGINAL AREAS OF GHANA AND MALI

By

Princess Hayford

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ABSTRACT

EVALUATING WATER-USE EFFICIENCY IN SORGHUM-PIGEONPEA (SORGHUM BICOLOR L. MOENCH-CAJANUS CAJAN [L] MILLSP.) DIVERSIFIED CROPPING SYSTEMS IN MARGINAL AREAS OF GHANA AND MALI

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Water use efficiency (WUE) is an important determinant of crop productivity in water-limited environments where crop yield is highly dependent on rainfall. Phosphorus and nitrogen are two major nutrients limiting crop production across farming communities in West Africa; however, fertilizers are often not affordable. Sorghum-pigeonpea cropping system could be an affordable, sustainable option for smallholder farmers to improve soil fertility and increase yields. WUE of field crops (cereals, legumes) can be quite variable which complicates the extrapolation of field results to other sites. Crop simulation models (CSM) are useful tools to evaluate the agronomic and environmental performance of farming systems, aiding to extrapolate field experimentation data across environments.

The objectives of this study were to determine the soil moisture distribution in the root zone of sorghum and pigeonpea, assess the effect of sole vs intercrop systems on crop yield and WUE, and simulate WUE in a sorghum-pigeonpea cropping system using APSIM. Field experiments were established for the 2015 and 2016 seasons under rain-fed conditions at four sites: two locations at the experimental field station of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Samanko (Sko), Bamako; one at the field station of the Institut d'Economie Rurale (IER) in Farako (Fko), Mali; and one location at the field station of the Savanna Agricultural Research Institute (SARI) in Wa, Ghana. Sorghum was planted as a sole and an intercrop with a medium duration (MD) and a long duration (LD) pigeonpea, with a

4 replicate, randomized complete block design. Access tubes were installed in all treatments within the rows of plants, to a depth of 100 cm. Soil moisture content was monitored over the growing season in all cropping systems using Time domain reflectometry (TDR). Growth, plant biomass and yield parameters were collected and analyzed.

Seasonal variation in rainfall, soil fertility, site and planting time affected phenology, grain yield and biomass production of sorghum and pigeonpea. Lack of adapted pigeonpea varieties limited grain yield, but biomass production in Mali at the adequate phosphorus fertility site SkoHP (7784 kg ha^{-1}) was almost twice that observed at the low P site SkoLP (3400 kg ha^{-1}). The LD variety was larger than the MD variety, and produced more grain yield. Intercropping sorghum with pigeonpea resulted in high grain yield, biomass and overall productivity in terms of land equivalent ratio. Also, plants under the ratoon system were highly productive.

Soil water storage was more under sole sorghum than intercropped sorghum/pigeonpea (LD) plots due to deeper soil water extraction by pigeonpea. Cropping system significantly influenced water use (WU), with higher WU in the intercrop systems than in sole crop stands. Pigeonpea LD variety had higher WUE relative to the pigeonpea MD variety.

The performance of the model in predicting crop phenology, WU and WUE under both sole and intercrop systems of sorghum were very well, with under-prediction of pigeonpea biomass and WUE. As pigeonpea is a novel crop to be grown in Ghana, adaptation of the crop to the environment needs work, and this poses a challenge to model parameterization as well. Overall these studies provided important contributions to understanding how to integrate pigeonpea into sorghum cropping systems in West Africa and the potential for multiple benefits associated with the integration of LD pigeonpea as a sorghum intercrop.

To my husband, Isaac Hayford

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

KEY TO ABBREVIATIONS

APSIM: Agricultural Production Systems sIMulator

CSM: Crop simulation models

ICRISAT: International Crops Research Institute for the Semi-Arid Tropics

IER: Institut d'Economie Rurale

P: Phosphorus

SARI: Savanna Agricultural Research Institute

SOC: Soil organic carbon

TDR: Time domain reflectometry

WA: West Africa

WUE: Water use efficiency

WU: Water use

CHAPTER 1

WATER USE EFFICIENCY OF INTERCROPS AND SOLE CROPS OF DIFFERENT LIFE FORMS

ABSTRACT

Water use efficiency (WUE) is an important determinant of crop productivity in water-limited environments. In these environments across West Africa, crop yield is highly dependent on rainfall and high variability in weather patterns is increasing the production risk associated with precipitation. Thus monitoring water distribution in the soil profile and the proportion available for plant use in the root zone becomes critical to understanding and improving crop production systems. The yield of crops is often influenced by the interaction of water and soil nutrient availability, as plants mostly take up soil nutrients conditioned by water supply. Improving the efficient use of water by plants under smallholder farming systems require affordable options such as crop choice and planting arrangement that aim at efficient and sustainable soil and water use. We evaluated cropping systems arrangements, and plant life form (duration of maturity), along with variable soil types and rainfall patterns as a way of determining the WUE of sorghum (*Sorghum bicolor*) and pigeonpea (*Cajanus cajan*).

The experiments were established under rain-fed conditions at three agroecological sites: two sites in Mali and one in Ghana, ranging from semi-arid to sub-humid. Two cultivars of pigeonpea, long and medium duration and sorghum were planted as sole, intercrop and ratoon crops. Access tubes were installed within the rows of plants to a depth of 100 cm in all treatments. Changes in soil moisture content over the growing season in all cropping systems were monitored using Time domain reflectometry (TDR). Biomass and grain yield were measured at the vegetative, flowering and physiological maturity stages of the crop growth.

The slow initial growth rate of pigeonpea affected its water use (WU) in the early stages. Total WU was regulated by total seasonal rainfall. P deficiency limited WU by crops at the SkoLP site. Cropping system significantly influenced WU, with higher WU in the intercrop systems than in sole crop stands. SkoHP and Wa accumulated higher biomass and grain yield. SkoLP had the lowest productivity in biomass and yield. The growth of the MD pigeonpea variety was suppressed by sorghum due to differences in height. Higher WUE in the intercrop systems than sole crop stands were associated with higher biomass. The LD pigeonpea variety produced more biomass and grain yield than the MD pigeonpea variety, and had 18% higher WUE than the MD variety in terms of numerical values. Overall, intercropping improved the productivity, WU and WUE of sorghum and pigeonpea.

INTRODUCTION

In the Sahelian-Sudano and Guinean regions of West Africa, the variable nature of rainfall may be seen as the major limiting factor to increased productivity. However, the seasonal distribution of water within the soil profile, the rate at which it is lost through vegetation and the proportion that remains in the root zone for plant utilization is more crucial in limiting agricultural productivity than the total amount of rainfall (Grema and Hess, 1994; Payne et al., 1990; Sivakumar and Wallace, 1991). The need to design cropping system and soil management strategies that optimizes efficient use of resources to achieve sustainable agricultural production cannot be over-emphasized (Sivakumar and Wallace, 1991). Wittwer (1975) pointed out that water is the second-most limiting factor, apart from farmland size, influencing food production in the semi-arid regions of Sub-Saharan Africa, and argued that high research priority should be given to improving the water use efficiency of plants. The understanding and measurement of water productivity is thus a critical step in working towards increasing food crop production and ensuring food security.

Water and soil nutrient supply are two major factors that influence the growth, development and grain yield of plants. There is an interaction between these two factors, and soil nutrients are most available to plants under optimum water supply (Ritchie, 1983). Improvement in the efficient use of water by plants is a high priority in agricultural research and food security issues (Katerji et al., 2008; Medrano et al., 2015; Wittwer, 1975). Water use efficiency (WUE), described as the ratio of biomass accumulation relative to water use, is an important measure that affects crop productivity in water-limited environments (Sinclair et al, 1984).

Of the few options available to farmers, crop choice and planting arrangement (row spacing and plant population) are affordable methods used to improve soil properties and water-use efficiency. The suite of crop choices currently used in West Africa involves a few long-season crops that produce vegetation in large amounts, as an additional benefit beyond production of food. Pigeonpea (*Cajanus cajan [L] Millsp.*) is a novel crop species in West Africa, and it has features that include multipurpose production of biomass above and belowground. This species has shown promise as a means to improve soil aggregation, organic matter, and nutrient status (Adu-Gyamfi et al., 2007; Snapp et al., 2003). Studies in the semi-arid and sub-humid tropics of East Africa report multiple ecosystem services and long-term sustainability from diversifying cropping systems with pigeonpea (Kimaro et al., 2009; Mafongoya et al., 2006; Snapp, et al., 2002). The shrubby growth habit of pigeonpea is potentially associated with the phenomenon of hydraulic lift (HL), a hypothesis which is supported by a field report from Zambia (Sekiya and Yano, 2004). If proven, this property of pigeonpea would further suit it as a water efficient crop plant, one that is highly suited as an intercrop species due to minimal competition for water.

Cropping systems involving pigeonpea in Ghana and Mali are very rare, even though pigeonpea can be seen in some home gardens. In Ghana, a few studies have evaluated crop rotations of maize with cowpea, pigeonpea and cassava (*Manihot esculenta*) (Adiku et al, 2009; Adjei-Nsiah et al, 2007; Agyare et al, 2002) and find that pigeonpea returns large quantities of crop residue to the soil, increases yield of subsequent maize crop and minimizes soil carbon loss. In a farmer-managed trial in Ghana, farmers selected the use of pigeonpea as a soil fertility improvement crop over mucuna (*Mucuna pruriens*) because pigeonpea provided immediate benefits as both a food and cash crop (Adjei-Nsiah et al., 2007). Thus, pigeonpea could play a positive role in food security.

A major research gap in understanding moisture and nutrient dynamics of cereal-legume intercrops is the role of growth habit (duration of growth type) of the two species as this influences resource use competition. For example, in sorghum and pigeonpea cropping systems in West Africa, there are varieties of both sorghum and pigeonpea that represent short and long duration growth types. That is, pigeonpea has extra-short, short, medium and long duration types that vary from 90 to 300 days. In addition, pigeonpea can be managed as a short-lived perennial with ratooning management to grow for two to three or more years. The medium duration pigeonpea has a faster growth rate and will likely have higher water uptake than long duration which usually uses residual moisture (Reddy, 1990a). The pattern of water absorption from the soil is different in annuals and perennials (Kramer, 1983). Perennials extract soil water more slowly than annual legumes and are inefficient at converting small to moderate amounts of rainfall into dry matter (Armstrong et al., 1999). Thus, determining yield potential of perennial species will require growing them over multiple years.

Another topic related specifically to pigeonpea is the limited understanding regarding the potential for enhanced water resources through hydraulic lift of water. This is a phenomenon documented mostly in the field with shrubs, trees and rangeland grasses. During the drier parts of the year, these plant species are associated with water movement up from subsoil and its release at night into the topsoil (Caldwell and Richards, 1989; Caldwell et al., 1998; Dawson, 1993; Richards and Caldwell, 1987). However, a number of studies have reported the occurrence of HL in herbaceous crop species either grown as sole crops or in association with shrubs (Corak et al., 1987; Kizito et al., 2006, 2007; Sekiya and Yano, 2004; Wan et al., 2000; Xu and Bland, 1993).

An agricultural field trial by Sekiya and Yano (2004) at the Zambia National Irrigation Station showed that the introduction of a deep-rooted crop into the system allowed maize to utilize otherwise unavailable water sources deep in the soil layers. The cropping systems were maize-pigeonpea and maize-sesbania (*Sesbania sesban*) intercrops. Hydraulic lift was only detected in pigeonpea, and to date, this is the only report that indicates HL in pigeonpea. Other studies conducted in Senegal with millet-shrub systems indicated the presence of hydraulic redistribution. This was demonstrated by the significantly greater moisture in the soil surrounding the shrub roots than in the soil distant from the roots. The shrubs extracted water from the lower portion of the profile, with no competition for water between the millet and either *G. senegalensis* or *P. reticulatum* (Kizito et al., 2006, 2007). Hydraulic lift may be beneficial to the plant conducting it and also as an important source of water for neighboring plants. The hydraulically lifted water is utilized by neighboring plants and has a positive influence on their water use patterns and growth (Dawson, 1993). For example, the association of a pigeonpea-maize system led to deeper water extraction by pigeonpea to the topsoil for maize, a shallow-rooted crop that had no direct access to deep water (Sekiya and Yano, 2004). Some other implications of hydraulic lift include nutrient acquisition, biogeochemical nutrient cycling processes, and root growth and persistence (Caldwell et al., 1998).

Water-use efficiency has a significant influence on overall performance of crops. Evaluation of crop WUE under different cropping systems and agro-ecological zones is fundamental to selecting crops and cropping systems combination suited for specific area. Although extensive research has been conducted on WUE in cereal-legume systems, plant growth habit and their role in efficient water use have not been investigated under a sorghum-pigeonpea system. The root growth dynamics of intercropped plants may differ from sole cropped plants due to different degrees of root interaction and competition. This can influence the way nutrients and water are utilized. Thus, the right choice of cropping system may greatly influence and thereby provide an important tool in management strategies that seek to improve water use and crop productivity. This research investigates whether or not a sorghum-pigeonpea intercrop system has both soil and water use advantages over a monoculture sorghum or pigeonpea crop. Since smallholder farmers will choose a cropping system that has both biological and financial advantages, and given increased interest in developing sustainable agricultural systems, there is clear justification for evaluating the water-use efficiency of different cropping systems. We hypothesized that: 1) Intercropping sorghum-pigeonpea increase WUE of each crop relative to their sole crops, and (2) The WUE of cropping systems will be influenced by the growth habit (medium vs long duration) of pigeonpea cultivar and the interaction with seasonal rainfall patterns. The overall aim of the study is to determine which pigeonpea cultivar is water use efficient as a sole or intercrop. The specific objectives are to: 1) Determine the soil moisture distribution in the root zone of sorghum and pigeonpea, 2) Assess the effect of cropping system on crop yield and water use efficiency, and 3) Evaluate which pigeonpea growth type is best suited for intercropping with sorghum to enhance water-use efficiency.

Water use efficiency in intercropping systems

Water uptake in intercropping system depends on the transpirational demand, spatial distribution and the rooting architecture of component species (Ozier-Lafontaine et al., 1998; Ozier-Lafontaine et al., 1997). In agroforestry systems, where trees have been intercropped with annual food crops and pasture, the association has been shown to improve plant water use. This is suggested by the higher efficiency in rainfall use due to reduced evaporative losses from bare soil, crop biomass and enhanced infiltration limiting surface runoff. An investigation into the soil water dynamics in a gliricidia (*Gliricidia sepium*), maize (*Zea mays*) and pigeonpea (*Cajanus cajan*) system was conducted in Southern Malawi, where severe pruning of the trees was employed as a way of eliminating soil moisture competition and enhancing crop growth. Water-use efficiency was higher in the tree-based systems than either sole maize or maize-pigeonpea systems. This increaed WUE was due to the dense canopy structure of gliricidia limiting soil evaporation (Chirwa et al., 2007). The effect of canopy structure in reducing soil evaporative losses was also reported by Droppelmann et al. (2000), when they studied the WUE and water uptake patterns in a run-off agroforestry system involving acacia (*Acacia saligna* (Labill.) H. Wendl.), sorghum (*Sorghum bicolor*) and cowpea (*Vigna unguiculata*) in Northern Kenya. Intercropping and high tree density increased WUE. The only difference between the treatments was the size of tree canopy structure, which the authors believed influenced WUE of the intercropped systems. Another study in a Mediterranean environment investigated the belowground interaction in a vine (*Vitis vinifera* L.)-tall fescue (*Festuca arundinacea* Shreb.) intercropping system and reported that the intercropping system showed higher soil water content indicating rainfall use efficiency by limiting surface runoff. However, intercropping resulted in a reduction in both vegetative and reprouctive growth in the vine, indicating competition between the component species (Celette et al., 2005). This efficient water use shown in agroforestry is a result of complementarity effect of component species having different rooting patterns. The authors support this statement by the results of the spatial analysis of root systems of the component species. The same spatial complementarity in root distribution is reported to enhance WUE in cereal-legume associations.

Factors influencing WUE

Enhanced WUE under cereal-legume association has been attributed to the reduction of soil erosion due to greater soil coverage, improved water storage, increased infiltration rate and the windbreak effects of plants in the association (Grema and Hess, 1994; Rusinamhodzi et al., 2012; Steiner, 1982; Zougmore et al., 2000). Intercropping pearl millet (*Pennisetum glaucum*) and pigeonpea (*Cajanus cajan*) enhanced WUE relative to both sole cropped pearl millet and pigeonpea. This field experiment was conducted at the Indian Agricultural Research Institute for two consecutive years, 2009 and 2010. In 2009, rainfall was low resulting in low biomass and reduced soil water extraction. However, the overall performance of the system showed higher productivity from pearl millet-pigeonpea intercrop than either sole cropped pearl millet or pigeonpea even under unreliable rainfall situations (Ansari et al., 2014). Contrary to this enhanced WUE, Chirwa et al. (2006) reported reduced WUE in either sole maize or maize-pigeonpea intercropped system relative to a gliricidia-maize-pigeonpea intercrop systems. Their result was based on the changes in soil water content only; no account was made for individual crop water use. This may have influenced the estimation of WUE as different crop species have different pattern of water uptake and use. Similarly, another field experiment conducted at the University of Maiduguri research farm in Nigeria showed that intercropping cowpea with pearl millet resulted in no increased rate of water use over sole cropped pearl millet (Grema and Hess, 1994). These conflicting results indicate total water use by crops varies substantially due to either limited rainfall or management.

Another factor influencing plant water uptake is soil nutrient levels. Fertilizer application has led to increased WUE (Asseng et al., 2001; Garabet et al., 1998; Turner, 1997; Zhang et al., 1998). The positive effect of soil nutrient levels and plant water uptake is known, however some of these studies have inconsistent results. Under unfertilized plot, interspecific competition for nutrient uptake between maize and pigeonpea resulted in yield reductions (Kimaro et al., 2009). On the other hand, Astatke et al. (1995) found no influence of fertilizer addition on soil moisture dynamics in a maize and wheat (*Triticum aestivum*) intercropped systems with lablab (Lablab purpureus), vetch (*Vicia dasycarpa*) and cowpea on a chromic vertisol (FAO and UNESCO, 1974). They applied two nitrogen levels (0 and 100 kg/ha) in the form of urea. This result may be due to the absence of phosphorus fertilizer as phosphorus increases root density and rooting depth, leading to increased water uptake and overall WUE (Payne et al., 1992), or soil type since considerable variability in WUE with soil type has been reported due to differences in water-holding capacity (Asseng et al., 2001; Yunusa et al., 1993). In a sorghum-pigeonpea system, increased WUE will be a combination of increased canopy cover, complimentary root systems and changes in soil nutrient.

Ecophysiology and mechanisms

The planned combination of plants within a cropping system and soil nutrient management strategies are important for improving food crop production. Extensive work has reported improved water use efficiency under intercropping systems (Black and Ong, 2000; Droppelmann et al, 2000; Morris and Garrity, 1993; Willey, 1990). This enhanced WUE may be due to factors such as rapid canopy expansion and greater ground cover, and differences in rooting characteristics (i.e. depth and expansion of root system) resulting in complementary soil resource use (Morris and Garrity, 1993; Ong et al., 2000; Rusinamhodzi, et al, 2012; Zougmore, et al, 2000). Similarly, the addition of adequate N and P fertilizers have been shown to support optimized water use in terms of crop production and to enhance the overall WUE of a cropping system (Asseng et al, 2001; Garabet et al, 1998; Turner, 1997; Ritchie, 1983). Increased WUE in sorghum-pigeonpea system will be achieved through a combination of the following mechanisms:

Canopy structure: In a sorghum-pigeonpea intercropping system, there will be complete canopy establishment to shade the soil and reduce evaporative loss from the soil surface. This canopy structure should significantly improve WUE, as surface run-off is reduced due to soil cover, enhancing infiltration.

Biomass production: The two crops have different maturity periods so that the major demands for resources such as light, water and nutrients will differ in time. Also, sorghum will accumulate dry matter and utilize resources during the initial slow growth period of pigeonpea, and since the reproductive growth of these two crops does not coincide, the yield of sorghum will not be affected. Thus their contrasting phenology will result in the intercrop making better use of resources over time than their respective sole crops.

Rooting system: There will be complementarity of water use as both crops will exploit different layers due to differences in rooting characteristics. Pigeonpea has a deep taproot with well-developed lateral roots that can extend more than 2-3 m deep. This helps the plant to extract water from deeper depths as soil water availability declines. Also as a semi-perennial, the plant will have different water uptake compared to sorghum, an annual. Apart from extracting water from deeper soil depths, pigeonpea can redistribute this water either downward or laterally to sorghum (Dawson, 1993; Kizito et al., 2012). Sorghum can use the extra water available for more biomass production. Sorghum has adventitious roots that may grow to depths of 1-2 m by the booting stage, and can efficiently extract water to a lateral distance of 1.6 m from the plant (Routley et al., 2003). In a sorghum-pigeonpea intercrop system, Natarajan and Willey (1980) reported sorghum had a greater root density with concentration in the upper 15 cm of soil while pigeonpea rooted more deeply. This suggests that sorghum usually extracts water from the top meter of the soil profile. In pigeonpea, the roots continue to accumulate dry matter and produce laterals throughout the growth of the plant until it is harvested (Chauhan, 1993). However, root growth in sorghum terminates at flowering stage (Robertson et al., 1993); this differs between genotypes as others continue to accumulate root biomass until the anthesis stage (Myers, 1980).

The rooting activities of sorghum and pigeonpea in the intercrop system can improve soil aggregate stability and increase soil organic matter, which would consequently reduce runoff and soil erosion. Ramzi et al. (2008) reported controlled soil and water loss under a barley-vetch intercrop system. Soil compaction can confine root proliferation within the surface layer of soil, and this can affect pigeonpea's ability to show any characteristic advantage of root development over sorghum (Ito et al., 1992).

Changes in nutrient dynamics: Pigeonpea will fix nitrogen in the soil allowing sorghum to use more soil N. Or there may be transfer of fixed N from pigeonpea to sorghum, enhancing the overall growth of the intercrop (Adjei-Nsiah et al., 2007).

Patterns of water use and hydraulic lift

Understanding the utilization of belowground resources by plants, such as water and nutrients is very important for plant growth and productivity. Plants take up water from different depths throughout the growing season, and may adjust their active zone of water uptake in response to changing environmental conditions and soil moisture availability (Asbjornsen et al., 2008). For example Sekiya and Araki, (2013), showed that pigeonpea (*Cajanus cajan*) and sesbania (*Sesbania sesban*) extracted water from deeper soil layers when the top soils became drier.

Patterns of plant water uptake in the soil profile are mainly determined by the differences in root depth or root length density. In pigeonpea, studies have examined how growth durations and roots have implications for soil water extraction (Subbarao et al., 2000; Matsunaga et al, 1994). However, this has not been studied extensively for all growth durations. Extra-short duration pigeonpea cultivars are inefficient in extracting water below 30 cm soil depth because of their shallow rooting system, and highly susceptible to drought stress (Nam et al., 1993; Subbarao et al., 2000). The long and medium duration cultivars have deep rooting systems which helps the plant with its soil moisture extraction pattern and adaptation to rain-fed production environments (Natarajan and Willey, 1980; Chauhan, 1993).

Some plant root systems have the potential of extracting water upward from moist deeper layers to drier upper portions of the soil profile. This phenomenon termed as HL has been observed in shrubs, in dry environments such as rangelands (Caldwell and Richards, 1989; Caldwell et al., 1998; Dawson, 1993). One report indicates that pigeonpea in a semi-arid environment may possess this hydraulic lift function, giving the crop the potential to enhance the sustainability of farming systems in dry areas of Sub-Saharan Africa (Sekiya and Yano, 2004). The hydraulically lifted water (HLW) utilized by neighboring plants is expected to have positive influence on their water use patterns and growth (Dawson, 1993). However, it is not clear if the HLW is beneficial to the plant conducting it, that is, does it make pigeonpea water use efficient? Also, the phenomenon of HL in pigeonpea may be dependent on the environment, root length density, plant form (medium or long duration) or cropping system. The understanding of the soil moisture dynamics in a sorghum-pigeonpea intercropping system, and the extent of HL if any in a sub-humid to semi-arid environment or for different soil types is unknown. It is very important to enhance knowledge of plant life form and interactions of plant species in terms of optimizing crop water use within cropping systems, particularly in dry areas with highly variable rainfall and urgent requirements for increased efficiency and sustainability.

Water use in medium and long duration pigeonpea

Morphological characteristics: Varietal differences have great influence on the development and growth of pigeonpea. But in general, the plant develops as semi-deciduous and shrub-like with growth of 1-4 m in height, and 1-4 m in basal stem (Francis, 2002). Stems become woody as they thicken and mature (Bisen and Sheldrake, 1981). Pigeonpea has tremendous variation for maturity period (120-256 days), and that forms the basis by which cultivars are categorized. They range from extra-short to long duration (Sharma et al, 1981).

The plant consists of a deep, strong, woody taproot with well-developed lateral roots in the superficial layers of the soil. The roots can extend more than 2 m deep, but most extensive development takes place in the upper 60 cm of the soil (Natarajan and Willey, 1980). Rooting depths are influenced by date of sowing and the availability of moisture in the soil. Also, the root system appears to be closely related to plant habit. Tall, compact varieties produce longer and more deeply penetrating roots, whereas spreading types produce shallower, more spreading, and denser root systems (Pathak, 1970). Short duration cultivars develop a smaller root system than long duration (Sheldrake and Narayanan, 1979). The roots continue to accumulate dry matter and produce laterals throughout the growth of the plant until harvested or killed (Chauhan, 1993). The continuous production of new roots enables the plant to exploit residual soil moisture during the off season periods.

Species water uptake and use: The pattern of water absorption from soil is different in annuals and perennials (Kramer, 1983) and plant form have influence on soil water use. Tall, upright varieties produce longer and more deeply penetrating roots, whereas spreading types produce more spreading and dense root systems (Pathak, 1970). The roots of perennial pigeonpea grew up to 4 m in southern China (Saxena, 2002).

Medium duration (5-6 months, 151-180 days) pigeonpea grows faster and will have higher water uptake than long duration pigeonpea. Perennials extract soil water more slowly than annual legumes and are inefficient at converting small to moderate amount of rainfall (20-50 mm) into dry matter (Armstrong et al., 1999).

Long duration tends to be tall because of prolonged vegetative phase. Long duration (6-9 months, >180 days) (Reddy, 1990b) species often uses residual moisture. Grema and Hess (1994) reported that in a millet-cowpea system, long duration cowpea made greater used of stored water in the root zone after millet harvest. Long duration may however suffer from terminal drought. For intercropping and mixed cropping under rain-fed conditions, long duration cultivars are preferable since they produce longer roots and therefore may not compete with companion crop species for underground water and nutrients during the early growth period (Tiwari and Singh, 1980). Medium duration cultivars tends to be more sensitive to competition from the companion crop, therefore, are not normally suitable for intercropping with tall cereals (Mergeai et al., 2001).

MATERIALS AND METHODS

Site description

Location: Field experiments were established under rain-fed conditions at three sites: two locations at the experimental field station of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Samanko (Sko), Mali; and one location at the field station of the Savanna Agricultural Research Institute (SARI) in Wa, Ghana (Figure 1.1). Sko is situated about 25 km SW of Bamako, Mali (8°54′W, 12°54′N, 328 m). Wa is in the northwestern corner of northern Ghana 194.92 km (10° 03' N, 2° 30' W, 319 m).

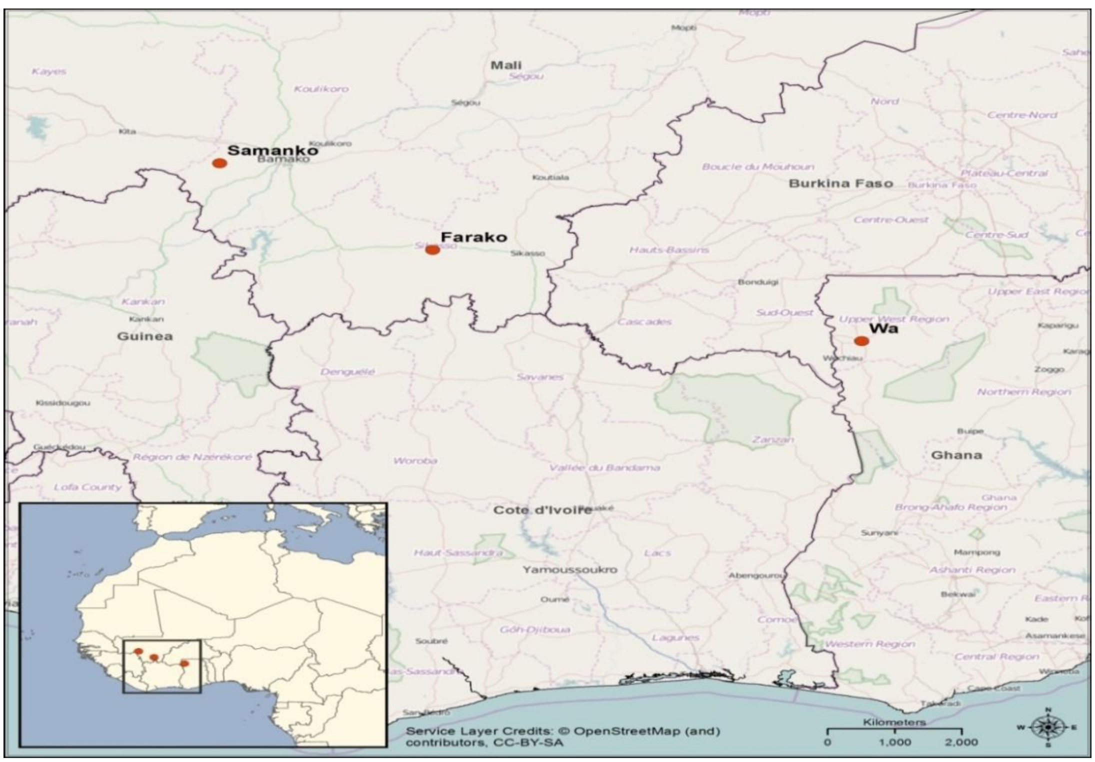

Figure 1.1 Field map of the study location. (Designed by Brad Peter (GCFSI, MSU).

Climate: The climate at Sko is typical of a Sudanean climate characterized by a unimodal rainy season (June-October), followed by a long, dry and cold (December-February) and hot (from March). The mean annual rainfall is about 1029 mm year^{-1} (15-yr, ICRISAT-Mali). Mean monthly maximum and minimum temperatures during the growing season are 38°C and 24.7°C for 2015, and 37.9°C and 26.0°C for 2016, respectively (Table 1.1). Wa climate is typical of Sub-humid tropics with a relatively longer rainfall season (May-November), with average rainfall of 1055 mm year^{-1} (15-yr, MoFA-Wa). The mean monthly maximum and minimum temperatures during the growing season are 26.6°C and 21.2°C for 2015, and 26.3°C and 21.1°C for 2016, respectively (Table 1.1).

Soils: The two sites at Sko varied in soil fertility, one being low phosphorus (LP) and the other high phosphorus (HP) (Table 1.2). Soils at Sko are light, generally sandy loam and of a tropical ferruginous washed-type (Sivakumar et al., 1984). SkoLP site is a well-drained sandy loam soil, which is low in fertility and available phosphorus. This site soil phosphorus status is a representative of many smallholder farmers' fields in West Africa (Bationo et al., 1998). On the other hand, the SkoHP site was a sandy loam with medium fertility and high levels of phosphorus. The soils in SkoHP were often saturated after rain events, with waterlogging in some parts of the field (personal observations). These soil types are two important soil types in Mali (Rattunde et al., 2013). The Wa experimental site was characterized as a well-drained sandy loam soil with high fertility (Table 1.2). The soil had moderate levels of available phosphorus, with gravel being present deep in the soil profile (personal observations). The predominant soil types in the Wa region are described as Ferric Lixisols and Luvisols (FAO, 2001).

Experimental design

All three experiments were laid out in the same manner, following a randomized complete block design with 4 replications. The treatments consisted of sole, intercropped, and ratooned cropping systems with sorghum and pigeonpea for a total of nine treatments represented at all three sites. The treatments are shown in Table 1.3. They comprised of five cropping system treatments with different growth types of pigeonpea: three sole crop systems, sorghum (SG), medium duration pigeonpea (MD) and long duration pigeonpea (LD); and two intercrop systems, sorghum-pigeonpea (MD) and sorghum-pigeonpea (LD).

Planting materials

The crops planted were sorghum and pigeonpea. Two varieties of pigeonpea were planted; ICEAP 00557 (MD, 153 days) and ICEAP 00982 (LD, 207 days). The sorghum variety planted was Fadda, a high yielding commercial hybrid variety grown by farmers in the region (Rattunde et al., 2013). The pigeonpea ICEAP 00557 seeds were sourced from ICRISAT-Nairobi (The variety was released in Malawi, Tanzania and Mozambique) and ICEAP 00982 and sorghum from ICRISAT-Bamako. MD variety is short-statured, compact and bushy. It has dark green leaves, reddish flowers and sensitive to insect attack. LD is a tall variety with light-green leaves and yellowish flowers. It has some tolerance to pest attack compared to MD. Fadda is a tall variety (2-3 m), with thin stem and matures in 128 days. It is a commercial hybrid seed.

Plant population density

The plant population density used for sole sorghum and pigeonpea was 88,000 and 44 000 per ha, respectively (Table 1.4).

The planting pattern for sorghum and pigeonpea in the intercrops was a 2:1 in-row substitutive design. The plant population for sorghum was considered based on the recommendations from ICRISAT-Mali (Rattunde et al., 2013; Rattunde et al., 2016) whereas the pigeonpea density was adapted from southern Malawi (Snapp et al., 2002). The goal was a modified substitutive design, with reduced plant population of pigeonpea to achieve a combined intercropped plant population density almost similar to a sole cropped sorghum. The plant population density of sorghum and pigeonpea in the intercrops were 44 000 and 22 000 plants/ha, respectively (Table 1.4).

Planting

Land preparation was done manually for the SkoLP site (hand-hoe ridges) and Wa site (hand-hoe flat). SkoHP was ploughed to approximately 25 cm depth with a tractor (moldboard plow and cultivated). The Sko trials were planted 8 and 9th of July in 2015, and 9 and 10th of July in 2016. Wa was planted later, 17 and 24th of July in 2015 and 2016 respectively. Sole sorghum and pigeonpea were planted at a spacing of 30 cm x 75 cm and 60 cm x 75 cm, respectively with two plants per hill. Pigeonpea in intercropped plots were thinned to one plant per hill at all locations (Table 1.4). SkoLP and SkoHP had treatment plot sizes of 6 m x 7.5 m with 8 rows. Wa had 4.5 m x 6 m with 6 rows. Plot size was reduced in Wa due to land availability.

Crop management

Weeds were controlled by using a hand hoe at three different times after planting. Insect pest damage on pigeonpea plants were controlled at 2-week intervals from the start of flowering to maturity by using K-optimal, a systemic insecticide (Lambda-cyhalothrine 15g/l +Acetamipride 20g/l; EC) in spraying the plants. The usually amount sprayed was 50 ml/knapsack. Insect pest damage was still evident even with this consistent spraying. Pigeonpea has little genetic resistance to a wide range of pod-boring and flower-feeding insects, which poses a significant challenge to designing effective pest management strategies and is a persistent barrier to broader adoption of this crop (Kaoneka et al., 2016).

SkoLP field was supplied with compost at 3 tons/ha, on dry weight basis. This was the only nutrient application at SkoLP, as this site was chosen for soils that are representative of on-farm environments in Mali, which are highly nutrient depleted. A basal dose of diammonium phosphate (DAP) at 100 kg fertilizer/ha to supply 18% of N and 46% of phosphate-P was applied to the plots at Wa and SkoHP. As well, a side-dress of urea was applied at 50 kg/ha (23% N) after the second weeding. Fertilizer was applied to all plots on the field.

Rainfall and temperature

The source for rainfall and temperature in Sko and Wa was General Research-Grade Weather Station (GRWS100, Campbell Scientific, Inc.), installed by ICRISAT-Mali in 2014.

Field observations and measurements

Biomass assessment: Destructive samplings were done at three growth stages (vegetative, flowering and physiological maturity) (Table 1.5 and 1.6). Five whole plants from each sole cropped plot and 6 plants from intercropped plots were cut at the base and separated into leaves, stems and panicle/pod. Sole sorghum plants sampled net plot was 1.125 m^2, 2.25 m^2 for sole pigeonpea and 1.35 m^2 for intercropped plots. Fresh weight of the leaves, stems and panicle/pod were taken. Subsample was taken from the various components and weighed separately. Subsampled plant parts were placed in an envelope, oven-dried for 3 days at 70°C and dry matter weight determined. For grain yield at physiological maturity, subsampled panicles/pods were put in muslin cloth bag and dried at air temperature for 2 to 3 weeks before threshing, then grain weight determined.

Soil sampling and analyses

Soil profile samples were taken to assess profile conditions, and variability across the field, at all three experimental fields (SkoLP, SkoHP, and Wa). To monitor the soil profile, soil pits were dug to a depth of 120 cm in June. Samples were taken at depths of 0-15 cm, 15-30 cm, 30-60 cm, 60-90 cm, and 90-120 cm. At each depth, soil samples were taken from the side of the pit where there was no disturbance, e.g., along the side with little or no influence from land cultivation. Additional samples were taken from three random points in each replicate block using a soil auger of 3 cm in diameter at the following depths: 0-15 cm, 15-30 cm and 30-60 cm, and composited by depth and block. These samples provided information on soil variability across the site. All soil samples were sieved (2 mm) at the ICRISAT Agronomy Lab in Bamako, Mali, then samples were air-dried and subsamples of 100 g sent to the Snapp lab (Michigan State University) for grinding, and physical and chemical analysis as follows.

*Soil texture***:** The hydrometer method was used to determined soil texture at the Snapp lab, dispersed and based on the principle of sedimentation (Stokes' Law) using a ASTM 152H-Type hydrometer) (Gee and Bauder, 1986).

Soil pH: The pH was determined using the 1:5 soil water suspension method (Department of Sustainable Natural Resources, 2013), with a Metler Toledo SevenEasy S20 pH meter.

Total soil nitrogen and carbon percent: Dry soil subsamples were ground to pass a 1 –mm sieve in a shatter mill. The ground soils were weighed on a microbalance into tin capsules for total C/N content analysis, which was determined by combustion. A Costech ECS 4010 combustion analyzer (Department of Forestry, MSU) was used.

The remaining of the soil samples were sent to the A and L Great Lakes Laboratories, Fort Wayne, IN for analysis of the following: available P, SOM and CEC using the Mehlich III procedure. Available phosphorus and exchangeable cations were extracted according to Mehlich III (Mehlich, 1984), and analyzed by inductively-coupled plasma spectrometry (ICP) in which the sample was excited in an argon plasma and the elements of interest were detected by a mass spectrometer. The P data were then correlated to and reported as Bray P-1 (Bray and Kurtz, 1945). The data for exchangeable cations were correlated to and reported as a 1N ammonium acetate extraction (McIntosh, 1969). CEC were calculated from the results for exchangeable cations. Organic matter was determined by loss on ignition at 360°C and the data correlated with and reported as Walkley–Black titration.

Access tubes installation

Fifteen access tubes were installed in each of the three sites, SkoLP, SkoHP and Wa respectively. Five treatments set, sole pigeonpea (MD); sole pigeonpea (LD); sole sorghum,

sorghum-pigeonpea intercrop (MD and LD) were selected and access tubes were installed in each treatment plot for each replication, thus 15 for 3 replications. A set of augering equipment that comprised of the pilot auger, stabilization plate with stakes, centring bush, hammer, and spatula was used for the installation. The access tubes component was comprised of the access tubes, black cap, and collar. After augering the hole, the access tube was pushed into the soil until the top of the access tube was level with the top of the centring bush. Hammering was done gently as the resistance increased. To finish off the installation, the collar and the black cap were fitted. A hole was made under a small plastic bucket with a lid and placed on the installed access tube to prevent water from entering the tube should the black cap be blown off by wind. A slightly unconventional method was used for the installation in Wa, due to the recalcitrance of the soil type. A version of the pilot auger slightly bigger in diameter than the access tube was fabricated and used. This was done after several efforts trying to use the designed pilot auger and stabilization plates. The soils at the location had more gravel that caused a lot of resistance. As the hole was made deep enough, the access tube was pushed down until the marked part of access tube was level with the top of the soil surface. To close any air gaps, soil sample from the hole was sieved and push down the hole with addition of water. This slurry was formed to ensure the access tube had direct contact with the soil.

Soil moisture monitoring

Soil moisture content was measured on a subset of the field experiment treatments. These included 5 treatments (PPM, PPL, SG, SG/PPM and SG/PPL (Table 1.3) at different stages of plant growth and development during the cropping season (Table 1.5 and 1.6). The 5 treatments were chosen as they helped tested the following hypothesis: (1) Intercropping sorghum-pigeonpea increases WUE relative to sole cropped sorghum, (2) The WUE of cropping systems will be influenced by the growth habit (medium vs long duration) of pigeonpea cultivar and the interaction with seasonal rainfall patterns. The first measurement was taken at planting. Soil water content were measured at incremental depths of 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-60 cm, and 60-100 cm using the Time domain reflectometry (TDR) profile probe type PR2 (Delta-T Devices Ltd, Cambridge, UK). One access tube was installed in each treatment plot to measure the volumetric water content changes during crop growth. The time-domain reflectometry (TDR) technique is one used to monitor the soil moisture content continually without affecting soil properties, and the TDR technique was used based on the detailed description given by Dalton (1992) and Zegelin et al. (1992). The profile probe determined soil water content in volumetric %. It was then converted to soil water content in mm^{-1} mm^{-1} by dividing each meter reading by 100 (i.e. thickness of soil depth).

Estimating water use and WUE

Calculation of water use (WU): This was measured by the difference between the amount of water in the soil at the beginning and end of growing season under each cropping system, and then added to interval rainfall amount. This was a modified version of the equation from Chirwa et al. (2007). The amount of stored soil water in the soil is indicated by the soil moisture readings.

$\mathrm{WU\ (mm)} = (\mathrm{IR}) + (SW_{start}) - (SW_{end})$……………………………………………………Equation 1

WUE: Water use efficiency was estimated with total aboveground biomass instead of grain yield. The estimation of WUE was given as the ratio of total aboveground biomass to WU of each cropping system (Katerji et al., 2008).

$$\text{WUE (kg ha}^{-1}\text{mm}^{-1}) = \frac{\text{Total biomass}}{\text{WU}} \qquad \text{Equation 2}$$

where WU = crop water use; IR= interval rainfall between crop growth stages; SWstart = soil water content of the root zone at the start of the growing season; and SWend= soil water content of the root zone at the end of the growing season.

Statistical analysis

Soil moisture and plant data values were analyzed using PROC MIXED. Cropping systems were modeled as fixed effects, and year, site, depth and replicates as random effects (SAS Institute Inc. Base SAS® 9.4, 2013). Soil moisture values were analyzed using analysis of variance to assess the effect of cropping system on soil water storage, extraction and crop water use. Total biomass yield was divided by crop water use to determine WUE of each cropping system (Katerji et al., 2008). Cropping system effect on WUE was tested using one-way ANOVA. Sorghum-pigeonpea intercropped system was compared to sole cropped sorghum to assess WUE of the two cropping systems, using a planned contrast. This tested directly hypothesis 1. For hypothesis 2, long and medium duration pigeonpea as sole or intercrop were compared through a planned comparison to test how the growth habits interact with the cropping system to influence WUE, then planned contrast were used to identify differences between the growth habits. Three-way ANOVA was used to test effect of year, site and cropping systems on WUE. T-test was used for all pairwise comparisons and significance differences among treatment means were separated using LSD at 5% level of significance. Soil moisture, total biomass and WUE results were presented in tables and graphs. Graphs were created using SigmaPlot version 12.5.

RESULTS

Rainfall and temperature

The rainfall distribution during the 2015 and 2016 growing period is presented in Figure 1.2 and 1.3. The total rainfall recorded during 2015 year for Samanko was 1080 mm, which was higher than the long-term (2000-2014) rainfall average of 1029 mm/yr at the Samanko experimental site (ICRISAT-Mali, climatic database 2014). Most of the rainfall events occurred during July-August at Samanko which accounted for 55% of the total rainfall recorded in 2015 year. Wa had very low rainfall in 2015 (727 mm), and it was not well distributed over the growing season as major rain events were recorded in September 2015. Sufficient rainfall was thus present during the flowering stage, however the year overall was very dry compared to the long-term average of 1055 mm/yr (Wa MoFA climatic database 2014).

In 2016, rainfall was unevenly distributed, but similar to long-term averages with 1184 mm recorded through the year at Samanko, and 851 mm at Wa. The highest rainfall at Samanko occurred in August, which accounted for 35% of the total rainfall recorded during the year. The major rainfall event at Wa was however recorded in May before sowing (Figure 1.3).

Mean maximum and minimum temperatures were monitored at automatic weather stations at Samanko and Wa during the 2015 and 2016 year are shown in Table 1.1. The average temperature ranged from 38.0 °C to 24.7 °C at Samanko and 33.8 °C to 23.1 °C at Wa during the 2015 year. Mean temperatures in 2016 were slightly lower in comparison with 2015 (Table 1.1).

Soil physical and chemical properties

Table 1.2 presents the physical and chemical properties of soils of the experimental sites. The soils were coarse across sites, particularly in the topsoil (72 to 84% sandy) and the Samanko site was acidic (pH from 5-6), whereas the Wa site was neutral (pH = 7). The soil organic carbon (SOC) status was low at all sites, from 0.23 to 0.44 g C/kg soil in the topsoil, and similar SOC levels were observed in the subsoil. Cation exchange capacity was high at the 60 cm depth across all sites.

Total inorganic phosphorus content was high at SkoHP (30 ppm in the topsoil), as expected. This site was managed through fertilizer amendment to provide sufficient soil P for cereal production, and the SkoLP site was about half this level. Wa had a very low phosphorus content at 7 ppm, which decreased with depth to 1 ppm (Table 1.2).

Soil water storage

Soil water storage over the 10-100 cm soil layer at SkoLP and SkoHP are presented in Figure 1.4a and b. The presence of pigeonpea in the intercropped was observed to affect moisture storage. The soil had the highest amount of water storage in late October through to mid- November (82 -132 DAS). There after soil moisture storage declined steadily.

Generally, soil water storage was significantly influenced by cropping system and site. Water storage under sole sorghum (147 mm) was more than under the intercropped sorghum/pigeonpea (LD) (117 mm) plots. Over the two years, soil water storage at the three sites differed. SkoLP (155 mm) had more water storage compared to Wa (112 mm) and SkoHP (109 mm). Total soil water storage was numerically higher in 2016 (130 mm) in comparison to 2015

(121 mm), but not significantly more, and no interactions with year were observed (Figure 1.4a and b).

Soil water extraction

Soil water extraction from the top 10-30 cm and bottom 40-100 cm soil profile layers varied considerably between cropping system, site, and depth. The general pattern observed was higher water extraction from the top (10-30 cm) than from the bottom (40-100 cm) soil layers (Figure 1.5 and 1.6), where 1.27 cm^3 cm^{-3} was extracted from the top and 0.89 cm^3 cm^{-3} from the bottom soil layers. Also, soil water extraction at the two sites at Sko was different with more water extracted at SkoLP (1.28 cm^3 cm^{-3}) than at SkoHP (0.88 cm^3 cm^{-3}). This site effect did not follow expected patterns, as plant growth was higher at SkoHP than SkoLP, and it may have been related to soil drainage differences.

Soil water extraction was significantly greater in the sole sorghum than in intercropped sorghum for cropping system main effect. The least water extracted was in the intercropped sorghum/pigeonpea (LD) (0.84 cm^3 cm^{-3}). There were no observed differences between the LD variety of pigeonpea and MD variety.

Crop Water Use (CWU)

Across the three growth stages, 2016 (203 mm) had high CWU relative to 2015 (190 mm). The site with the highest CWU was SkoHP (235 mm), followed by SkoLP (215 mm), and the Wa site had the lowest CWU at 143 mm, from the vegetative through to the physiological maturity stage. Water use in 2016 (286 mm) was much higher in comparison with 2015 (142 mm) at the vegetative growth stage. Also, a significant site by year interaction observed, as CWU in 2016 at SkoHP (327 mm) and SkoLP (325 mm) were higher than Wa (207 mm), whereas in 2015 CWU at Wa (150 mm) and SkoHP (149 mm) were higher than SkoLP (126 mm).

In 2015, CWU was satisfactory during the vegetative through to the physiological maturity stages (Table 1.6). An observed site and year interaction at the vegetative stage was due to the high CWU in 2016 at SkoHP (327 mm) and SkoLP (319 mm) relative to CWU at Wa in 2016 (204 mm). In 2015, CWU at Wa (176 mm) was greater than SkoHP (147 mm) and SkoLP (129 mm). The flowering stage site by year interaction on the other hand, basically resulted from the high CWU in 2015 at SkoLP (465 mm) and SkoHP (455 mm) which was different from CWU at Wa in 2015 (180 mm) and 2016 (132 mm).

Across sites, water use started to increase approximately from 45 DAS (vegetative stage) through to flowering and decreased at the physiological maturity stage. At this stage, year effect of CWU was observed where 2016 (79 mm) year being significantly different from 2015 (55 mm) year. Pigeonpea water use was influenced by site and year at both the vegetative and flowering growth stages. There were also significant site and year interactions (Table 1.7). There was also no significant difference between the LD pigeonpea variety and MD pigeonpea variety (Table 1.7). Similar to pigeonpea, sorghum WU was significantly influenced by only site and year (Table 1.8).

Pigeonpea grain yields

Overall, pigeonpea grain yield produced was low in this study, as we observed yields of almost nil to 113 kg ha^{-1}, which is about 5% of the yield potential reported for these varieties (which is about 2000 kg ha^{-1}). Grain yield produced in 2016 (113 kg ha^{-1}) was higher in comparison with 2015 (43 kg ha^{-1}). Cropping system also influenced pigeonpea grain yield, where sole pigeonpea produced an average of overall 89 kg ha^{-1} compared to 67 kg ha^{-1} in an intercrop system with sorghum. A trend was observed for the LD variety grain yield to be higher than MD (Table 1.9), and an average of 119 kg ha^{-1} (average of 46 kg ha^{-1} and 192 kg ha^{-1}, across sites and years) for the LD variety, compared to an average of 60 kg ha^{-1} for the MD variety (average of 37 kg ha^{-1} and 83 kg ha^{-1}, across sites and years).

Grain yield pooled over the two years (2015 and 2016) were numerically high at SkoHP (110 kg ha^{-1}) followed by Wa (65 kg ha^{-1}) and SkoLP (59 kg ha^{-1}), however there were no observed site differences in yield. A significant interaction was observed between site and year as a result of grain yield production in two sites being about 100-200 kg ha^{-1}, compared to much lower levels in 2016 at these sites. In contrast, the other site SkoLP (59 kg ha^{-1}) had generally low yields, and particularly so in 2015.

Sorghum grain yield

In contrast to pigeonpea, sorghum grain yield was not affected by cropping systems (Table 1.10). The only factors that influenced sorghum grain yield were year and site. Yields were higher in 2016 (1549 kg ha^{-1}) than in 2015 (1100 kg ha^{-1}). Over the two years, grain yields at the SkoHP site were high (1804 kg ha^{-1}), followed by Wa (1317 kg ha^{-1}) and lowest at SkoLP (853 kg ha^{-1}). The significant site by year interaction resulted from first the significantly low yields production from SkoLP (263 kg ha^{-1} and 1443 kg ha^{-1}) in 2015 and 2016, respectively then secondly the highest yield from SkoHP (2035 kg ha^{-1}) in 2015.

Aboveground biomass production

Pigeonpea biomass

Response of biomass was similar to grain yield, just much more pronounced. Overall, there was a cropping system effect, with total aboveground biomass being higher in sole crop (3054 kg ha^{-1}) than in intercrop system (2309 kg ha^{-1}) (Table 1.9). Further, total biomass was higher in a LD variety of pigeonpea compared to a MD variety (*P value* = <.0001). The suppressive effect of an intercrop relative to sole crop was pronounced for the MD variety.

A site effect was also observed, due to total biomass being higher at Wa and SkoHP sites relative to SkoLP site. Significant interactions were found between cropping system and year, as well as cropping system, site and year (Table 1.9).

A main effect of year was observed, as pigeonpea biomass accumulation was higher in 2016 (3044 kg ha^{-1}) in comparison with 2015 (2318 kg ha^{-1}) (Table 3). Main effect of sites shown is due to biomass production being high at Wa (3016 kg ha^{-1}) and SkoHP (2795 kg ha^{-1}), compared to SkoLP (2232 kg ha^{-1}), averaged over the two years.

The significant interactions between cropping system, site and year was observed, as high sole crop biomass occurred at Wa (3631 kg ha^{-1}) compared to SkoLP (2252 kg ha^{-1}) in 2015 (Figure 1.7a) and SkoHP produced high sole crop biomass (3776 kg ha^{-1}) in 2016, whereas the other two sites were about 3000 kg ha^{-1} in 2016. Biomass production was high in intercrop systems at Wa (2225 kg ha^{-1} and 3138 kg ha^{-1}) in 2015 and 2016.

Sorghum biomass

Total aboveground biomass of sorghum was different across sites, and there was also a significant site by year interaction. However, similar to sorghum grain yield, there was no significant difference between cropping systems (Table 1.10). The main site effect observed was due to the high biomass production at Wa (5690 kg ha^{-1}) and SkoHP (5666 kg ha^{-1}) sites, substantially more so than at SkoLP (2044 kg ha^{-1}). Likewise, the significant site by year interaction was due to the lower biomass accumulation at SkoLP in 2015 compared to the other two sites. Plant growth and development at SkoLP in 2015 was affected by insect damage with damage reflected more in intercropped sorghum/pigeonpea (MD) (Table 1.8, Figure 1.9a and b). Overall, numerical but not significant differences were observed for sole sorghum, with high biomass compared to intercropped sorghum.

Water use efficiency (WUE)

Pigeonpea WUE

The sole cropped pigeonpea was numerically associated with higher WUE (55%) than intercrop systems (45%) but no significant effect was observed. Numerical values show that sole pigeonpea (LD) and sorghum/pigeonpea intercrop (LD) had WUE of 63 kg $ha^{-1}mm^{-1}$ and 54 kg $ha^{-1}mm^{-1}$ respectively, compared to that of sole pigeonpea (MD) 43 kg $ha^{-1}mm^{-1}$ and sorghum/pigeonpea intercrop (MD) 32 kg $ha^{-1}mm^{-1}$ (Table 1.9).

Pigeonpea WUE did vary across site, with high WUE at SkoLP (61 kg $ha^{-1}mm^{-1}$) followed by SkoHP (55 kg $ha^{-1}mm^{-1}$), and Wa at (28 kg $ha^{-1}mm^{-1}$). This difference was largely due to the differences in rainfall across sites.

Sorghum WUE

Cropping systems and site did not influence WUE of sorghum in this study. However, there was significant site by year interaction for WUE (Table 1.10). SkoHP recorded the highest WUE (94 kg $ha^{-1}mm^{-1}$) followed by SkoLP (55 kg $ha^{-1}mm^{-1}$) and Wa (53 kg $ha^{-1}mm^{-1}$). Further, in 2015 SkoHP recorded the highest WUE of 136 kg $ha^{-1}mm^{-1}$ resulting in a significant site by year interaction.

Soil moisture and total aboveground biomass

To evaluate how biomass was related to soil moisture in the profile, total aboveground biomass and soil moisture means were averaged over all cropping systems, and years, and plotted for the two Sko sites (Figure 1.10a and b). Very little relationship was found between soil moisture and total biomass at SkoLP (Figure 1.10a), with a co-efficient of determination (R^2) of 0.13. At the SkoHP site on the other hand, soil moisture was positively related to total biomass (Figure 1.10b), (*F value = 5.76, P = 0.032*). A co-efficient of determination (R^2) of 0.31 implies that about 31% of the increase in biomass was explained by its association with soil moisture.

DISCUSSION

Soil moisture distribution and dynamics

Soil moisture is controlled by complex interactions involving soil, plants, and climate (Puma et al., 2005). The soil water storage capacity is defined as the total amount of water that is stored in the soil within the plant's root zone (Bullied and Entz, 1999). The soil moisture change at the 10-100 cm soil depth over the two years period at SkoLP and SkoHP was chosen to represent soil moisture dynamics in the root zone in a nutrient limiting and non-limiting conditions, respectively (Figure 1.4). There were considerable variations in water storage in the soil profile at the two sites with SkoLP (155 mm) storing significantly more water than SkoHP (109 mm). The high available soil water at SkoLP is not unexpected as biomass production and grain yields were low as expected in this site, which was chosen for its nutrient deficiency status. SkoHP, a high fertility site had more biomass in the plots resulting in higher soil water consumption.

It is also possible that soil texture at the two sites may have helped account for the soil water storage differences observed, although both sites were sandy. The SkoLP site had slightly more clay content than SkoHP (Table 2.1). Clay content influences soil water content by regulating the soil texture and water holding capacity, thus enhancing moisture retention, as shown by the positive relationship between clay content and soil water content observed in earlier studies (Wang et al., 2016). Also, higher clay content levels have been shown to limit soil water drainage (Kizito et al., 2007).

Soil water storage trends also revealed higher storage below sole sorghum than the intercropped sorghum/pigeonpea (LD) plots. Pigeonpea roots may have extracted water from deeper soil layers hence the lower water storage observed in intercrop systems. Consistent with this finding is work done in Senegal where soil water storage at 1.10 -3.50 m depth range was limited for crop-shrub intercrops compared to sole crops of either peanut or millet (Kizito et al., 2007). This has been attributed to the roots of shrubs being effective at water extraction from deep soil layers (Gaze et al, 1998; Kizito et al., 2006).

Sole sorghum extracted greater soil water in the root zone than intercrop sorghum, a likely consequence of rapid early growth relative to the slow growth of pigeonpea. Water uptake by roots would also depend on the pattern of water loss by the shoot, and differences in water uptake at key stages could be due to a sparing use of soil moisture earlier on when the soil was wet (Vadez et al., 2008). Sorghum has an adventitious root system primarily concentrated in the topsoil (Lehmann et al, 1998; Routley et al., 2003). In a sorghum-pigeonpea intercrop system, Natarajan and Willey (1980) reported sorghum had a greater root density with concentration in the upper 15 cm of soil while pigeonpea rooted more deeply. This suggests that sorghum usually extracts water from the top meter of the soil profile. Similarly, Zhang et al. (2000) have indicated that differences in soil water extraction could arise from differences in rooting depth and density, the soil water potential to which roots can extract water, canopy development, and stomatal control of water loss. Soil compaction can confine root proliferation within the surface layer of soil, and this can affect pigeonpea's ability to show any characteristic advantage of root development over sorghum (Ito et al., 1992). Soil water extraction by plants during the growing period occurred mostly in the upper soil layers (10-30 cm) where most of the roots were located. Both sorghum and pigeonpea could have been extracting water from the upper profile soil layers but at different times over the growing season.

The pattern of water absorption from soil is different in annuals and perennials (Kramer, 1983) and plant form have influence on soil water use. The root system in pigeonpea appears to be closely related to plant habit. Tall, upright varieties (associated with medium duration growth habit) produce deeply penetrating roots, whereas indeterminate long duration types produce spreading and dense root systems (Pathak, 1970). However, in our study the two pigeonpea varieties showed no significant differences in soil moisture extraction. It may be difficult to observe subtle differences in root system architecture in terms of soil water uptake, as shown by Siddique et al. (2001), who found no differences in soil moisture extraction and rooting depth by various grain legume species. The reasons for this observation are a combination of factors. First, it has been noted in Western Australia that on shallow (30-40 cm) sandy loam soils, species with the potential for deep rooting are unlikely to give greater water uptake, because root penetration and final rooting depth are largely restricted by hard subsoil clay and limited depth of wetting (Siddique et al., 2001). Secondly, either the LD pigeonpea variety may have been exploiting water resources beyond the maximum measured soil depth (100 cm) (Kizito et al., 2007). The MD pigeonpea (152 days) variety grows faster and have higher water uptake than LD pigeonpea (206 days).

Perennials and LD varieties may extract soil water more slowly than annual, shorter duration legumes and may be inefficient at converting small to moderate amount of rainfall (20-50 mm) into dry matter (Armstrong et al., 1999). Significantly more water was extracted at SkoLP than SkoHP site. This indicates that the soil profile at SkoHP did encounter significant profile water saturation making it difficult for water extraction by plant roots. The soils in SkoHP were often saturated after rain events, with waterlogging in some parts of the field (personal observations).

Sorghum growth was used as the baseline for timing of soil moisture monitoring. Since the two crops have different morphological and physiological differences, it is likely we were biased, and this may have resulted in taking measurements on pigeonpea at the wrong time. Therefore matching pigeonpea phenological development with sorghum can explain why few genotype differences were observed.

Water use under sole and intercrop systems

Water use in sole crops

Water use is the sum of water used for transpiration and that evaporated from the soil from planting to physiological maturity. The main effect of cropping system on WU was only significant at the vegetative stage of growth at Wa where sole pigeonpea (LD) had significantly low WU, presumably due to phenology as the long duration growth habit of pigeonpea has a slow initial growth rate. Water use pattern depends on soil cover, with soil evaporation mostly occurring early in the growing season when ground cover by the crop is small (Siddique and Sedgley, 1986; Siddique et al., 1990).

At the flowering stage, progressive plant growth resulted in a corresponding increase in WU until a maximum was reached. Towards physiological maturity, WU declined rapidly with an increase in plant canopy development. This declined in WU was likely due to a much greater leaf area which resulted in enhanced canopy structure by plants with proportionate reduction in both transpiration and soil evaporation.

Similar to pigeonpea, in sorghum early vegetative state of 21 to 45 DAP, water use was low due to a small leaf surface area. The water requirement then increased until the flowering stage (82 DAP). Maximum WU occurred at the flowering stage. During the physiological maturity stage (132 DAP), water requirement decreased gradually as the crop begins to senesce and mature. This agrees with previous report on sorghum water use (Assefa and Staggenborg, 2011; Assefa et al., 2010). The cumulative total water use by sole sorghum over the growing season was approximately 588 mm. A sorghum variety maturing within 120-130 days is reported to require approximately 450-650 mm of water during its growing season (FAO, 1991); thus this result was consistent with expected.

Water use in intercrops

Cropping system significantly influenced WU, with higher WU in the intercrop systems than in sole crop stands. High WU may be due to improved canopy structure reducing unproductive water loss from the bare soil, and enhanced infiltration under intercropping relative to sole crop. A number of studies have shown improved WU under intercrop systems relative to sole cropped stands (Chimonyo et al., 2016; Chirwa et al., 2006; Droppelmann et al., 2000; Morris and Garrity, 1993).

Grain yield - pigeonpea

Rainfall during the growing season and its distribution is often a determinant of pigeonpea growth and grain production under rain-fed conditions, and large inter-annual fluctuations often result in variable yields (Lawn and Troedson, 1990; Troedson et al., 1990) Zhang et al., 2000).

Total rainfall over the two years was variable and unevenly distributed over the growing periods (Figure 1.2 and 1.3), even though the rainfall recorded for Sko in 2015 was above long term average. This variable rainfall pattern may have contributed to the low yields, although it was more likely that the very low yields were due to mal-adaptation to the sites. Pigeonpea has historically rarely been grown in West Africa, and genetic adaptation may be required as we observed yields of 43 kg ha^{-1} to 113 kg ha^{-1}, which is far below the yield potential reported for these varieties (about 2000 kg ha^{-1}). In East Africa (Høgh-Jensen et al., 2007) observed mean grain yields (over 2002-2004) of pigeonpea varying between 172 and 740 kg ha^{-1} across four on-farm sites in Tanzania and Malawi.

The reasons for the observed low yields in our study may be due to a combination of factors that are often grouped together as 'adaptation'. Flower drop and drying, poor pod set and poor seed quality was observed at all three sites. Poor seed quality and low plant density of pigeonpea often results in low yields (Høgh-Jensen et al., 2007). Appropriate insecticide use was applied frequently to manage pests; however, this could not overcome completely insect attacks due to the intensity of pest presence, perhaps attracted by the nutrient-dense pigeonpea resource. Reduction in grain yield may also be due to poor mobilization of assimilates to grain. Partitioning of assimilates among various plant parts with particular allocation to the harvested part, are important processes determining final yield (Fukai and Trenbath, 1993). As final yield depends on total biomass production, this could help explain the observation that grain yield was higher in the LD pigeonpea variety than the MD variety.

Intercropping has been reported to give significant yield increase over sole cropping in terms of overall biomass production and grain yield especially when component crops differ in phenology (Kimaro et al., 2009; Tobita et al., 1994; West and Griffith, 1992; Zhang and Li, 2003). Results from the present study agrees with these reports as the combined two intercrop systems yielded higher than either sole crop stand of component crops. This was due to overall efficient resource use in the intercropping system.

In an intercrop with a tall and short component crop species, the growth of the shorter crop is often suppressed due the dominance from the taller component (Rao and Willey, 1980). In the present study, it is apparent from the results that tall-growing sorghum significantly shaded the MD pigeonpea variety causing reduced light interception and subsequent root system development. This lead to low grain yield in intercropped MD pigeonpea variety. The height of sorghum was 2.7 m compared 1.2 m for the MD pigeonpea variety. This agrees with the results reported by (Ghosh, 2004) on how the yield of groundnut in the intercrop was affected by cereal fodders. Yield suppression under intercropping systems has been reported, and the present study is in agreement with other results. For example, maize intercropped with pigeonpea in semi-arid conditions led to similar or less yield than sole cropped maize (Chikowo et al., 2004; Rao and Mathuva, 2000; Snapp et al., 2002). Also, millet intercropped with cowpea resulted in a significant grain yield reduction of intercropped millet compared to sole cropped millet (Grema and Hess, 1994). Medium duration cultivars tends to be more sensitive to competition from the companion crop, therefore, are not normally suitable for intercropping with tall cereals (Mergeai et al., 2001). It was hypothesized that intercropping sorghum with pigeonpea increases yield and this was achieved.

Grain yield - sorghum

The sorghum variety used in this study was *Fadda*, a high yielding commercial hybrid variety grown by farmers in the region (Rattunde et al., 2013), and with a grain yield potential of 4.5 t/ha (Sorghum Technical Sheet, IER-ICRISAT). Overall, grain yield was statistically not different by cropping system, however numerically we observed a modest yield reduction of 6% to 17% for intercropped vs sole cropped sorghum. In a study to assess the performance of eight sorghum hybrids grown as sole crops under farmer's conditions in Mali, Rattunde et al. (2013)

reported mean grain yield ranging from 1530 kg ha^{-1} and 2840 kg ha^{-1} for *Fadda*. The lack of reduction in sorghum yield, when grown as an intercrop is suggestive that the cropping system arrangement, planting density and growth habit were such that pigeonpea did not compete for resources with sorghum. It is also possible that the biological nitrogen fixation associated with pigeonpea could have helped minimized competition for soil nitrogen resources with sorghum, enhancing the overall growth of the intercrop (Adjei-Nsiah et al., 2007). Similarly, a study in India on sorghum intercropped with green gram/cowpea reported a modest yield reduction of sorghum of 13.7% relative to a sole crop stand, and this was in part attributed to improved nitrogen supply to sorghum from the legume counterpart (Tanwar et al., 2014). However, nitrogen transfer within a season between legume and cereal species has rarely been documented, and transfer over time through decomposition of pigeonpea residues is more likely to benefit sorghum in subsequent years.

Over the two years, sorghum grain yields from the three sites varied. The low soil P site produced the lowest yields consistently, which was expected given the important role that P plays in plant nutrition, and its role as a major production constraint in West Africa smallholder farms (Leiser et al., 2012). The SkoHP site produced the highest yield overall at 1804 kg ha^{-1}, and at the low phosphorus site, a 53% reduction was observed relative to SkoHP.

Also, in 2015, SkoLP sorghum plants suffered damage from sorghum midge *Contarinia sorghicola* (Coquillett) despite insecticide control efforts; this type of midge damage has been observed previously due to the delayed maturity caused by low fertility (Rattunde et al., 2016). Sorghum grain yield reduction (2-59%) on low phosphorus trials at Samanko and Kolombada experimental sites has been reported in Mali (Leiser et al., 2012). Limited soil phosphorus availability is a serious constraint to sorghum growth and development in West Africa (Buerkert et al., 2001). In Ghana, significant increase in sorghum biomass and grain production can be achieved following the addition of N and P fertilizers (Buah et al., 2012).

Aboveground biomass

Pigeonpea

The biomass of pigeonpea was lower in the intercrop than in the sole crop, and the LD pigeonpea variety accumulated higher biomass compared to the MD variety of pigeonpea (Figure 1.7 and 1.8). Varietal differences have great influence on the development and growth of pigeonpea (Francis, 2002), and may have caused the observed differences in biomass accumulation of the two pigeonpea varieties. The MD pigeonpea variety is relatively short-statured (1.1 m), and grows faster which may lead to low biomass accumulation compared to the LD pigeonpea which is a tall (2.1 m) variety with prolonged vegetative phase, resulting in more biomass accumulation.

Growth of pigeonpea generally followed environmental conditions, as sites varied in seasonal rainfall (789-1132 mm), duration of the rainy season (86-94 days), soil fertility, and mean temperature (23-38°C), giving rise to considerable variation in grain yield, biomass and WUE. The SkoHP and Wa sites accumulated higher biomass relative to SkoLP site, presumably due to fertilizer additions at SkoHP and Wa whereas SkoLP is maintained as a low phosphorus site representative of many smallholder farmers' fields in West Africa (Bationo et al., 1998). Similar to grain yield, pigeonpea biomass accumulation was 14% higher in the mesic rainfall season, 2016, in comparison to 2015, where biomass of sole pigeonpea varieties was highest in SkoHP, and low in Wa (Figure 7b). The biomass production at Wa especially for the LD pigeonpea variety may be associated with favorable growing temperatures (23-33° C, Table 2) close to optimum temperature for development in pigeonpea of ≤ 24° C (Carberry et al., 2001), and medium fertile, deep soils. Further the variation in total biomass can be partly explained by variation in soil moisture, as observed for the SkoHP site where there was a positive correlation of total biomass to soil moisture (Boyer, 1996; Taylor et al., 1983), and high WU was observed at SkoHP.

Sorghum biomass

Grain yields were not reduced, and biomass of sorghum in intercropped systems was similar to that of sole sorghum. Site variations were also evident in that the Wa and SkoHP sites accumulated almost twice as much biomass relative to SkoLP, reflecting the low P status of this site. The high soil moisture at the SkoLP site was expected to accelerate high vegetative growth but this was not the case, possibly due to nutrient limitations at this unfertilized, farmer-field representative site. There was also a positive relationship between total WU and total biomass produced (R^2 = 0.97) (Figure 1.11), suggesting the accumulation of biomass by the plants depend on water use. Dry matter production by a crop is proportional to the amount of water used (Boyer, 1996; Tanner and Sinclair, 1983). Likewise in sorghum, a positive relationship between biomass and ET is reported (Assefa and Staggenborg, 2011; Hanks et al., 1969).

Water use efficiency

The higher the productivity per unit water use, the higher the WUE indicating that water consumption of a crop is directly related to dry matter production (Boyer, 1996; Taylor et al., 1983). However, Fischer and Turner (1978) indicated that high WUE may not always reflect high productivity, just low water use. This is the first study we know of on water use and WUE of pigeonpea in Ghana and Mali. Overall, we found that cropping system had an effect on WUE, with higher WUE under intercrop systems (54%) than sole crops (46%). This is consistent with our hypothesis, as shoot architecture in the intercrop systems often leads to a more complete canopy cover of the soil that can reduce soil evaporation and enhance WU.

Although no differences were observed in WU by plant species growth type (pigeonpea LD vs MD), nor were site effects marked on WU, yet higher WUE of the pigeonpea LD variety was observed relative to the pigeonpea MD variety. This may be due to access and utilization of water stored in the soil profile from previous wet years. This is in agreement with the report of Reddy (1990) that LD pigeonpea species often uses residual moisture. The two pigeonpea varieties may have different water-use strategies to adapt to limited water availability, and in their ability to extract water from the soil. However, the variability of growth in the present study may have precluded differences being observed; indeed we found a lack of locally adapted pigeonpea varieties – none of those evaluated performed well.

Intercropping sorghum with either the LD or MD pigeonpea variety increased WUE by 79% relative to sole crop sorghum. This increased WUE was achieved through rapid canopy expansion and greater ground cover, higher overall biomass production and potentially differences in rooting characteristics resulting in complementary water use. This result is consistent with several reports in the literature (Chimonyo et al., 2016; Droppelmann et al., 2000; Ansari et al., 2014; Morris and Garrity, 1993; Willey, 1990; Yin et al., 2015). Increased WUE in the intercrop system was more associated with decreased water use relative to the biomass production (Narayanan et al., 2013). Intercropping sorghum with pigeonpea therefore increases the effective use of water due to larger amount of biomass accumulated in the combined crop presence relative to either grown as a sole crop (Blum, 2009), an advantageous trait under water limited environments if the goal is to produce more biomass.

CONCLUSION

Overall a lack of adapted pigeonpea varieties limited our ability to assess growth habit or cropping system effects on grain yield. However, in terms of biomass WU and WUE was assessed, and it was found that sole sorghum stored more water than intercropped sorghum/pigeonpea (LD) plots. This was apparently due to deeper soil water extraction by pigeonpea, and both sorghum and pigeonpea extracted soil water from the upper profile soil layers but at different times over the growing season. Short-statured MD pigeonpea variety did not appear to be suitable for intercropping with this tall *'Fadda'* sorghum variety as the LD pigeonpea variety produced more biomass and grain yield than the MD pigeonpea variety, and sorghum grain yields were not reduced. Overall, intercropping improved the productivity of the combined system, and resulted in enhanced water use where water use efficiency under intercrop systems was higher and more stable across years than sole crops.

APPENDIX

Table 1.1 Mean monthly maximum and minimum temperature during the 2015 and 2016 years at Sko (Mali) and Wa (Ghana).

Months	Mean Temperature (°C)			
	Samanko			
	2015		**2016**	
	Max.	Min.	Max.	Min.
May	43.5	26.6	42.7	27.5
June	40.4	24.8	40.1	26.8
July	36.3	24.9	35.2	25.7
August	35.5	23.9	34.2	25.4
September	35.7	23.8	36.5	25.3
October	36.9	24.2	38.9	25.5
	Wa			
May	38.3	25.3	35.1	23.6
June	34.2	23.7	32.8	23.0
July	32.9	22.9	31.5	22.5
August	30.5	22.3	31.1	22.1
September	31.9	22.1	32.4	22.0
October	34.7	22.5	35.3	22.1

Source: GRWS100 (2015, 2016) at ICRISAT and SARI.

Table 1.2 Soil properties measured in all three experimental sites. Soil texture is indicated by sand, silt and clay percent. Total soil carbon is indicated by SOC%, pH is the measure of the acidity or basicity of soil, and inorganic P is based on Bray extract (Mehlich III). Means (n = 4) are followed by standard deviations in parentheses.

Depth (cm)	Sand %	Clay %	Silt %	pH	SOC	Inorganic P (ppm)	CEC (cmolkg^{1})
SkoLP							
0-15	73 (10.5)	11 (1.3)	16 (11.3)	6 (0.3)	0.29 (0.05)	16.0 (5.43)	2.98 (1.19)
15-30	76 (7.5)	15 (2.1)	9 (6.2)	5 (0.1)	0.26 (0.01)	9.25 (1.09)	3.18 (1.52)
30-60	62 (8.8)	29 (8.2)	9 (6.9)	5 (0.5)	0.30 (0.02)	1.03 (0.04)	7.10 (2.33)
SkoHP							
0-15	72 (0.9)	7 (0.5)	20 (1.0)	5 (0.1)	0.38 (0.06)	30.0 (4.2)	2.60 (1.12)
15-30	72 (0.9)	12 (5.7)	16 (4.9)	5 (0.6)	0.36 (0.05)	21.5 (2.1)	3.05 (1.34)
30-60	68 (1.8)	12 (2.1)	19 (0.5)	5 (0.4)	0.32 (0.01)	10.8 (0.8)	4.28 (1.61)
Wa							
0-15	84 (3.8)	8 (1.1)	8 (2.3)	7 (0.1)	0.44 (0.44)	7.00 (0.71)	3.23 (0.34)
15-30	71 (9.2)	18 (7.8)	12 (3.7)	7 (0.3)	0.24 (0.01)	1.03 (0.04)	2.80 (1.76)
30-60	66 (8.1)	22 (4.7)	12 (4.3)	7 (0.2)	0.23 (0.05)	1.03 (0.04)	4.95 (0.76)

Table 1.3 Treatment structure across all sites.

Treatment No.	Treatment ID	Description
1	SG/PP MD	Intercrop sorghum-pigeonpea (medium duration)
2	SG/PP LD	Intercrop sorghum-pigeonpea (long duration)
3	PP MD	Sole pigeonpea (medium duration)
4	PP LD	Sole pigeonpea (long duration)
5	SG	Sole sorghum
6	SG/PP MD RT	Intercrop sorghum-pigeonpea (medium duration), ratooned
7	SG/PP LD RT	Intercrop sorghum-pigeonpea (long duration), ratooned
8	PP MD RT	Sole pigeonpea (medium duration), ratooned
9	SG RT	Sole sorghum, ratooned

Table 1.4 Cropping systems and plant population densities across experimental sites.

Cropping system	Planting pattern	Plant spacing (cm)	Plant population density
Sole sorghum (SG)	2 plants per hill	30 x 75	88,000
Sole pigeonpea (PP)	2 plants per hill	60 x 75	44,000
Sorghum-pigeonpea (2:1 in-row intercropping)	2 hills of SG to every hill of PP	SG: 30 x 75 PP: 60 x 75	SG: 44,000 PP: 22,000

Table 1.5 Plant and soil moisture measurement dates and corresponding plant development stages during the 2015 growing season at SkoLP, SkoHP and Wa sites.

Plant growth stage	Date of measurements (2015-2016)			Measurements taken
	SkoLP	**SkoHP**	**Wa**	
3 weeks after planting	28 July	29 July	7 August	Soil moisture
Vegetative	20 August	21 August	2 September	Biomass, soil moisture, chlorophyll
Flowering	15 October	12 October	2 October	Biomass, soil moisture, chlorophyll
Physiological maturity	15 November	21 November	6 November	Biomass, soil moisture, chlorophyll
21d after SG harvest	21 December	22 December	10 December	Soil moisture, chlorophyll
42d after SG harvest	6 January, 2016	7 January, 2016	21 January, 2016	Soil moisture, chlorophyll
65d after SG harvest	30 January, 2016	31 January, 2016	13 February, 2016	Soil moisture, chlorophyll
130d after SG harvest	5 April, 2016	6 April, 2016	18 March, 2016	Soil moisture, chlorophyll

Table 1.6 Plant and soil moisture measurement dates and corresponding plant development stages during the 2016 growing season at SkoLP, SkoHP and Wa sites.

Plant growth stage	Date of measurements (2016-2017)			Measurements taken
	SkoLP	**SkoHP**	**Wa**	
3 weeks after planting	28 July	29 July	8 August	Soil moisture
Vegetative	20 August	21 August	9 September	Biomass, soil moisture, chlorophyll
Flowering	15 October	12 October	1 October	Biomass, soil moisture, chlorophyll
Physiological maturity	15 November	21 November	2 November	Biomass, soil moisture, chlorophyll
21d after SG harvest	21 December	22 December	28 November	Soil moisture, chlorophyll
42d after SG harvest	6 January, 2017	7 January, 2017	19 January	Soil moisture, chlorophyll
65d after SG harvest	30 January, 2017	31 January, 2017	11 February, 2017	Soil moisture, chlorophyll
130d after SG harvest	5 April, 2017	6 April, 2017	17 March, 2017	Soil moisture, chlorophyll

Table 1.7 Analysis of variance results presented for cropping system, site and season effects on pigeonpea water use at vegetative, flowering and physiological maturity growth stages from SkoLP, SkoHP and Wa sites for 2015 and 2016. Water use was determined by difference between soil water at sowing and maturity, added to interval rainfall at each growth stage.

Site	Cropping System	45 DAS* (Vegetative)		(80 - 125 DAS) Flowering		(153 - 207 DAS) Maturity	
		2015	**2016**	**2015**	**2016**	**2015**	**2016**
SkoLP	Sole Pigeonpea (LD)	123	327	472	294	27	59
	Sole Pigeonpea (MD)	124	332	472	309	26	63
	Sorghum/Pigeonpea (LD)	124	315	460	291	17	50
	Sorghum/Pigeonpea (MD)	132	325	465	300	9	53
SkoHP	Sole Pigeonpea (LD)	141	326	477	334	28	99
	Sole Pigeonpea (MD)	154	329	488	319	48	61
	Sorghum/Pigeonpea (LD)	147	326	487	332	46	81
	Sorghum/Pigeonpea (MD)	153	327	487	320	51	69
Wa	Sole Pigeonpea (LD)	59b	212	118	155	100	84
	Sole Pigeonpea (MD)	178a	212	190	113	83	98
	Sorghum/Pigeonpea (LD)	186a	207	181	131	103	105
	Sorghum/Pigeonpea (MD)	179a	198	193	105	126	124
	ANOVA						
	Cropping system	0.0283		0.8084		0.8015	
	Site	0.0027		<.0001		0.0076	
	Year	<.0001		<.0001		0.0641	
	Site x Year	<.0001		<.0001		0.4213	
	Cropping system x Year	0.0101		0.1451		0.7311	
	Cropping system x Site x Year	0.0176		0.0603		0.9821	
	Contrasts						
	Intercrop vs sole crop	0.16 (0.6876)		0.00 (0.9789)		0.13 (0.7194)	
	Pigeonpea LD vs MD	0.62 (0.4331)		0.02 (0.8785)		0.22 (0.6405)	

*DAS: Days after sowing

Table 1.8 Analysis of variance results presented for cropping system, site and season effects on sorghum water use at vegetative, flowering and physiological maturity growth stages from SkoLP, SkoHP and Wa sites for 2015 and 2016. Water use was determined by difference between soil water at sowing and maturity, added to interval rainfall at each growth stage.

Site	Cropping System	45 DAS (Vegetative)		(82 DAS) Flowering		(132 DAS) Maturity	
		2015	**2016**	**2015**	**2016**	**2015**	**2016**
SkoLP	Sole Sorghum	130	315	380	288	22	51
	Sorghum/Pigeonpea (LD)	124	315	375	300	14	50
	Sorghum/Pigeonpea (MD)	132	325	383	291	9	53
SkoHP	Sole Sorghum	140	328	366	390	19	86
	Sorghum/Pigeonpea (LD)	147	327	409	487	46	81
	Sorghum/Pigeonpea (MD)	153	326	404	486	51	69
Wa	Sole Sorghum	164	206	166	159	69	180
	Sorghum/Pigeonpea (LD)	186	207	181	131	105	102
	Sorghum/Pigeonpea (MD)	179	198	193	105	124	128
	ANOVA						
	Cropping system	0.7673		0.6236		0.8478	
	Site	0.0022		<.0001		0.0119	
	Year	<.0001		<.0001		0.0107	
	Site x Year	<.0001		0.0003		0.9920	
	Cropping system x Year	0.7988		0.0348		0.2757	
	Cropping system x Site x Year	0.9331		0.1772		0.5249	

*DAS: Days after sowing

Table 1.9 Analysis of variance results presented for cropping system, site and season effects on pigeonpea grain yield, total biomass and water use efficiency based on total biomass at physiological maturity from SkoLP, SkoHP and Wa sites for 2015 and 2016 years.

Site	Cropping System	Grain Yield ($kg\ ha^{-1}$)		Total Biomass ($kg\ ha^{-1}$)		Water Use Efficiency ($kg\ ha^{-1}mm^{-1}$)	
		2015	**2016**	**2015**	**2016**	**2015**	**2016**
SkoLP	Sole Pigeonpea (LD)	17b	75ab	2782a	4799a	93	93
	Sole Pigeonpea (MD)	17b	154a	1721b	1519b	37	20
	Sorghum/Pigeonpea (LD)	53a	110a	1713b	3288a	69	77
	Sorghum/Pigeonpea (MD)	20b	24b	926b	1110b	70	31
SkoHP	Sole Pigeonpea (LD)	30a	448a	1809	5492a	32	66
	Sole Pigeonpea (MD)	48a	36b	3060	2060b	119	38
	Sorghum/Pigeonpea (LD)	47a	204ab	2413	4600a	51	68
	Sorghum/Pigeonpea (MD)	34a	37b	1686	1245b	46	19
Wa	Sole Pigeonpea (LD)	92ab	54	4478a	3812ab	70	23
	Sole Pigeonpea (MD)	45bc	58	2784b	2327bc	25	20
	Sorghum/Pigeonpea (LD)	109a	98	3309ab	4270a	34	27
	Sorghum/Pigeonpea (MD)	12c	55	1141c	2007c	12	16
	ANOVA						
	Cropping system	0.0109		<.0001		0.2313	
	Site	0.2209		0.0323		0.0313	
	Year	0.0019		0.0010		0.2528	
	Site x Year	0.0307		0.1620		0.9964	
	Cropping system x Year	0.1607		0.0007		0.6004	
	Cropping system x Site x Year	0.0090		0.0119		0.5322	
	Contrasts						
	Intercrop vs sole crop	0.82 (0.3662)		8.56 (0.0043)		0.81 (0.3710)	
	Pigeonpea LD vs MD	2.87 (0.0937)		20.18 (<.0001)		1.61 (0.2084)	

*Within a site, means for cropping systems in each year followed by same letters are not significantly different at p=≤ 0.05. Cropping systems performed different at the three sites between the two years.

Table 1.10 Analysis of variance results presented for cropping system, site and season effects on sorghum grain yield, total biomass and water use efficiency based on total biomass at physiological maturity from SkoLP, SkoHP and Wa sites for 2015 and 2016 years.

Site	Cropping System	Grain Yield ($kg\ ha^{-1}$)		Total Biomass ($kg\ ha^{-1}$)		Water Use Efficiency ($kg\ ha^{-1} mm^{-1}$)	
		2015	**2016**	**2015**	**2016**	**2015**	**2016**
SkoLP	Sole Sorghum	169	1866	811	4260	10	125
	Sorghum/Pigeonpea (LD)	478	1167	1132	2824	44	69
	Sorghum/Pigeonpea (MD)	143	1296	493	2745	28	55
SkoHP	Sole Sorghum	2285	1645	9212	3181	55	46
	Sorghum/Pigeonpea (LD)	2403	1573	8467	3231	194	43
	Sorghum/Pigeonpea (MD)	1417	1502	5967	3937	160	66
Wa	Sole Sorghum	966	1770	5381	7467	82	51
	Sorghum/Pigeonpea (LD)	989	1351	5540	4491	69	35
	Sorghum/Pigeonpea (MD)	1049	1776	6208	5057	43	37
	ANOVA						
	Cropping system	0.3335		0.2270		0.7122	
	Site	0.0226		0.0003		0.1297	
	Year	0.0092		0.0999		0.2448	
	Site x Year	0.0010		<.0001		0.0036	
	Cropping system x Year	0.2683		0.3113		0.1137	
	Cropping system x Site x Year	0.7459		0.0642		0.5031	

No significant cropping system effect observed but there were numerical differences of cropping systems at the three sites between the two years.

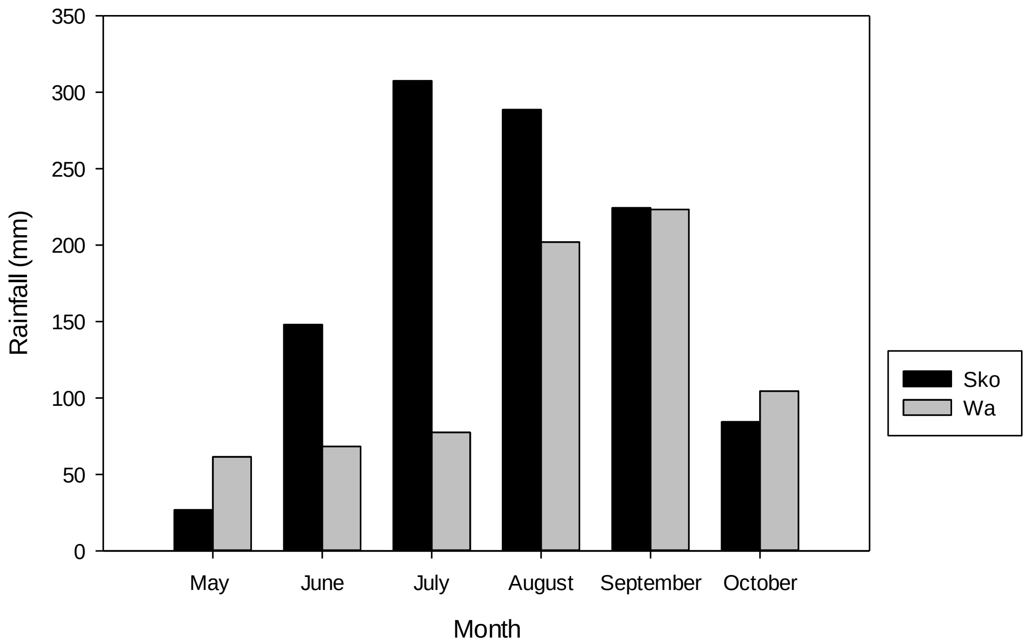

Figure 1.2 Monthly rainfall in mm from May to October during the 2015 growing season for Sko (Mali) and Wa (Ghana). Data recorded on-site using GRWS100 installed in 2014 by ICRISAT.

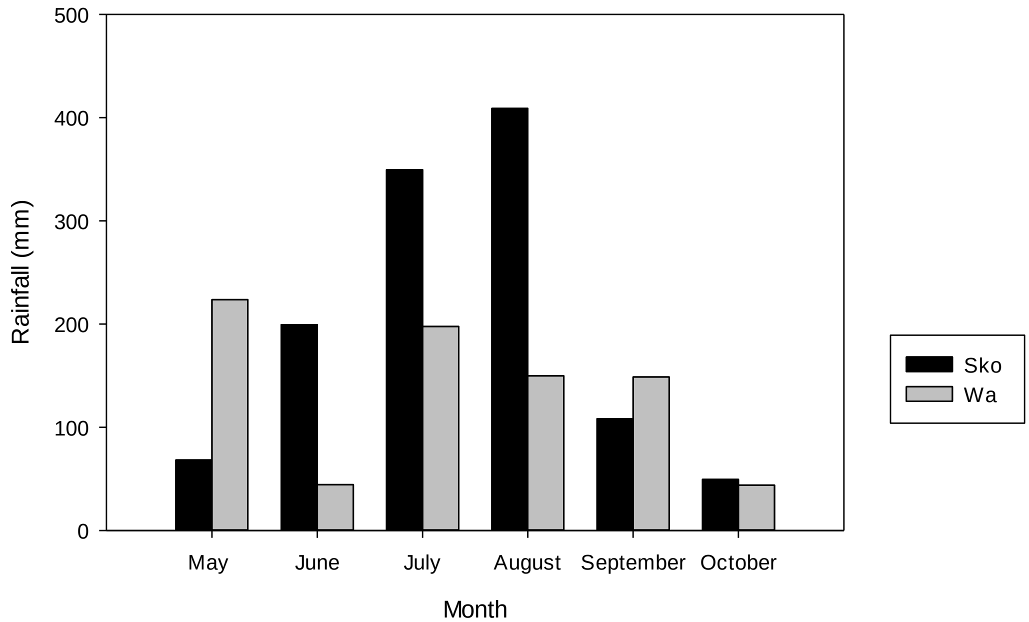

Figure 1.3 Monthly rainfall in mm from May to October during the 2016 growing season for Sko (Mali) and Wa (Ghana). Data recorded on-site using GRWS100 installed in 2014 by ICRISAT.

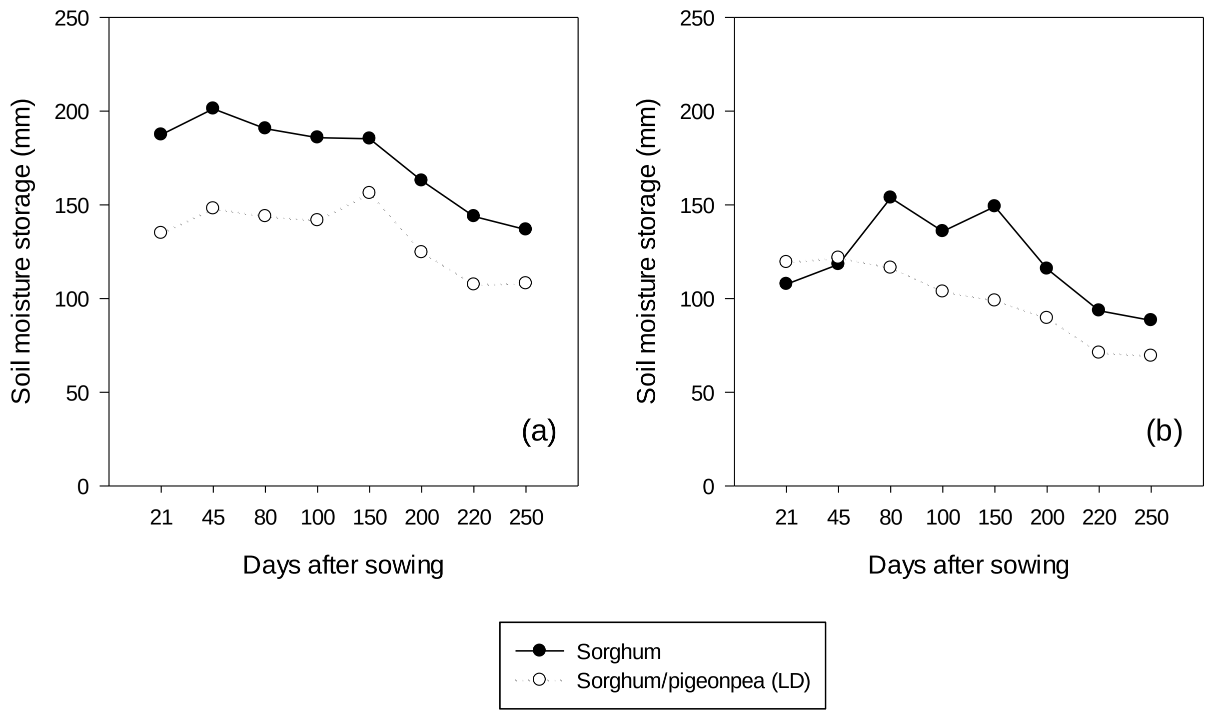

Figure 1.4 Dynamics of measured soil water storage under the sole sorghum and intercropped sorghum/pigeonpea cropping systems averaged over two years period (2015 and 2016) at Sko, Mali: (a) SkoLP (b) SkoHP. Sole sorghum stored significantly more water than intercropped sorghum/pigeonpea.

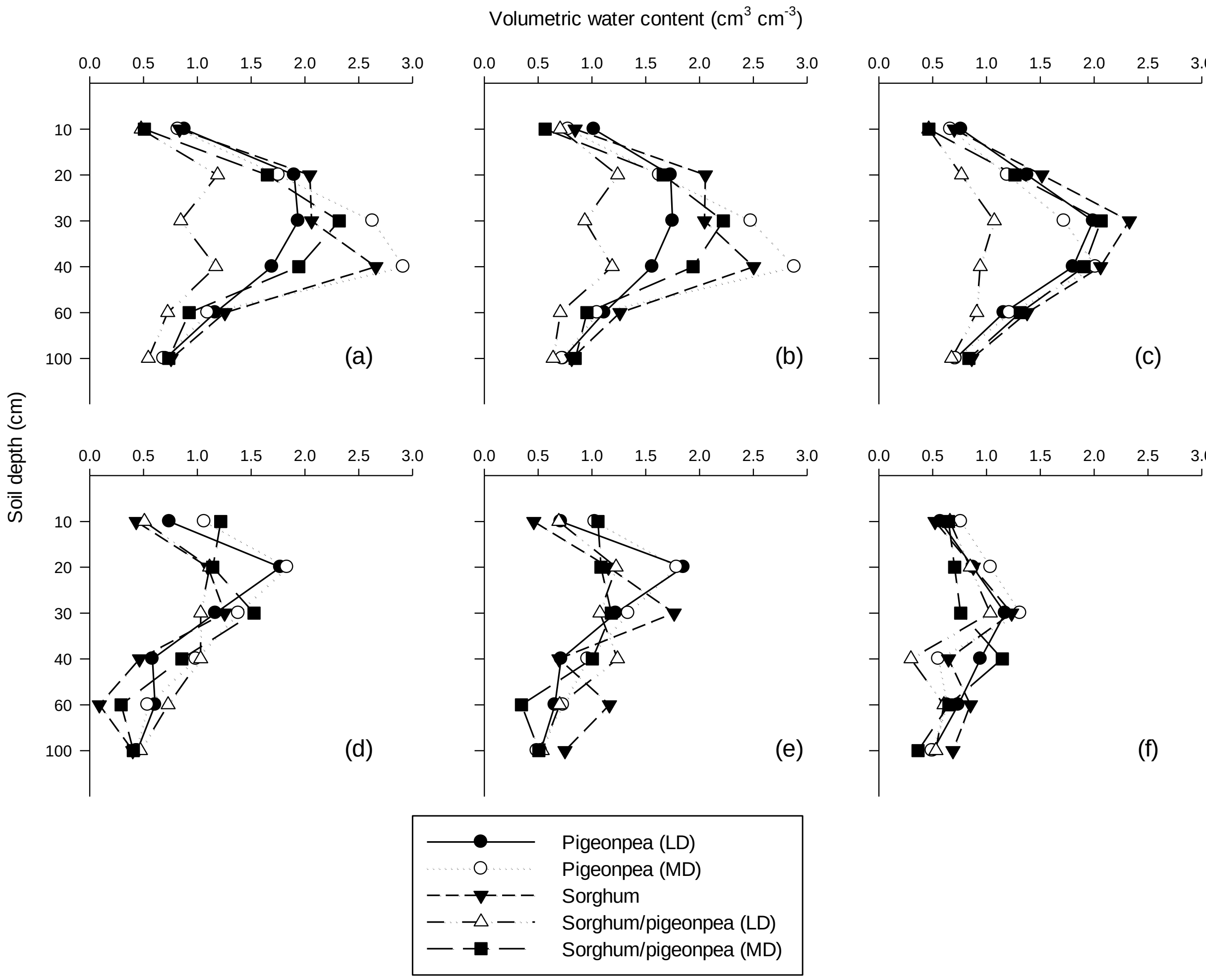

Figure 1.5 Water extraction of sorghum and pigeonpea cropping systems in 2015 at Sko, Mali: (a) SkoLP vegetative, (b) SkoLP flowering, (c) SkoLP maturity, (d) SkoHP vegetative, (e) SkoHP flowering, (f) SkoHP maturity. SkoLP site extracted more water than the SkoHP site. There was more water extraction at the top layers than bottom layers across the two sites.

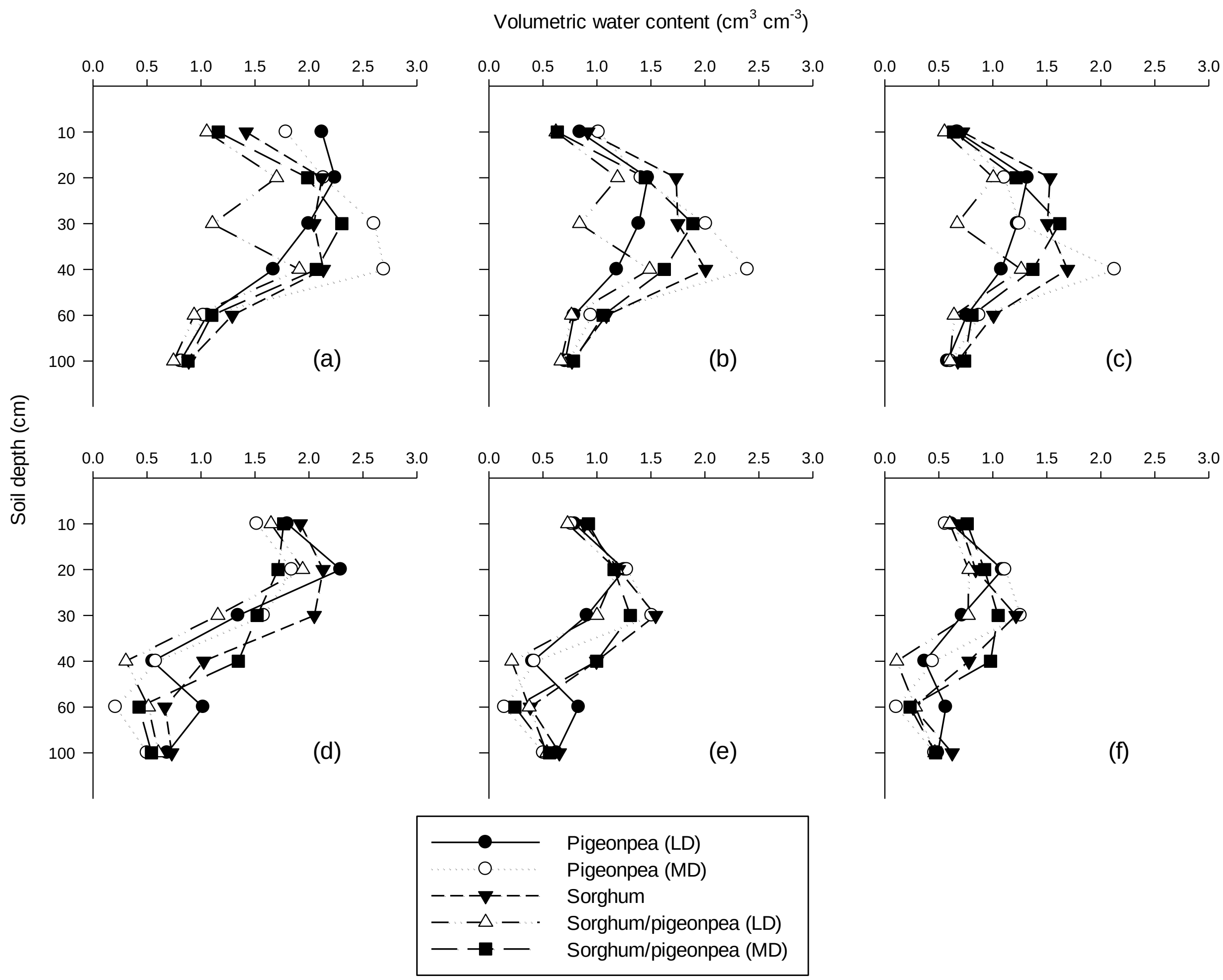

Figure 1.6 Water extraction of sorghum and pigeonpea cropping systems in 2016 at Sko, Mali: (a) SkoLP vegetative, (b) SkoLP flowering, (c) SkoLP maturity, (d) SkoHP vegetative, (e) SkoHP flowering, (f) SkoHP maturity. SkoLP site extracted more water than the SkoHP site. There was more water extraction at the top layers than bottom layers across the two sites.

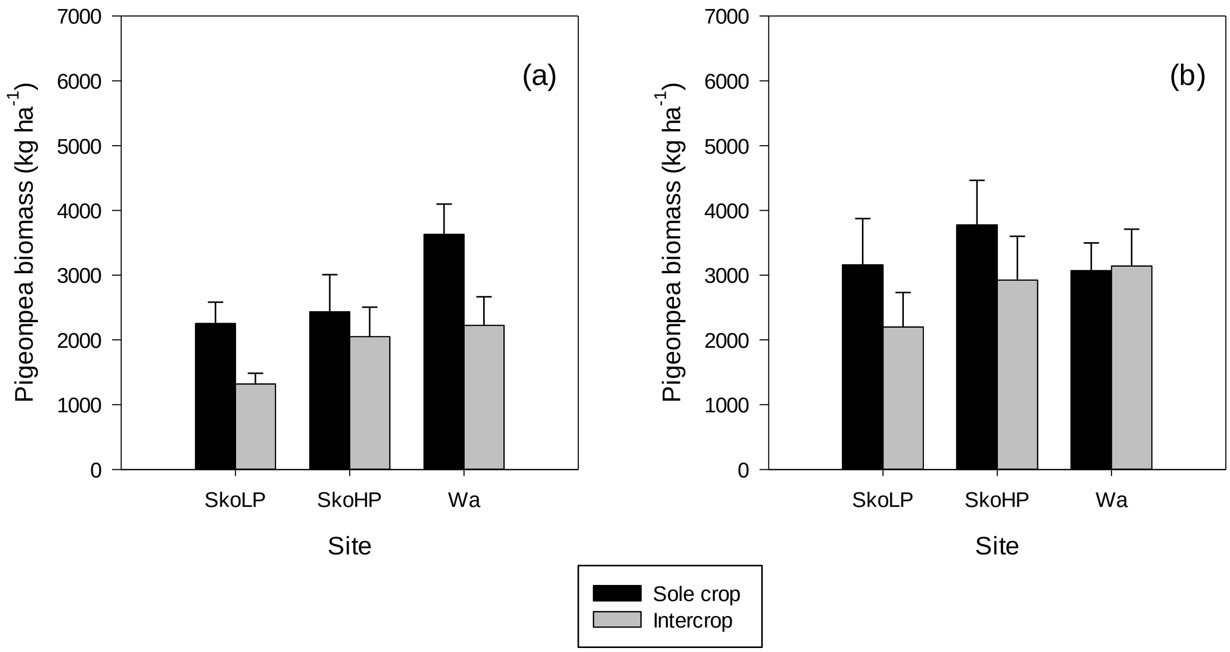

Figure 1.7 Pigeonpea aboveground biomass under sole crop and intercrop systems averaged across pigeonpea variety by the three sites for (a) 2015 and (b) 2016. Error bars represent standard error of cropping system means. Sole crop system was statistically different from intercrop systems.

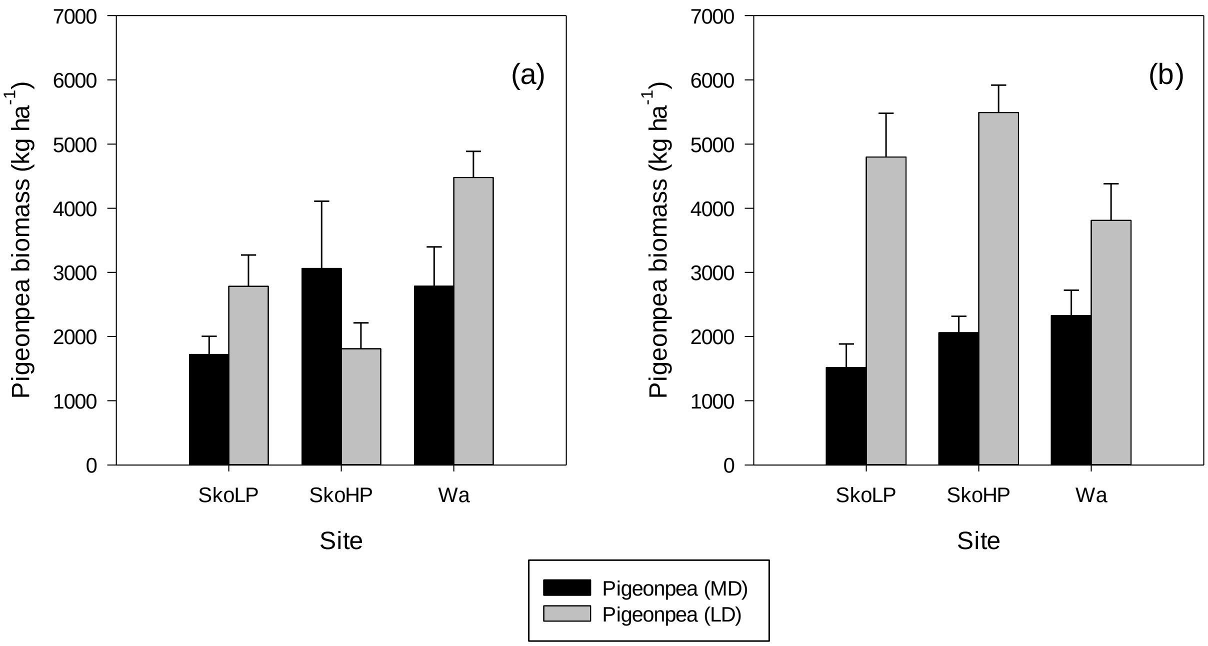

Figure 1.8 Aboveground biomass of pigeonpea (MD) and pigeonpea (LD) varieties across all cropping system by the three sites for (a) 2015 and (b) 2016. Error bars represent standard error of cropping system means. Total biomass in the LD pigeonpea variety was statistically different from the MD variety.

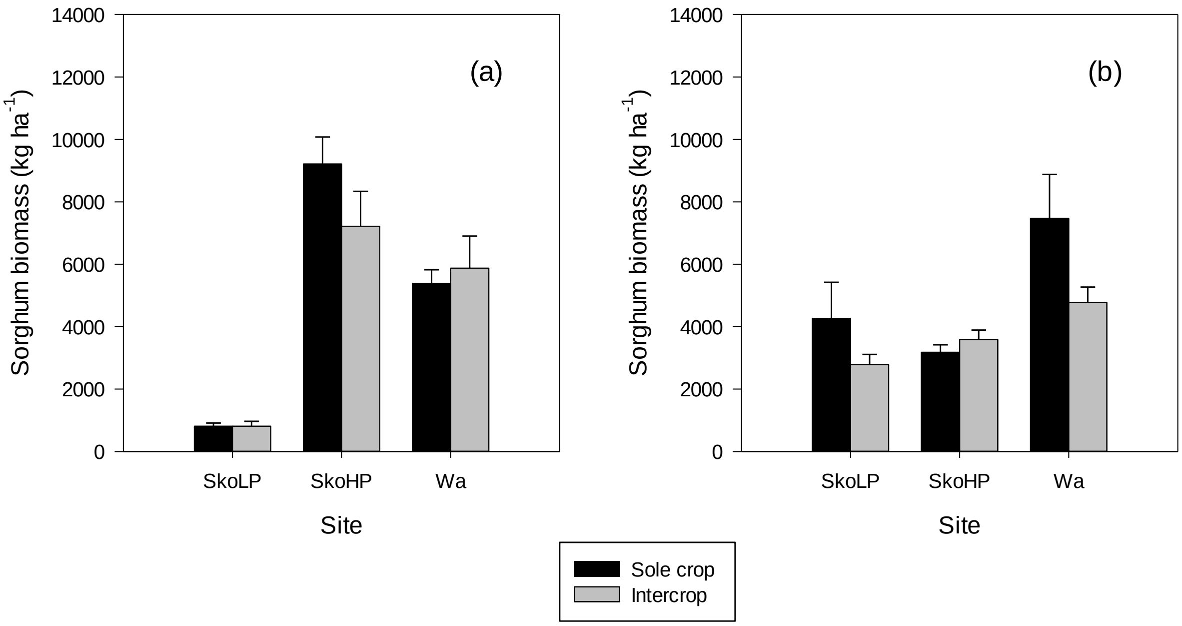

Figure 1.9 Sorghum aboveground biomass under sole crop and intercrop systems across the three sites for (a) 2015 and (b) 2016 years. Error bars represent standard error of cropping system means. Sole sorghum was numerically higher than intercropped sorghum. Insect damage at SkoLP in 2015 affected plant growth and development.

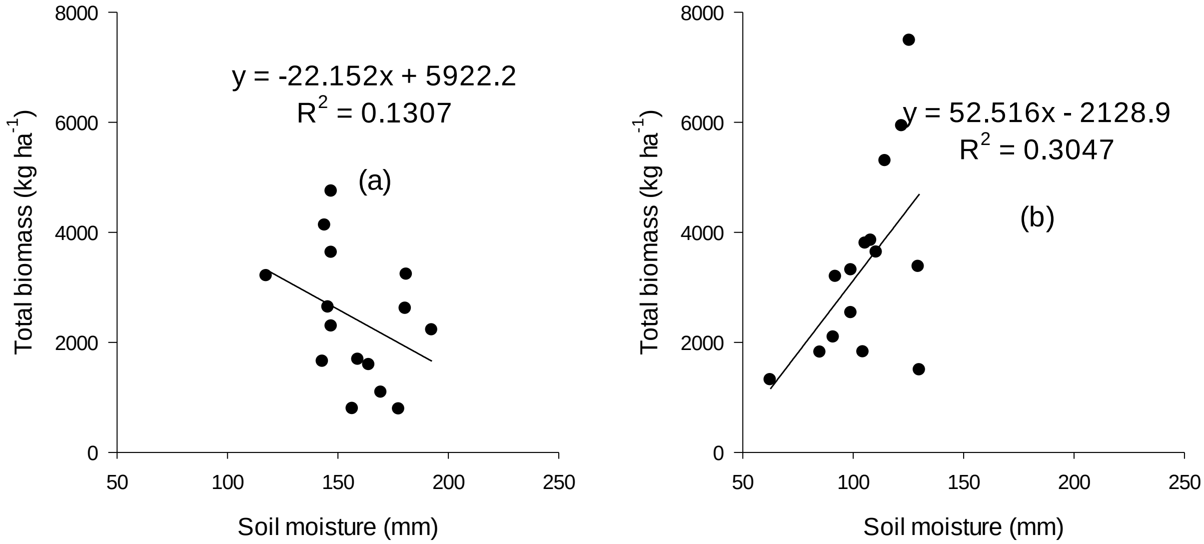

Figure 1.10 Relationship between soil moisture and total biomass measured at maturity (n =15) over two years (2015 and 2016) at Sko, Mali: (a) SkoLP (b) SkoHP.

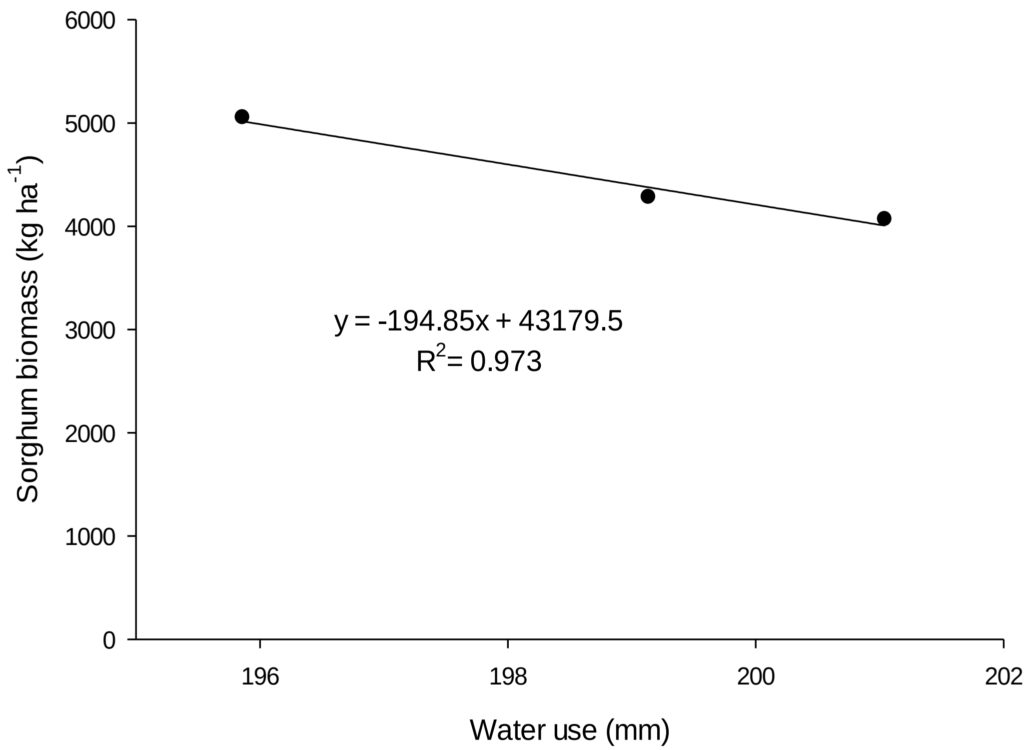

Figure 1.11 Relationship between sorghum aboveground biomass and total water use over two years (2015 and 2016) across sites.

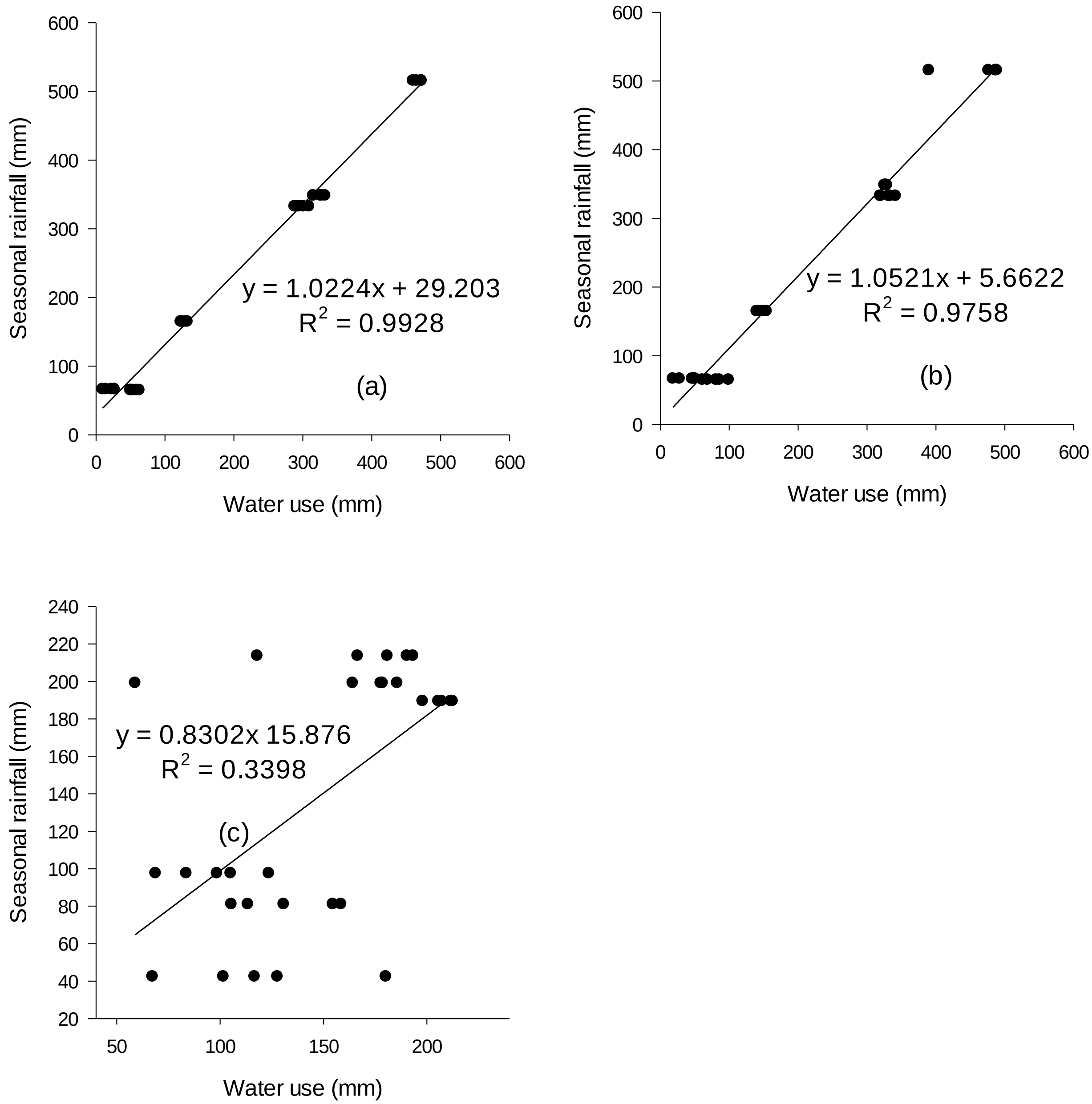

Figure 1.12 Relationship between total seasonal rainfall and total water use at the three sites: (a) SkoLP (b) SkoHP (c) Wa, averaged over two years (2015 and 2016).

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CHAPTER 2

AGRONOMIC PERFORMANCE OF PERENNIAL GENOTYPES AND DIFFERENT GROWTH HABITS OF PIGEONPEA

ABSTRACT

Legume diversification can help improve soil fertility management and are particularly important for smallholder farmers in West Africa. Phosphorus and nitrogen are two major nutrients limiting crop production across farming communities in the region; however, fertilizers are often not affordable. Pigeonpea has been identified as a means to diversify cereal production systems in the semi-arid and sub-humid tropics of East Africa, where studies have reported multiple ecosystem services and long-term sustainability. However, research is highly limited on pigeonpea as a soil amendment crop in West Africa. Sorghum/pigeonpea cropping system could be an affordable, sustainable option for smallholder farmers to improve soil fertility and increase yields. The aim of the study was to evaluate sorghum and pigeonpea productivity under variable soil and weather conditions, for diverse germplasm that includes medium duration (MD), long duration (LD) and a perennial growth habit. Field experiments were established for the 2015 and 2016 seasons under rain-fed conditions at four sites: three locations in southern Mali and one in northern Ghana. Sorghum and two pigeonpea varieties were planted as sole and intercrop cropping systems in a randomized complete block design with 4 replications. Growth, plant biomass and yield parameters were collected at flowering, physiological maturity and harvest. Land equivalent ratio (LER) was used to evaluate productivity of the intercrop system. Site, year and cropping systems caused significant variations in measured parameters.

Pigeonpea yield was low across sites with the exception of Fko in Mali, which produced grain yield of 1782 kg ha^{-1}, and tall pigeonpea at 2.2 m. Overall biomass production in 2015 (4382 kg ha^{-1}) was high in comparison with 2016 (2921 kg ha^{-1}). The biomass production in Mali at the adequate phosphorus fertility site SkoHP (7784 kg ha^{-1}) was almost twice that observed at the low P site SkoLP (3400 kg ha^{-1}). The LD variety was higher than the MD variety in terms of plant height, biomass and grain yield. Cropping systems effect on sorghum grain yield was inconsistent, however the overall sorghum yield in the two intercrop systems was about 60% compared to sole cropped sorghum. Given the modest negative effect on sorghum yield of the short-statured MD pigeonpea variety, this was evidence that this may be a more suitable growth habit for intercropping with sorghum than the LD variety. The land equivalent ratio of 1.6 observed for MD pigeonpea intercropped with sorghum also supported this observation. Overall, the calculated LER gave values greater than one, consistent with a biomass production advantage for a sorghum/pigeonpea intercrop relative to either plant grown alone. Ratooning of both species was also assessed in this study and while not always successful in terms of successful regrowth after ratooning. Yet for plants that did regrow, a markedly increased productivity of both pigeonpea and sorghum was observed in ratooned plants relative to year one.

INTRODUCTION

Soils in the Sahelian-Sudano and Guinean regions of West Africa (WA) have inherently low fertility status that poses great challenge to agricultural production (Bationo, *et al*., 2007; Obeng 1978). Phosphorus (P) is one of the major limiting nutrients to crop production in WA (Bationo et al., 1998; Buerkert et al., 2001; Buresh et al., 1997). These soils have extremely low P fixing capacity with available P less than 2 mg P/kg while the amount of total P ranges between 25 to 340 mg/kg with a mean of 109 mg /kg (Figure 2.1) (Manu et al., 1991; Doumbia et al., 1993). Although soils may have acceptable total P contents, the quantity of plant-available P is often very limited, because the majority of soil P (70-90%), and the little P applied as inorganic fertilizer, is being fixed in the soil as non-available P for plants (Holford, 1997). An adequate supply of P is needed for flowering and seed production, uniform and early crop maturity, leaf expansion, shoot growth and increased resistance to plant diseases (Marschner, 1995). Application of P fertilizer is therefore important for increase crop growth and yield. Bationo et al. (2007) outlined some agronomic practices including combining of organic and inorganic fertilizer, crop rotation, intercropping, among others as sustainable management options for P deficient soils in WA.

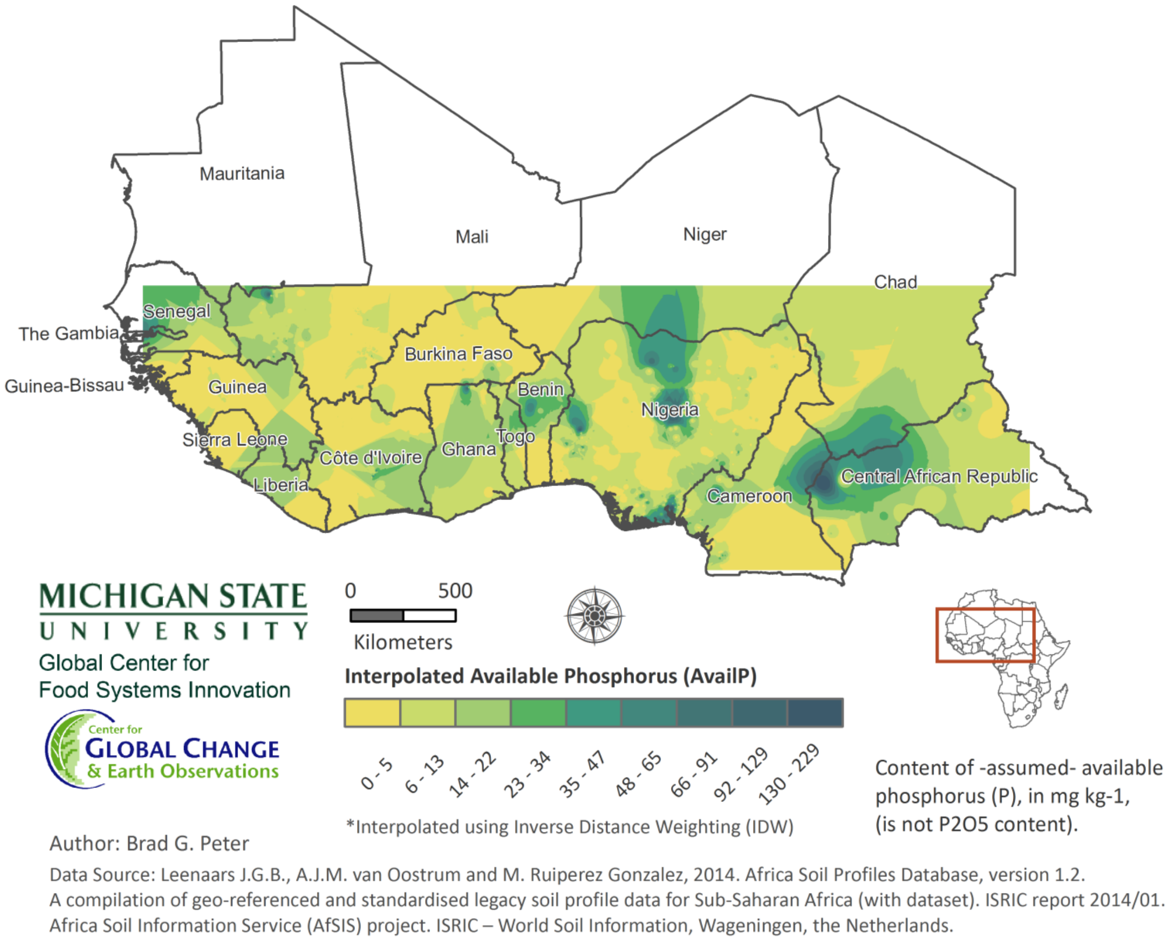

Figure 2.1 Soil phosphorus map for West Africa.

Pigeonpea, a leguminous crop with features that include multipurpose production of biomass above and belowground is known to increase the total plant available phosphorus (P) pools in cropping system because of its deep rooting system, and potential ability to access sparingly soluble P sources (Ae et al., 1990; Ishikawa et al., 2002; Subbarao et al., 1997). The plant grows well in the P-deficient soils of the tropical environment (Fujita et al., 2004) and has a low critical requirement of P concentration for dry matter production compared to other major protein crops like soybean (Adu-Gyamfi et al., 1990).

However, there is also some evidence of low biomass production of pigeonpea grown on low P soils (Adu-Gyamfi et al., 1990; Fujita et al., 2004). Plants differ greatly in their ability to grow on soils with low P status and respond to P inputs. These differences are related to the efficiency of plants to take up and use soil P (Buresh et al., 1997). In pigeonpea, large genotypic differences exist in response to P uptake, and P-use efficiency (Fujita et al., 2004; Subbarao et al., 1997; Vesterager et al., 2006).

Sorghum is a staple crop and one of the important cereals for food security grown by most smallholder farmers in WA due to its adaption to low soil fertility (Leiser et al., 2012) and climate variability (Haussmann et al., 2012). However, limited soil phosphorus availability is a serious constraint to sorghum growth and development (Buerkert et al., 2001). Substantial increases in sorghum biomass and grain yield following the addition of N and P fertilizers have been reported (Buah et al., 2012; Hussein and Alva, 2014; Zaongo et al., 1997); however due to socioeconomic constraints, P-fertilizer use by most smallholder farmers in WA is among the lowest in the world (Gemenet et al., 2016; Nwoke et al., 2004).

Farming systems in the region have evolved from the traditional fallow system to a more intensified continuous cultivation of a piece of land due to rapid population growth, demand for agricultural commodities and pressure on natural resources. This has resulted in loss of soil fertility over the period, as there has been little investment by farmers in nutrient amendments such as fertilizer or manure (Sanchez et al., 1997). Continuous cultivation with few or no external inputs depletes soil nutrients resulting in low nutrient balances (Braimoh and Vlek, 2004; Smaling et al,, 1997). Sustaining food crop production now requires more system diversification and improved soil management strategies.

The sequence and arrangement of crops cultivated is one of the chief means by which farmers can achieve efficient use of natural resources to provide stable and high-returns. Further, the combinations of crops must be ecologically sustainable. Incorporation of legumes into cropping systems is an ideal approach because component crops have contrasting maturities and functions, leading to complementary resource use (Willey and Reddy, 1981). Legumes have symbiotic relationships with bacteria that often result in biological nitrogen fixation, replenishing nitrogen in an available form. Intercropping systems are complex, and have been investigated in great detail for their effects on soil fertility improvement, yield stability, improved diet, food security and income (Chikowo et al., 2004; Adjei-Nsiah et al., 2007; Kerr et al., 2007, Zhang et al, 2008, Myaka et al., 2006, Ghosh et al, 2006).

Efficient resource use in intercropping system leading to overall yield increase is widely established (Kimaro et al., 2009; Tobita et al., 1994; West and Griffith, 1992; Zhang and Li, 2003). In spite of this yield advantage, other studies have reported probable yield suppression due to competition for soil nutrients and or soil moisture. For example, maize intercropped with pigeonpea in semi-arid conditions led to similar or less yield than sole cropped maize (Chikowo et al., 2004; Rao and Mathuva, 2000; Snapp et al., 2002). Also, millet intercropped with cowpea resulted in a significant grain yield reduction of intercropped millet compared to sole cropped millet (Grema and Hess, 1994). Intercropped cowpea yield was not affected. This yield suppression may be due to depletion of available resources like water and soil nutrients by the legume at the expense of the cereal (Salako and Tian, 2003), or other factors such as plant population density, row arrangement or soil moisture deficit (Rao and Willey, 1983).

Most studies on cereal-legume association have reported minimal competition due to temporal separation of component crops in the association. Sorghum-pigeonpea is a classic example of temporal combination, in that it combines fast-growing sorghum with slow-growing pigeonpea which minimizes resource competition (Willey, 1990). Temporal separation exists in a sorghum-pigeonpea intercropping system, however results are often contradictory as both yield increase and suppression have been observed under these systems in different environments (Natarajan and Willey, 1980; Tobita et al., 1994; Willey and Reddy, 1981b). One study on the agronomic performance of sorghum-pigeonpea association revealed that intercropped pigeonpea suffered from considerable competition for light because of the vigorous growth of sorghum (Natarajan and Willey, 1980; Willey and Reddy, 1981b). In contrast, Tobita et al. (1994) reported competition for soil nutrients in a sorghum-pigeonpea intercropping system since total dry weight and grain yield at harvesting were lower in the intercrops than in sole crops. The competition between component crops was more evident in soil supplied with higher amounts of nitrogen. There is therefore evidence of both below and aboveground competition in a sorghum-pigeonpea system. The question here is which of these factors actually contribute to this competition.

To design optimal cropping systems leading to high yield, there is a need to understand the mechanisms involved in a sorghum-pigeonpea intercrop system and evaluate its performance under the low soil P conditions prevalent in farming communities across WA. The objective of the study was to evaluate sorghum/pigeonpea productivity under variable soil and weather conditions.

MATERIALS AND METHODS

Site description

Location: Field experiments were established under rain-fed conditions at four sites: two locations at the experimental field station of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Samanko (Sko), Bamako; one at the field station of the Institut d'Economie Rurale (IER) in Farako (Fko), both in Mali; and one location at the field station of the Savanna Agricultural Research Institute (SARI) in Wa, Ghana. Samanko (Sko) is situated about 25 km SW of Bamako, Mali (8°54′W, 12°54′N, 328 m). Farako is located about 388 km SW of Bamako (11° 12' 48.9"N, 5° 27' 16.7"W, 400 m). Wa is in the northwestern corner of northern Ghana 194.92 km (10° 03' N, 2° 30' W, 319 m).

Climate: The climate at Sko is typical of a Sudanean climate characterized by a unimodal rainy season (June-October), followed by a long, dry and cold (December-February) and hot (from March). The mean annual rainfall is about 1029 mm year^{-1} (15-yr, ICRISAT-Mali). Mean monthly maximum and minimum temperatures during the growing season are 38°C and 24.7°C for 2015, and 37.9°C and 26.0°C for 2016, respectively (Table 2.1). Fko on the other hand, has a climate of a humid environment characterized by a unimodal rainy season. The mean annual rainfall is 1130 mm year^{-1}. Mean monthly maximum and minimum temperatures during the growing season are 34.7°C and 24.2°C for 2015, and 34.4°C and 23.6°C for 2016, respectively (Table 2.1). The Wa site has a climate typical of Sub-humid tropics with a relatively longer rainfall season (May-November), with average rainfall of 1055 mm year^{-1} (15-yr, MoFA-Wa).

The mean monthly maximum and minimum temperatures during the growing season are 26.6°C and 21.2°C for 2015, and 26.3°C and 21.1°C for 2016, respectively (Table 2.1).

Soils: The two sites at Sko varied in soil fertility, one being low phosphorus (LP) and the other high phosphorus (HP) (Table 2.2). Soils at Sko are light, generally sandy loam and of a tropical ferruginous washed-type (Sivakumar et al., 1984). SkoLP site is a well-drained sandy loam soil, which is low in fertility and available phosphorus. This site soil phosphorus status is a representative of many smallholder farmers' fields in West Africa (Bationo et al., 1998). On the other hand, the SkoHP site was also a sandy loam with medium fertility and high levels of phosphorus. The soils in SkoHP were often saturated after rain events, with waterlogging in some parts of the field (personal observations). These soil types are two important soil types in Mali (Rattunde et al., 2013). Fko also has soils of the ferruginous washed-type, with predominance of sands. The site was characterized as sandy loam with high fertility and relatively high levels of phosphorus. The predominant soil types in the region are classified as acidic Acrisol (FAO, 2001). The experimental site had been under fallow for 2 years. The Wa experimental site was characterized as a well-drained sandy loam soil with moderate fertility (Table 2.2). The soil had moderate levels of available phosphorus, with gravel being present deep in the soil profile (personal observations). The predominant soil types in the Wa region are described as Ferric Lixisols and Luvisols (FAO, 2001).

Experimental design

All four experiments were laid out in the same manner, following a randomized complete block design with 4 replications. The treatments consisted of sole, intercropped, and ratooned cropping systems with sorghum and pigeonpea for a total of fourteen (SkoLP), ten (SkoHP), and twelve (Fko and Wa) treatments represented at all four sites. The treatments are shown in Table 2.3. They comprised of five cropping system treatments with different growth types of pigeonpea: three sole crop systems, sorghum (SG), medium duration pigeonpea (PP MD) and long duration pigeonpea (PP LD); and two intercrop systems, sorghum/pigeonpea (SG/PP MD), sorghum/pigeonpea (SG/PP LD), sorghum-pigeonpea rotations with MD and LD.

Planting materials

The crops planted were sorghum and pigeonpea. Two varieties of pigeonpea were planted; ICEAP 00557 (MD, 153 days) and ICEAP 00982 (LD, 207 days) (Table 2.5). The sorghum variety planted was Fadda, a high yielding commercial hybrid variety grown by farmers in the region (Rattunde et al., 2013). The pigeonpea ICEAP 00557 seeds were sourced from ICRISAT- Nairobi (The variety was released in Malawi, Tanzania and Mozambique) and ICEAP 00982 and sorghum from ICRISAT-Bamako. Perennial sorghum was sourced from Georgia and Kansa (Stan Cox) while the perennial pigeonpea was a landrace harvested at Sotuba in Bamako. MDP variety is short-statured, compact and bushy. It has dark green leaves, reddish flowers and sensitive to insect attack. The pigeonpea LD is a tall variety with light-green leaves and yellowish flowers. It has some tolerance to pest attack compared to the MD variety. Fadda is a tall variety (2-3 m), with thin stem and matures in 131 days. It is a commercial hybrid seed.

Plant population density

The plant population density that was aimed for in this field experiment for sole sorghum and pigeonpea was 88,000 and 44 000 per ha, respectively (Table 2.6). The planting pattern for sorghum and pigeonpea in the intercrops was a 2:1 in-row substitutive design. This plant population for sorghum was based on recommendations from crop scientists at ICRISAT-Mali (Rattunde et al., 2013; Rattunde et al., 2016) whereas the pigeonpea plant density was adapted from recommendations used in southern Malawi (Snapp et al., 2002). The goal was a modified substitutive design, with reduced plant population of pigeonpea to achieve a combined intercropped plant population density almost similar to a sole cropped sorghum. The plant population density goal for the intercrop system was sorghum and pigeonpea at 44 000 and 22 000 plants/ha, respectively (Table 2.6). As shown in the table, the plant population densities achieved in the field experimentation were close to the target goals.

Planting

Land preparation was done manually for the SkoLP, Fko sites (hand-hoe ridges) and Wa site (hand-hoe flat). SkoHP was ploughed to approximately 25 cm depth with a tractor (moldboard plow and cultivated). The Fko trials were planted earlier, 1st and 6th July in 2015 and 2016 respectively. The Sko trials followed on 8 and 9th of July in 2015, and 9 and 10th of July in 2016. Wa was planted later, 17 and 24th of July in 2015 and 2016 respectively. Sole sorghum and pigeonpea were planted at a spacing of 30 cm x 75 cm and 60 cm x 75 cm, respectively with two plants per hill to achieve a plant population density of 88,000 and 44 000 per ha, respectively (Table 2.6).

The planting pattern for sorghum and pigeonpea in the intercrops was a 2:1 in-row substitutive design. Pigeonpea in intercropped plots were thinned to one plant per hill at all locations. The goal was a modified substitutive design, with reduced plant population of pigeonpea to achieve a combined intercropped plant population density similar to a sole cropped sorghum. The plant population density of sorghum and pigeonpea in the intercrops were 44 000 and 22 000 plants/ha, respectively (Table 2.6). SkoLP, SkoHP and Fko had treatment plot sizes of 6 m x 7.5 m with 8 rows. Wa had 4.5 m x 6 m with 6 rows. Plot size was reduced in Wa due to land availability.

Crop management

Weeds were controlled by using a hand hoe at three different times after planting. Insect pest damage on pigeonpea plants were controlled at 2-week intervals from the start of flowering to maturity by using K-optimal, a systemic insecticide (Lambda-cyhalothrine 15 g/l +Acetamipride 20g/l; EC) in spraying the plants. The usual amount sprayed was 50 ml/knapsack. Insect pest damage was still evident even with this consistent spraying. Pigeonpea has little genetic resistance to a wide range of pod-boring and flower-feeding insects, which poses a significant challenge to designing effective pest management strategies and is a persistent barrier to broader adoption of this crop (Kaoneka et al., 2016).

SkoLP field was supplied with compost at 3 tons/ha, on dry weight basis. This was the only nutrient application at SkoLP, as this site was chosen for soils that are representative of on-farm environments in Mali, which are highly nutrient depleted. A basal dose of diammonium phosphate (DAP) at 100 kg fertilizer/ha to supply 18% of N and 46% of phosphate-P was applied to the plots at SkoHP, Fko and Wa. As well, a side-dress of urea was applied at 50 kg/ha (23% N) after the second weeding. Fertilizer was applied to all plots on the field.

Rainfall and temperature

The source for rainfall and temperature in Sko and Wa was from General Research-Grade Weather Station (GRWS100, Campbell Scientific, Inc.), installed by ICRISAT-Mali in 2014. Rainfall guage was used at Fko.

Field observations and measurements

Plant growth

Days to 50% flowering: Number of days from emergence until 50% of the plants in a plot had at least one open flower. This was done by tagging 10 plants and when 5 were seen with open flower was recorded as days to 50% flowering.

Days to physiological maturity: Number of days from emergence until 75% of the pods/panicles in a plot turned brown (straw color). This inspection was made on three consecutive times (every two days) of the entire plot, and average of the three dates represents the number of days.

Plant height: Plant height was measured from the base of the plant to the tip of the main stem. Measurements were taken at about 50% flowering and physiological maturity on three randomly selected plants per plot, and the average represented the plant height for that plot.

Chlorophyll content: Leaf chlorophyll measurements were taken at the vegetative, flowering and physiological maturity stages of plant growth. Pigeonpea leaves are trifoliate compound with the central leaflet longer than the lateral ones; therefore, the measurement was taken on the central leaflet. Three readings were taken on upper, middle and lower branches of each pigeonpea plant using the atLEAF Chlorophyll meter (FT Green LLC, Wilmington, DE), for three plants per plot. In the case of sorghum, readings were taken from the youngest fully developed leaf on three plants in a plot. Three plants were sampled for pigeonpea and sorghum. The average of the three readings was determined for each plant species per plot.

Total dry matter and grain yield at harvest

The mature pigeonpea pods (brown-colored) were harvested by handpicking the pods as described by (Chauhan et al., 1987). The pigeonpea plant requires close observation during the maturity stage to ensure the mature pods can be harvested on time. This challenge was addressed through multiple observations on a weekly basis and multiple harvests of pigeonpea (when pods are brown-colored). However, it was difficult in some cases to prevent insect attack as described earlier, and some pods had no grain. Poor grain formation was observed in all four experimental sites. Sorghum was harvested by cutting the panicles of the grain with machetes.

Plants were harvested from a net plot of 5.4 m^2 (4 rows x 6 hills starting from the midpoints of the plot) for yield assessment for intercropped sorghum/pigeonpea and sole sorghum, then 7.2 m^2 for pigeonpea, respectively. Before harvesting, the number of plants and panicles in the sampled area were counted. The plants were cut and separated into leaves, stems and panicle/pod. Fresh weight of the leaves, stems and panicle/pod were taken. A subsample was taken from the various components and weighed separately. The subsampled stems and leaves were tied with a rope and dried at air temperature for 2 to 3 weeks before taking the dry weight. Finally, total aboveground biomass was determined and expressed in kg ha^{-1}. For determining grain yield, subsampled panicles/pods were put in muslin cloth bag and dried at air temperature for 2 to 3 weeks. Grain moisture was determined by wet weight basis of air dried subsample of grain. Grain moisture was adjusted at 12% moisture for sorghum and pigeonpea.

Yield components: A sample of 100 seeds was taken from yield of each plot, sorted out and counted. This was weighed using a weighing balance to determine 100-seed weight. Harvest index was calculated as the ratio between grain weight and total aboveground biomass at harvest in each plot.

Ratooning

This practice allows multiple harvesting from a single planting and it is done by cutting the plant at a particular height. Both sorghum and pigeonpea treatments used for this observation were ratooned at a cutting height of 30 cm above soil level. The cutting in pigeonpea was done such that a couple of leaves were left on the stem to enhance continuity of growth. At the end of the 2014-cropping season, the first ratooning was done. The sorghum plants ratooned at 30 cm had very bad regrowth compared to the sorghum plants cut at the base (ground level) after harvesting in 2014. Due to this observation, all ratooned sorghum plants were cut at the base after the final harvesting in 2015. Also, only MD pigeonpea plants were ratooned for the second time, the LD plants were not ratooned.

Soil sampling and analyses

Soil profile samples were taken to assess profile conditions, and variability across the field, at all four experimental fields (SkoLP, SkoHP, Fko, and Wa). To monitor the soil profile, soil pits were dug to a depth of 120 cm in June. Samples were taken at depths of 0-15 cm, 15-30 cm, 30-60 cm, 60-90 cm, and 90-120 cm. At each depth, soil samples were taken from the side of the pit where there was no disturbance, e.g., along the side with little or no influence from land cultivation. Additional samples were taken from three random points in each replicate block using a soil auger of 3 cm in diameter at the following depths: 0-15 cm, 15-30 cm and 30-60 cm, and composited by depth and block. These samples provided information on soil variability across the site. All soil samples were sieved (2 mm) at the ICRISAT Agronomy Lab in Bamako, Mali, then samples were air-dried, and subsamples of 100 g sent to the Snapp lab (Michigan State University) for grinding, and physical and chemical analysis as follows.

*Soil texture***:** The hydrometer method was used to determined soil texture at the Snapp lab, dispersed and based on the principle of sedimentation (Stokes' Law) using a ASTM 152H-Type hydrometer) (Gee and Bauder, 1986).

Soil pH: The pH was determined using the 1:5 soil water suspension method (Department of Sustainable Natural Resources, 2013), with a Metler Toledo SevenEasy S20 pH meter.

Total soil nitrogen and carbon percent: Dry soil subsamples were ground to pass a 1 –mm sieve in a shatter mill. The ground soils were weighed on a microbalance into tin capsules for total C/N content analysis, which was determined by combustion. A Costech ECS 4010 combustion analyzer (Department of Forestry, MSU) was used.

The remaining of the soil samples were sent to the A and L Great Lakes Laboratories, Fort Wayne, IN for analysis of the following: available P, SOM and CEC using the Mehlich III procedure. Available phosphorus and exchangeable cations were extracted according to Mehlich III (Mehlich, 1984), and analyzed by inductively-coupled plasma spectrometry (ICP) in which the sample was excited in an argon plasma and the elements of interest were detected by a mass spectrometer. The P data were then correlated to and reported as Bray P-1 (Bray and Kurtz, 1945). The data for exchangeable cations were correlated to and reported as a 1N ammonium acetate extraction (McIntosh, 1969). CEC were calculated from the results for exchangeable cations. Organic matter was determined by loss on ignition at 360°C and the data correlated with and reported as Walkley–Black titration.

Land Equivalent Ratio (LER)

Performance of the intercrop systems was evaluated using Land Equivalent Ratio (LER) as described by Willey (1979):

$$\text{LER} = L_a + L_b = \frac{Y_a}{S_a} + \frac{Y_b}{S_b} \qquad \text{Equation 3}$$

where: LER = Land equivalent ratio; L_a and L_b are LERs of component crop a (sorghum) and b (pigeonpea); Y_a and Y_b represent intercrop yield component crop a (sorghum), and b (pigeonpea), respectively, S_a and S_b are their respective sole.

Statistical analysis

Data were analyzed using PROC MIXED. Cropping systems were modeled as fixed effects, and year, site, and replicates as random effects (SAS Institute Inc. Base SAS® 9.4, 2013). Cropping system effect on yield was tested using one-way ANOVA. Sorghum-pigeonpea intercropped system was compared to sole cropped sorghum to assess performance of the two cropping systems, using a planned contrast. This tested directly hypothesis 3. For hypothesis 4, long and medium duration pigeonpea as sole or intercrop were compared through a planned comparison to test how the growth habits interact with the cropping system to influence yield, then planned contrast were used to identify differences between the growth habits. Three-way ANOVA was used to test effect of year, site and cropping systems on yield. T-test was used for all pairwise comparisons and significance differences among treatment means were separated using LSD at 5% level of significance. Results were presented in tables and graphs. Graphs were created using SigmaPlot version 12.5.

RESULTS

Rainfall and temperature

The rainfall distribution during the 2015 and 2016 growing period is presented in Figure 2.2 and 2.3. The total rainfall recorded during 2015 year for Sko was 1080 mm, which was higher than the long-term (2000-2014) rainfall average of 1029 mm/yr at the Sko experimental site (ICRISAT-Mali, climatic database 2014). Most of the rainfall events occurred during July-August at Sko which accounted for 55% of the total rainfall recorded in 2015 year. Fko had the highest rainfall of 1288 mm in 2015, which was well distributed. The month of August received the most rainfall event accounting for 34% of the total rainfall recorded. Wa however, had very low rainfall in 2015 (727 mm), and it was not well distributed over the growing season as major rain events were recorded in September 2015. Sufficient rainfall was thus present during the flowering stage; however, the year overall was dry compared to the long-term average of 1055 mm/yr (Wa MoFA climatic database 2014).

In 2016, rainfall was unevenly distributed, but similar to long-term averages with 1184 mm recorded through the year at Sko, 1278 mm at Fko, and 851 mm at Wa. The highest rainfall at Sko occurred in August, which accounted for 35% of the total rainfall recorded during the year. Likewise, at Fko July received the highest rainfall, which accounted for 30% of the total rainfall. The major rainfall event at Wa was however recorded in May before sowing (Figure 2. 3).

Mean maximum and minimum temperatures at Sko and Wa for the 2015 and 2016 year were monitored at automatic weather stations. Temperatures for Fko were sourced from NASA (Table 2.1). The average temperature ranged from 38.0 °C to 24.7 °C at Sko, 34.7 °C to 24.2 °C at Fko, and 33.8 °C to 23.1 °C at Wa during the 2015 year. Mean temperatures in 2016 were slightly lower in comparison with 2015 (Table 2.1).

Soil physical and chemical properties

Table 2.2 presents the physical and chemical properties of soils of the experimental sites. The soils were coarse across sites, particularly in the topsoil (72 to 84% sandy) and the Sko and Fko sites was acidic (pH from 5-6), whereas the Wa site was neutral (pH = 7). The soil organic carbon (SOC) status was low at all sites, from 0.23% to 0.5% in the topsoil, and similar SOC levels were observed in the subsoil. Cation exchange capacity was high at the 60 cm depth across all sites.

Total inorganic phosphorus content was high at SkoHP (30 ppm in the topsoil), as excepted this site was managed through fertilizer amendment to provide sufficient soil P for cereal production, and the SkoLP site was about half this level. Fko had relatively high phosphorus content at 20.8 ppm, which decreased with depth to 4 ppm. The lowest phosphorus content was at the Wa site, which also decreased with depth to 1 ppm (Table 2.2).

Pigeonpea growth and development

Number of days to 50% flowering and 75% physiological maturity

Overall, days to 50% flowering and 75% maturity were significantly different between cropping systems, sites and year (Table 2.7). Sole pigeonpea MD and intercropped pigeonpea MD both reached 50% flowering in 80 and 84 days respectively and was different from sole pigeonpea LD (122 days) and intercropped pigeonpea LD (124 days) cropping systems.

The significant year effect was due to plants reaching 50% flowering earlier in 2015 (102 days) in comparison to 2016 (103 days). Plants at Fko reached 50% flowering earlier in 81 days which was significantly different from Wa (101 days), SkoLP (113 days) and SkoHP (117 days), resulting in significant site effect. The LD pigeonpea variety was significantly different from the MD variety.

As expected, MD pigeonpea reached 75% physiological maturity at 151 and 155 days much faster than the LD pigeonpea at 206 – 208 days. Plants in 2015 (176 days) reached physiological maturity significantly earlier compared to 2016 (184 days). The pigeonpea plants growing at Wa reached physiological maturity earlier in 146 days which was significantly different from Fko (186 days), SkoHP (193 days) and SkoLP (194 days).

Plant height

Pigeonpea height was measured at the flowering and physiological maturity growth stages; however, data was very similar at both stages and only the physiological maturity stage data is reported. Plant height was affected by plant growth habit, cropping system and site.

The LD pigeonpea variety grew taller in both the sole (2.6 m) and intercrop (2.5 m) cropping systems than the MD variety (Figure 2.4). The Fko site had tall plants (2.2 m) which was different from SkoHP (1.9 m), SkoLP (1.8 m) and Wa (1.7 m). Intercropping did not affect plant height significantly (Figure 2.4).

Chlorophyll content

Pigeonpea chlorophyll content at physiological maturity was significantly influenced by cropping system, site and year, but data is not presented. There was also significant site and year, and significant cropping system by site and year interactions. Cropping system was significant, where cropping systems with the MD pigeonpea variety had high chlorophyll (59) in comparisons with the chlorophyll content (55) of the LD variety cropping systems. The observed variation between the MD pigeonpea variety and the LD variety is due to their differences in leaf color. The MD pigeonpea variety has a very dark green leaf whereas the LD variety has a light green leaf.

Pigeonpea grain yield

Pigeonpea grain yield produced at final harvest was low at all sites, with the exception of Fko. The effect of cropping system will only be considered for this site, as the other sites had grain yields that were below 300 kg ha^{-1}, and so clearly not adapted to these environments and so not a meaningful test of cropping system (Table 2.8).

The cropping system by year interaction resulted from the high grain yield produced by sole pigeonpea LD in 2015 (1090 kg ha^{-1}) and intercropped pigeonpea MD in 2016 (1007 kg ha^{-1}) which was 5 times higher than grain yield produced by sole pigeonpea MD in 2015 (183 kg ha^{-1}) and 2016 (208 kg ha^{-1}). There was also significant cropping system by site and year interactions which was due to first, the significantly high grain yield production from sole pigeonpea LD in 2015 (4193 kg ha^{-1}) and intercropped pigeonpea MD in 2016 (3551 kg ha^{-1}) at Fko, then the lowest grain yield from intercropped pigeonpea MD (21 kg ha^{-1}) in 2015 at SkoHP and intercropped pigeonpea LD (20 kg ha^{-1}) in 2016 at Wa. Intercrops were not significantly different from sole crops. The LD and MD pigeonpea variety yields were too variable to detect significant differences.

100-seed weight

Cropping system influenced seed weight (Table 2.8). Sole pigeonpea LD had significantly the highest average grams of 100-seed weight (10.9 g) which was different from other cropping systems. The lowest weight was achieved by intercropped MD pigeonpea with a mean of 8.2 g. Intercrops were significantly different from sole crops. Likewise, the LD pigeonpea variety was significantly different from the MD variety (Table 2.8).

The 2016 (9.6 g) year produced significantly higher seed weight in comparison with 2015 (8.8 g) year. There were no significant interactions. Site had a significant effect whereby, Fko produced significantly the highest seed weight of 12.0 g which was significantly different from SkoHP (8.8 g), SkoLP (8.2 g) and Wa (7.8 g).

Overall, pigeonpea HI was very low across sites. Fko was the only site with a reasonable HI of 16.1%. Data is not presented.

Pigeonpea biomass

Total aboveground biomass production at final harvest was significantly influenced by cropping system, site and year (Table 2.8). Significant interactions were found between site and year, cropping system and year, as well as cropping system, site and year.

Cropping system effect was a result of the significantly higher biomass produced by sole pigeonpea LD (6168 kg ha^{-1}) compared to 2883 kg ha^{-1} in the intercrop system with sorghum. The lowest aboveground biomass was produced by intercrop pigeonpea MD (2022 kg ha^{-1}). The LD pigeonpea variety produced significantly higher aboveground biomass compared to the MD pigeonpea variety. Intercrops were significantly different from sole crops.

Total biomass produced in 2015 (4382 kg ha^{-1}) was significantly higher in comparison with 2016 (2921 kg ha^{-1}) year. Over the two years (2015 and 2016), biomass production at Fko (5104 kg ha^{-1}) was higher followed by SkoHP (4070 kg ha^{-1}). These two sites were significantly different from SkoLP (3004 kg ha^{-1}) and Wa (2430 kg ha^{-1}). The significant site by year interaction resulted from the high biomass production at Fko in 2015 (7843 kg ha^{-1}) which was twice the biomass produced at the other three sites. The lowest biomass was produced by Wa (2081 kg ha^{-1}) in 2015 and SkoLP (2015 kg ha^{-1}) in 2016. There was significant cropping system by year interaction whereby, sole pigeonpea LD in 2015 (8079 kg ha^{-1}) produced twice the biomass produced by all cropping systems. In contrast, intercropped pigeonpea MD produced the lowest biomass in 2016 (1731 kg ha^{-1}) year.

Finally, the significant cropping system by site and year interaction resulted from first the significantly high biomass production from sole pigeonpea LD at Fko (16091 kg ha^{-1}) in 2015, then secondly the lowest biomass from intercropped pigeonpea LD (765 kg ha^{-1}) and intercropped pigeonpea MD (844 kg ha^{-1}) at SkoLP in 2015 and 2016, respectively.

Sorghum growth and development

Number of days to 50% flowering and 75% physiological maturity

Days to 50% flowering were significantly different between cropping systems, sites and year (Table 2.9). Cropping system significantly affected days to 50% flowering. Sorghum/pigeonpea intercropped (MD) reached 50% flowering earlier in 80 days and was significantly different from sole sorghum (83 days) and sorghum/pigeonpea intercropped (LD) (82 days) cropping systems. Intercropping enhanced early flowering but showed no significant differences (Table 2.9). The significant year effect was due to plants reaching 50% flowering earlier in 2015 (76 days) in comparison to 2016 (87 days). Plants at Wa reached 50% flowering earlier in 72 days which was significantly different from the other three sites.

Days to 75% physiological maturity were influenced by cropping system, site and year (Table 2.9). There were no observed significant interactions. Sorghum/pigeonpea intercropped (LD) reached maturity in 130 days and was different from the other two cropping systems. Intercropped systems reached maturity earlier than sole sorghum but with no significant differences.

Plants in 2015 (127 days) reached physiological maturity significantly earlier compared to 2016 (135 days). The sorghum plants growing at Wa reached physiological maturity earlier in 105 days which was significantly different from Fko (118 days), SkoLP (136 days) and SkoHP (166 days).

Plant height

The growth of sorghum in terms of height was measured at both the flowering and physiological maturity stages (Figure 2.5). However, the growth trends stayed consistent and results were presented for the physiological maturity stage. Plant height was affected by cropping system, site and year, but with modest differences (2.6 to 2.8 m). In 2015, plants grew taller (2.8 m) than the 2016 (2.6 m) year. The significant site by year interaction resulted from the plant height at SkoHP and Fko (2.8 m) in 2015, whereas short plants were observed at SkoLP in 2015 (1.9 m) and 2016 (2.0 m) (Figure 2.5).

Chlorophyll content

Sorghum chlorophyll content was not affected by cropping system. The only factors that influenced chlorophyll content were year and site. Data is thus not reported here.

Sorghum grain yield

Sorghum grain yield was significantly influenced by cropping system, site and year (Table 2.10). Sole sorghum produced significantly the highest grain yield of 2194 kg ha^{-1} which was different from 1726 kg ha^{-1} and 1634 kg ha^{-1} produced by intercropped sorghum/pigeonpea (MD) and intercropped sorghum/pigeonpea (LD) respectively. Yields were significantly higher in 2016 (1962 kg ha^{-1}) in comparison with 2016 year (1741 kg ha^{-1}).

Over the two years, grain yields from the four sites were different, with SkoHP (2940 kg ha^{-1}) producing high yields, followed by Fko (1710 kg ha^{-1}) and Wa (1530 kg ha^{-1}). SkoLP produced the lowest yield of 1230 kg ha^{-1}. Likewise, the significant site by year interaction was due to the low grain yield produced at SkoLP (480 kg ha^{-1}) in 2015. High yield was produced by sole sorghum (5059 kg ha^{-1}) at SkoHP in 2015, and low yields were produced by sorghum/intercropped (MD and LD) at SkoLP (400 kg ha^{-1} and 300 kg ha^{-1}, respectively) in 2015 and from sorghum/intercropped (LD) at Wa (490 kg ha^{-1}) in 2016.

100-seed weight

Unlike pigeonpea, sorghum seed weight was not affected by cropping system (Table 2.10). The only factor which influenced seed weight was site, and there was a site by year interaction. The average seed weight pooled over the two years (2015 and 2016) was 2.0 g. This seed weight of 2.0 g is consistent with the 2.1 g seed weight generally observed for the Fadda variety (IER-ICRISAT, 2015). The site effect resulted from the high seed weight produced at the SkoHP (2.2 g) site relative to SkoLP (2.1 g), Fko (2.0 g), and the lowest seed weight was produced at Wa (1.6 g). It appears that the low seed weight at Wa was due to the lower grain yield production in 2016 and also the short growing season which affected grain filling. Sorghum HI was not affected by cropping system and data is not reported.

Sorghum biomass

All factors with the exception of year affected biomass accumulation in sorghum (Table 2.10). Sole sorghum had high biomass (7720 kg ha^{-1}), compared to intercropped sorghum/pigeonpea (MD) (6110 kg ha^{-1}) and intercropped sorghum/pigeonpea (LD) (5830 kg ha^{-1}). The main site effect observed was due to the high biomass of 8700 kg ha^{-1} and 7780 kg ha^{-1} respectively, produced at Wa and SkoHP, which were greater than Fko (6330 kg ha^{-1}), and the very low biomass at the SkoLP site (3400 kg ha^{-1})

There was significant site by year interaction, which resulted from the significantly high biomass produced at SkoHP (10059 kg ha^{-1}) and Wa (9345 kg ha^{-1}) in 2015 then the lowest at SkoLP in 2015 (1793 kg ha^{-1}) and 2016 (5012 kg ha^{-1}). Likewise, the significant cropping system by site and year interaction resulted from firstly, the significantly high biomass produced by sole sorghum (14156 kg ha^{-1}) at SkoHP in 2015, then secondly, the lowest biomass from sorghum/intercropped (MD and LD) at SkoLP (1463 kg ha^{-1} and 1195 kg ha^{-1}, respectively) in 2015, and from sorghum/intercropped (LD) at SkoHP (4134 kg ha^{-1}) in 2016. Intercrops were significantly different from sole crops (Figure 2.6).

Land Equivalent Ratio (LER)

The biomass productivity of the intercrop system was evaluated using LER. Site and site by year interaction were the only significant factors observed (Table 2.12). LER at each site was greater than 1.0. The Fko and Wa sites (2.00 and 1.88, respectively) had significantly larger LER than the SkoLP (1.12) and SkoHP (1.08) sites.

All the cropping systems across sites had LER greater than 1.0 except, sorghum/pigeonpea MD at SkoHP. Even though, cropping system showed no significant differences, numerically the sorghum/pigeonpea MD (1.58) intercropping system had a higher LER than sorghum/pigeonpea LD system (1.45).

Relative yields of sorghum ranged from 0.55 to 1.21 and 0.33 to 1.18 for pigeonpea. The Fko and Wa sites were significantly different from the Sko sites for both crops. From the results, it seems sorghum biomass was the main determinant of LER (Table 2.12).

Ratoon performance

Most of the ratooned plants could not survive the dry season (Table 2.13). However, the few that survived were large and productive. The Fko site had the overall highest number of ratooned plants. The overall grain yield from ratooned pigeonpea was 2260 kg ha^{-1} (Table 2.15). The year variation was mainly due to the number of plants that survived till final harvesting. The intercropped pigeonpea LD variety produced the highest grain yield, whiles the MD pigeonpea produced the lowest grain yield (Fig 2.7). Grain yields from ratooned pigeonpea were high at Fko.

Biomass production of ratooned plants was high across site, with an overall yield of 15,250 kg ha^{-1} (Table 2.15). The perennial pigeonpea at SkoLP produced the highest biomass yield of 87,028 kg ha^{-1} (Table 2.15). There was significant site by year interaction. Ratooned pigeonpea plants grew taller across site with an average height of 2.5 m. Sorghum regrowth only occurred at Farako. The highest grain and biomass yields were produced by ratooned sole sorghum (Table 2.14).

DISCUSSION

Pigeonpea growth and development

The sites selected for this study includes both Sahelian-Sudano and Guinean regions of West Africa. The soil and weather conditions during the crop growth varied considerably among the sites and seasons to cause large differences in yield, biomass and other parameters evaluated.

Pigeonpea phenology is influenced by a combination of factors such as photoperiod, temperature, rainfall, location, season and time of sowing (Carberry et al., 2001; Omanga, et al., 1995; Ram et al., 2011; Silim et al., 2006). The differences in these factors therefore led to the observed variations in days to 50% flowering and days to physiological maturity between the pigeonpea varieties and the studied sites. Rainfall at Fko may have contributed to early flowering period which accelerated flower initiation. This site variation in days to flowering is reported by Silim et al. (2006).

Flowering of the LD pigeonpea variety was a major problem especially at Sko and Wa. Most plants from these two locations had problems with flower bud initiation and pod set, resulting in low grain yield. Maturity duration is a major factor determining the adaptation of varieties to various agroclimatic areas and cropping systems (Sharma et al., 1981). Temperature may have been a factor affecting flowering of the LD pigeonpea variety as the prevailing temperatures at these locations range from 23-37°C. This is higher than the optimum temperature required for flowering in the long-duration types (Silim et al., 2006). Silim et al. (2006) have reported that pigeonpea in general tends to have specific and narrow adaptation. The medium duration types however, can have relative wide adaptability (Mligo and Craufurd, 2005).

Late sowing at Wa in both years due to research logistics shortened the growing period of pigeonpea plants. This agrees with the results of Ram et al. (2011). They observed a decrease in number of days to physiological maturity following delayed sowing at India. The mean days to physiological maturity obtained in this study for the MD pigeonpea (153 days) and LD pigeonpea (207 days) compared favorably with the broad maturity classification of medium (155 days) and long (>180 days) (Reddy, 1990a). Flowering pattern was indeterminate whereby flowers were borne in auxiliary buds of all branches of the plants and with longer flowering duration. Flower color was red for the MD pigeonpea and yellow for the LD pigeonpea varieties.

Plant height

Plant height in pigeonpea is affected by maturity duration, photoperiod, and environment (Reddy, 1990a). The significant differences between the LD pigeonpea variety and the MD variety may be attributed to maturity duration as LD varieties are generally tall, because of their prolonged vegetative phase, while short-duration or early-maturing are comparatively short in stature (Reddy, 1990a).

In the present study, plant height was influenced by the rainfall and soil nutrient status in the growing environment. Based on rainfall, the studied sites can be classified as high (Fko), medium (Sko) and low (Wa). All the sites, with the exception of SkoLP received fertilizer addition. SkoLP was a low phosphorus farmer-field representative site, recorded relatively the shortest plant height. The favorable effect of phosphorus application on plant height has been reported previously (Kumar et., 2012; Singh et al., 2016). Fko, the high rainfall site recorded the overall tallest height which was comparable to the 1.5 - 2.0 m height range for pigeonpea

(Reddy, 1990a). Intercropping did not influence plant height. The decrease in the overall intercrop plant height may be due to the inherent short plant height of the pigeonpea MD variety.

Pigeonpea yield and yield component

Pigeonpea yield reduction under intercropping systems is common in smallholder farming communities in Africa and these have been attributed to a number of factors. Firstly, the yield reduction is due to lack of adapted varieties specifically to intercropping and rainfall variability (Nguluu et al., 2014; Saxena et al., 2018). Secondly, the little understanding of pigeonpea growth and development under different cropping systems and major or micro environmental stresses could also be a factor (Saxena et al., 2018). Plant breeders are still working towards finding an ideal pigeonpea plant type that would perform efficiently under different growing conditions. In the present study, we discuss the benefits associated with a sorghum-pigeonpea intercropping system in terms of grain and biomass yield, and land equivalent ratio. The study also highlights how both pigeonpea and sorghum can produce fodder for livestock feed without compromising grain yield of sorghum. This is particularly important as livestock are common in every household in the study area.

Grain yield

Pigeonpea grain yields in this study were extremely low across sites, with the exception of one site in one year. The reasons for the observed low yields are due to flower loss, poor pod set and poor seed quality due to how the pigeonpea varieties used in this study are poorly adapted to the study environments. Plant population density of pigeonpea recommended from Southern Africa resulted in low yields in this study; this may be due to the very low soil fertility status of the research sites, although fertility amendments were applied to address this. It is also possible that yields were suppressed due to temperature conditions, soil moisture or other climatic properties at these study sites. The production of pigeonpea is strongly dependent on the amount of rainfall and whether phenology matches the available soil moisture supply (Lawn and Troedson, 1990; Troedson et al., 1990). There is therefore need to improve pigeonpea adaptation through selection of varieties for West African environments.

100-seed weight

Seed weight is an important yield component and varies widely within varieties. The weight of 100 seed of pigeonpea ranges from 2.8 to 22.4 g. However, majority of varieties possess 100-seed weight between 7.0 and 9.5 g (Reddy, 1990a). Intercropping resulted in 1.2% increase in seed weight. This agrees with Ghosh et al. (2006), who reported a 9% increase in seed weight of intercropped pigeonpea.

Varietal differences in seed weight were observed in this study. The LD pigeonpea variety had an overall 100-seed weight of 9.9 g and 8.5 g for the MD variety. The high grain yield and seed weight from the LD pigeonpea variety can be attributed to its efficiency in translocating photosynthate to the reproductive parts hence higher yields. Biomass accumulation and photosynthate translocation are key factors to 100-seed weight (Robertson et al., 2001). This is also governed by yield components like plant height at maturity.

Total biomass

Biomass from combined species intercropping systems was 63% higher than in sole crop stands. However, separating the component species shows a reduced biomass accumulation of pigeonpea under the intercropping system relative to sole cropped pigeonpea. This was as expected due to competition between the two crops, but there was a lot of variability observed. The competition between component crops was more evident in the MD pigeonpea variety and soil with low amounts of available phosphorus. Tobita et al. (1994) have reported competition in a sorghum-pigeonpea intercropping systems in an Indian field study, where total dry weight and grain yield at harvesting was low in the intercrops compared to in sole crops.

Over the two years of the study, aboveground biomass was generally lower in the MD than in the LD pigeonpea variety. This was consistent across sites and years, with the exception of the adequate P status site SkoHP, where the two varieties produced similar biomass (about 5 t/ha). Favorable response of phosphorus application on pigeonpea growth has been reported (Kumar et., 2012; Singh et al., 2016). As indicated by Francis (2002) that varietal differences have great influence on the development and growth of pigeonpea. Also, the prolonged vegetative phase of the LD pigeonpea variety enhances its biomass accumulation. The MD pigeonpea variety is short-statured (1.1 m) and grows fast which may lead to low biomass accumulation.

Pigeonpea mean biomass production varied over the two years, 2015 produced 40% more biomass than 2016. The 2015 total seasonal rainfall across site was 48% lower than 2016 but it was evenly distributed. Overall, the Fko site had the highest biomass production, with Wa producing the lowest. The high biomass accumulation at Fko was supported by high rainfall, early planting, and a soil available P content at Fko, which was four times higher than that at Wa (Table 2.2). P stress at Wa may have contributed to the poor growth of pigeonpea at this site. It is also possible that there was a temperature effect, as Wa is a relatively cool environment, low rainfall site whilst Fko is a high rainfall, warm site. The overall planting dates at Wa was late due to research logistics, and as reported in previous studies this may well have reduced plant growth and development (Kumar et al., 2008).

Sorghum growth and development

Sorghum landraces in West Africa flower within 60-180 days after sowing and the growth duration is always related to the length of the rainy season. Photoperiod-sensitivity determines the triggering of the flowering time and modifies rates of development (Weltzien, 2014). The Fadda variety, when sown on July 1 flowers within 84-91 days after sowing depending on soil fertility (IER-ICRISAT, 2015).

In the present study, time required from planting to flowering and physiological maturity depended on planting date and prevailing environmental conditions at the growing sites. At Wa planting was late due to research logistics and this planting time was observed to shorten the growing length of sorghum. The sorghum plants growing at Wa flowered and reached physiological maturity earlier than at the other sites. The location and planting time had a major influence on growth phenology, as indicated by a reduction of by about one-third in time to flowering and maturity.

Plant height

The plant height of the *Fadda* variety is 2-3 m and the height of 2.7 m recorded in this study is in that range. Numerically, sorghum plants under the intercrop systems appeared to be slightly taller, however no difference was observed. The overall plant height from SkoLP site was reduced by 47% relative to SkoHP. This is consistent with other observations that low P fertility is associated with short stature sorghum plants, as shown in a field study by Leiser et al. (2012) who observed a reduction of 22% in sorghum plant height on P deficient soils in Mali.

Sorghum yield and yield component

Grain yield

Growth, development and yield of grain sorghum depend on environmental conditions such as temperature and rainfall (Prasad et al., 2008). Considerable variations in measured parameters were observed as the studied sites varied in total seasonal rainfall (789-1283 mm), duration of the rainy season (81-94 days) and mean temperature (23-38°C).

Overall, sorghum grain yield produced was below the yield potential of 4.5 t/ha for the *Fadda* variety. Mean grain yield over the two years was different, 2016 produced 53% higher yields than 2015. This yield variation appeared to be related to rainfall and sorghum midge damage. Total seasonal rainfall in 2016 was 52% higher than 2015. Also, in 2015, SkoLP sorghum plants suffered severe damage from sorghum midge *Contarinia sorghicola* (Coquillett), which is reported to be related to the severe stress of growth at a very low fertility site (Rattunde et al., 2016). Relative to sole cropped sorghum, yield under intercropped sorghum was almost always lower, approximately 39% and 32% at SkoHP and Wa, respectively in 2016, whereas variable results were observed in 2015. The overall sorghum yield of the two intercrop systems was 60% compared to sole cropped sorghum, as expected given the 2:1 plant population of sorghum to pigeonpea in the intercropped modified substitutive design. It is possible that the biological nitrogen fixation capacity of pigeonpea could have minimized competition for soil nitrogen resources with sorghum, enhancing the overall growth of the intercrop (Adjei-Nsiah et al., 2007). As expected given the substantial biomass produced by LD pigeonpea, sorghum grain yield was more suppressed by the LD pigeonpea variety than the MD variety. Thus, in terms of grain yield impacts on sorghum, there was evidence that the MD pigeonpea variety may be more suitable for intercropping with sorghum than the LD variety.

Over the two years, grain yields varied by site. The major factor that affected grain yield appeared to be soil fertility, as indicated by performance at the two sites at Sko which included a 30% reduction in grain yield at SkoLP relative to SkoHP, which is a site designed to evaluate effects of low soil phosphorus availability. Lower yields on phosphorus deficient soils have been reported previously in Mali (Leiser et al., 2012, 2014). Nutrient limitations affect many aspects of plant growth and development as adequate phosphorus is needed for flowering and seed production, uniform and early crop maturity, leaf expansion, shoot growth and increased resistance to plant diseases (Marschner, 1995). In West Africa, limited soil phosphorus availability is a serious constraint to sorghum growth and development (Buerkert et al., 2001).

At SkoHP, a site that is located nearby to SkoLP, this high phosphorus site produced the highest yield overall of 2939 $kgha^{-1}$. Indeed, substantial increases in sorghum biomass and grain yield can be achieved following the addition of N and P fertilizers (Buah et al., 2012; Hussein and Alva, 2014; Zaongo et al., 1997); however it is also important to evaluate the performance of sorghum and sorghum-pigeonpea intercrops under the low soil P conditions that are prevalent in farming communities across West Africa (Rattunde et al., 2013; Weltzien, 2014). Phosphorus deficiency problems in WA is managed through the integrated soil fertility management (ISFM) practices, and one widely used system approach involves crop-tree-livestock integration (Gemenet et al., 2016). In the Sahelian zones of WA, the agroforestry parklands involve various tree species grown together with important annual crops in a system shown to provide soil cover that reduces erosion and buffers the impact of climate change (Bayala et al.,2013). The sorghum-pigeonpea cropping system in this study is in line with this system approach of improving soil P deficiency. Pigeonpea is known to increase the total plant available P pools in cropping system because of its deep rooting system, and potential ability to access sparingly soluble P sources (Ae et al., 1990; Ishikawa et al., 2002; Subbarao et al., 1997). The plant also grows well in the P-deficient soils of the tropical environment (Fujita et al., 2004).

Total Biomass

Site variations and a soil fertility effect were very evident on growth, as the total aboveground biomass at SkoHP, Fko and Wa sites was 7 times more than the biomass accumulated at SkoLP. P deficiency seriously reduces the biomass production of grain sorghum plants as plants responded to higher phosphorus supply by producing higher biomass and leaf area (Ripley et al., 2004). The results are consistent with grain yield of sorghum responding to fertilizer additions, as shown by the three sites in both seasons, with increased shoot size relative to SkoLP, presumably due to improved nutritional status of the soil. In sorghum, plant height is highly correlated with biomass yield (Burks et al., 2015; Murray et al., 2008; Shukla et al., 2017). This agrees with this study as reduced plant height at SkoLP lead to a corresponding reduction in biomass production. Hussein and Alva (2014) and Fracasso et al. (2016) have also attributed a reduction in stem biomass of sorghum to a reduction in plant height.

Land equivalent ratio (LER)

The advantages of intercropping relative to sole cropping is commonly expressed in terms of LER, defined as the relative land area under sole crops that is required to produce the yield achieved in intercrops. LER values greater than 1.0 indicates an advantage of intercropping while below 1.0 show a disadvantage (Mead and Willey, 1980; Willey, 1979). Due to poor adaptation of the two pigeonpea varieties, grain yields were very low, except at Fko, so it will be necessary to test adapted varieties before performance can be adequately assessed of the cropping systems in terms of grain yield. Thus, LER was calculated based on biomass yield.

All LER values obtained were above 1.0 except at SkoHP. This indicates that generally a higher total yield could be obtained from sorghum/pigeonpea intercropping compared to sole crop stands. This is similar to the LER findings for sorghum/pigeonpea intercrops in India, as shown by Tobita et al. (1994). The observed variability of pigeonpea biomass across sites influenced LER, where a low LER at SkoHP may have been related to modest growth of pigeonpea relative to sorghum at SkoHP. Overall, the intercrop system with MD pigeonpea was associated with an LER of 1.58 compared to 1.45 with the LD pigeonpea variety. This is consistent with the MD pigeonpea variety as being a land use efficient intercrop with sorghum. Relative yields of sorghum and pigeonpea were low across sites with the exception of Fko and Wa. Intercropping of sorghum with both varieties of pigeonpea at Fko and with the MD variety at Wa are all land use efficient systems.

Ratoon performance

Ratoon cropping is a practice of raising a fresh crop from the either the crown, suckers and tillers of the original planting material (Sundara, 2010). It is a system of multiple cropping with the advantage of producing two harvests from a single planting, with the potential of eliminating seed/planting material cost and ensuring better utilization of growing season and production resources (Gerik et al., 1990; Sundara, 2010). Evaluating the perennial characteristic of sorghum and pigeonpea is important for smallholder farmers in WA constrained with land and planting material cost. The result shows that the sorghum and pigeonpea varieties we tested have great potential for production of good quality grain and fodder yields when grown as perennials through ratooning.

Very low plant number was recorded in all ratoon crop treatments, largely due to high mortality rate (about 44% of plants died before the start of the next cropping season). In the first year of ratooning, plant growth was satisfactory as the surviving plants developed large canopy after receiving rains in the month of June-July. However, the second cutting of the MD pigeonpea variety in 2015 resulted in some mortality. This might be due to the long dry season which caused wilting of the plants. The LD pigeonpea plants that were not cut developed full canopy and no plant mortality were recorded (Figure 2.10). Termites and ants were also another factor at SkoLP and Wa that might have affected the survival of ratoon crops.

Ratooning increased the productivity of both pigeonpea and sorghum. The ratooned pigeonpea plants grew taller with thicker stems and produced more flowers and pods (Figure 2.8). Flower drop and abortion was less in the ratoon crops. The number of primary and secondary branches was higher in ratoon crops, even in the MD pigeonpea variety (Figure 2.9). These factors directly contributed to higher grain and biomass yield recorded in the ratoon crops. For the Fadda variety, cutting the plants at the ground level was beneficial for regrowth. Plant height of all ratoon crops under the different cropping systems was higher than their respective main crops.

The significant site and year interaction for biomass production suggest the productivity of the ratoon crops was solely dependent on the prevailing environmental conditions at the site. Pigeonpea and sorghum has been reported to possess greater ratoonability (Daniel and Ong, 1990; Rogé et al., 2016; Rusinamhodzi et al., 2017). Total aboveground biomass and grain yield produced by perennial pigeonpea is comparable to that reported by Daniel and Ong (1990) in India.

From the results, it is evident that development and partitioning of assimilates differ between main and ratoon crops of the same species. Ratooning allowed the crop to allocate larger proportion of assimilates to pod and grain compared to the main crops. Pigeonpea grain yield was extremely low in the main crops. Also, ratooning enabled the plants to develop deep roots to access sufficient soil water. Ratooning thus enhance higher yield.

Pigeonpea has other diverse uses apart from grains for human consumption and soil fertility improvement. Studies have demonstrated the potential of using pigeonpea fodder to supplement livestock feed (Agyare et al., 2002; Daniel and Ong, 1990; Karachi and Zengo, 1998; Rao et al., 2002). In northern Ghana, there is evident of a farmer obtaining an average of 6.1 t DM ha^{-1} of pigeonpea fodder annually by pruning at 60 cm over a two year period (Agyare et al., 2002). Similarly, Daniel and Ong (1990) also reports average fodder yield of 3.5 to 6.0 t ha^{-1} from pruning pigeonpea at 25 and 50 cm. These results are comparable to biomass production of pigeonpea following ratooning of 15.3 to 87.0 t ha^{-1} observed in this study. The plant can also be used as live fences and stakes in yam production. Phatak et al. (1993) reports the used of pigeonpea as live fences, windbreaks and in soil conversation in Africa. The stems can be used as fuelwood, basket weaving, and roofing in Africa villages (Odeny, 2007). Pigeonpea also has the same benefits outlined for the agroforestry tree species grown together with important annual crops in the Sahelian zones of WA (Bayala et al., 2013). These diverse uses of pigeonpea highlight the potential of the crop as highly productive for integration in cropping systems in Ghana and Mali.

CONCLUSION

The low yields obtained in this study suggest poor adaptability of the pigeonpea varieties to the studied area. Seasonal variation in rainfall, soil fertility, site and planting time affected phenology, grain yield and biomass production of sorghum and pigeonpea. Flowering of the LD pigeonpea variety was a major problem at the SkoLP and Wa sites. Intercropping sorghum with pigeonpea resulted in increased sorghum yield, biomass and overall productivity (LER) of both crops. The LD pigeonpea variety is more productive in terms of biomass than the MD pigeonpea variety. Productivity of pigeonpea and sorghum was high under the ratoon system. Pigeonpea results may be inconclusive due to the large variability observed and the very low grain yields. There is need for future research on P responses of sorghum/pigeonpea intercrop using more improved pigeonpea varieties and focusing more on grain yield potential.

APPENDIX

Table 2.1 Mean monthly maximum and minimum temperature during the 2015 and 2016 years at Sko, Fko and Wa.

Months	Mean Temperature (°C)			
	Samanko			
	2015		**2016**	
	Max.	Min.	Max.	Min.
May	43.5	26.6	42.7	27.5
June	40.4	24.8	40.1	26.8
July	36.3	24.9	35.2	25.7
August	35.5	23.9	34.2	25.4
September	35.7	23.8	36.5	25.3
October	36.9	24.2	38.9	25.5
	Farako			
May	37.3	25.9	39.8	27.8
June	37.0	25.3	35.8	25.0
July	34.8	24.5	28.6	19.4
August	30.8	22.8	31.3	22.6
September	32.1	22.6	32.7	22.5
October	36.2	23.8	38.3	24.6
	Wa			
May	27.8	23.9	27.8	23.4
June	25.7	20.1	26.7	21.3
July	25.1	19.1	21.9	16.4
August	26	19.5	26.4	20.5
September	27.2	21.4	27.3	21.7
October	27.7	22.9	27.6	23.2

Source: GRWS100 (2015, 2016) at ICRISAT and SARI for Sko and Wa; NASA for Fko

Table 2.2 Soil properties measured in all experimental sites. Soil texture is indicated by sand, silt and clay percent. Total soil carbon is indicated by SOC%, pH is the measure of the acidity or basicity of soil, and inorganic P is based on Bray extract (Mehlich III). Means (n = 4) are followed by standard deviations in parentheses.

Depth (cm)	Sand %	Clay %	Silt %	pH	SOC	Inorganic P (ppm)	CEC (cmolkg[1])
SkoLP							
0-15	73 (10.5)	11 (1.3)	16 (11.3)	6 (0.3)	0.29 (0.05)	16.0 (5.43)	2.98 (1.19)
15-30	76 (7.5)	15 (2.1)	9 (6.2)	5 (0.1)	0.26 (0.01)	9.25 (1.09)	3.18 (1.52)
30-60	62 (8.8)	29 (8.2)	9 (6.9)	5 (0.5)	0.30 (0.02)	1.03 (0.04)	7.10 (2.33)
SkoHP							
0-15	72 (0.9)	7 (0.5)	20 (1.0)	5 (0.1)	0.38 (0.06)	30.0 (4.2)	2.60 (1.12)
15-30	72 (0.9)	12 (5.7)	16 (4.9)	5 (0.6)	0.36 (0.05)	21.5 (2.1)	3.05 (1.34)
30-60	68 (1.8)	12 (2.1)	19 (0.5)	5 (0.4)	0.32 (0.01)	10.8 (0.8)	4.28 (1.61)
Fko							
0-15	81 (3.3)	11 (2.1)	7 (1.8)	5 (0.4)	0.5 (0.12)	20.8 (4.7)	3.6 (2.38)
15-30	82 (5.2)	13 (2.1)	6 (3.3)	6 (0.5)	0.5 (0.07)	15.5 (3.3)	3.9 (1.20)
30-60	55 (10.9)	33 (7.7)	12 (4.7)	6 (0.6)	0.4 (0.05)	4.0 (2.2)	6.4 (2.75)
Wa							
0-15	84 (3.8)	8 (1.1)	8 (2.3)	7 (0.1)	0.44 (0.44)	7.00 (0.71)	3.23 (0.34)
15-30	71 (9.2)	18 (7.8)	12 (3.7)	7 (0.3)	0.24 (0.01)	1.03 (0.04)	2.80 (1.76)
30-60	66 (8.1)	22 (4.7)	12 (4.3)	7 (0.2)	0.23 (0.05)	1.03 (0.04)	4.95 (0.76)

Table 2.3 Treatment structure across all sites.

Treatment No.	Treatment ID	Description
1	SG/PP MD	Intercrop sorghum-pigeonpea (medium duration)
2	SG/PP LD	Intercrop sorghum-pigeonpea (long duration)
3	PP MD	Sole pigeonpea (medium duration)
4	PP LD	Sole pigeonpea (long duration)
5	SG	Sole sorghum
6	SG/PP MD RT	Intercrop sorghum-pigeonpea (medium duration), ratooned
7	SG/PP LD RT	Intercrop sorghum-pigeonpea (long duration), ratooned
8	PP MD RT	Sole pigeonpea (medium duration), ratooned
9	SG RT	Sole sorghum, ratooned

Table 2.4 Additional treatment by sites.

Treatment No.	Treatment ID	Description
SkoLP		
5	SG-PP MD	Sole sorghum rotation (medium duration)
11	SG RT	Sole sorghum, ratooned
13	Per SG	Perennial sorghum
14	Per PP	Perennial pigeonpea
Fko		
5	SG-PP MD	Sole sorghum rotation (medium duration)
Wa		
5	SG-PP MD	Sole sorghum rotation (medium duration)

Table 2.5 Cultivar description and average days to physiological maturity of sorghum and pigeonpea across sites.

Crop species	Cultivar and seed source	Cultivar characteristics
Sorghum	*Fadda* (ICRISAT-Bamako)	Tall, 2-3m, thin stem, 131d, sensitive to striga, photosentive
Pigeonpea	*ICEAP 00557* (ICRISAT- Nairobi)	Medium duration, short-statured, compact and bushy, dark-green leaves, reddish flowered, sensitive to pests, 153d
	ICEAP 00982 (ICRISAT- Bamako)	Long duration, tall cultivar, yellow flowered, light-green leaves, some tolerance to pests, 207d

Table 2.6 Summary of treatment combinations actual and targeted plant population densities at harvest.

Site	Cropping system	Actual plant density at harvest (plants ha^{-1})				Harvested area (m^2)	Targeted plant density (plants ha^{-1})	
		2015		2016				
		Sorghum	Pigeonpea	Sorghum	Pigeonpea		Sorghum	Pigeonpea
SkoLP	Sole Pigeonpea (LD)		39 000		40 000	7.2		44 000
	Sole Pigeonpea (MD)		41 000		40 000	7.2		44 000
	Sole Sorghum	53 000		67 000		5.4	88 000	
	Sorghum/Pigeonpea (LD)	21 000	22 000	36 000	19 000	5.4	44 000	22 000
	Sorghum/Pigeonpea (MD)	31 000	22 000	38 000	22 000	5.4	44 000	22 000
SkoHP	Sole Pigeonpea (LD)		40 000		39 000	7.2		44 000
	Sole Pigeonpea (MD)		40 000		34 000	7.2		44 000
	Sole Sorghum	82 000		70 000		5.4	88 000	
	Sorghum/Pigeonpea (LD)	44 000	21 000	36 000	20 000	5.4	44 000	22 000
	Sorghum/Pigeonpea (MD)	44 000	22 000	31 000	21 000	5.4	44 000	22 000
Farako	Sole Pigeonpea (LD)		40 000		43 000	7.2		44 000
	Sole Pigeonpea (MD)		44 000		44 000	7.2		44 000
	Sole Sorghum	84 000		80 000		5.4	88 000	
	Sorghum/Pigeonpea (LD)	40 000	20 000	44 000	22 000	5.4	44 000	22 000
	Sorghum/Pigeonpea (MD)	44 000	22 000	44 000	22 000	5.4	44 000	22 000
Wa	Sole Pigeonpea (LD)		37 000		43 000	7.2		44 000
	Sole Pigeonpea (MD)		44 000		41 000	7.2		44 000
	Sole Sorghum	84 000		82 000		5.4	88 000	
	Sorghum/Pigeonpea (LD)	44 000	21 000	42 000	22 000	5.4	44 000	22 000
	Sorghum/Pigeonpea (MD)	41 000	22 000	43 000	22 000	5.4	44 000	22 000

Table 2.7 Sowing dates, mean number of days to flowering and physiological maturity of pigeonpea grown for two years under different cropping system and at four sites.

Site	Cropping System	Sowing dates		Days to 50% flowering		Days to maturity	
		2015	**2016**	**2015**	**2016**	**2015**	**2016**
SkoLP	Sole Pigeonpea (LD)	07.09.2015	07.08.2016	144b	137b	216b	220b
	Sole Pigeonpea (MD)			77d	88d	165d	160d
	Sorghum/Pigeonpea (LD)			145a	138a	218a	240a
	Sorghum/Pigeonpea (MD)			83c	92c	171c	164c
	Mean			113B*		194A	
SkoHP	Sole Pigeonpea (LD)	07.10.2015	07.09.2016	163b	123b	246b	214b
	Sole Pigeonpea (MD)			100d	75d	161d	150d
	Sorghum/Pigeonpea (LD)			164a	124a	247a	215a
	Sorghum/Pigeonpea (MD)			103c	81c	163c	155c
	Mean			117A		193B	
Fko	Sole Pigeonpea (LD)	07.01.2015	07.06.2016	78c	124a	192a	191c
	Sole Pigeonpea (MD)			78c	65d	170d	191c
	Sorghum/Pigeonpea (LD)			84a	71	176b	197a
	Sorghum/Pigeonpea (MD)			81b	68c	173c	194b
	Mean			81D		186C	
Wa	Sole Pigeonpea (LD)	07.24.2015	07.17.2016	101a	150b	158b	207b
	Sole Pigeonpea (MD)			66c	80d	98d	116d
	Sorghum/Pigeonpea (LD)			101a	152a	160a	209a
	Sorghum/Pigeonpea (MD)			70b	85c	102c	121c
	Mean			101C		146D	
	Mean			103		180	
	CV%			21		15	
	LSD ($P \leq 0.05$)			11		14	

*Upper case letters denote statistically significant ($P \leq 0.05$) differences across sites. Lower case letters denote significant differences among treatments given as cropping systems within a site.

Table 2.8 Analysis of variance results presented for cropping system, site and season effects on pigeonpea grain yield, total biomass, and 100-seed weight at final harvesting from SkoLP, SkoHP, Fko and Wa sites for 2015 and 2016 years.

Site	Cropping System	Grain Yield (kg ha^{-1})		100-seed weight (g)		Total Biomass (kg ha^{-1})	
		2015	**2016**	**2015**	**2016**	**2015**	**2016**
SkoLP	Sole Pigeonpea (LD)	69	33b	10.3a	10.0	8896a	3050a
	Sole Pigeonpea (MD)	48	120a	7.0b	8.0	4992ab	1875bc
	Sorghum/Pigeonpea (LD)	60	44b	7.3ab	8.8	1320b	2292ab
	Sorghum/Pigeonpea (MD)	192	35b	5.3b	9.4	765b	844c
SkoHP	Sole Pigeonpea (LD)	31ab	91	12.0a	11.1a	5332a	5525a
	Sole Pigeonpea (MD)	72a	191	7.9b	7.9bc	5633a	5154a
	Sorghum/Pigeonpea (LD)	21ab	72	8.1b	9.7ab	2153b	5378a
	Sorghum/Pigeonpea (MD)	20b	219	7.0b	6.8c	1334b	2049b
Fko	Sole Pigeonpea (LD)	4050a	1037bc	11.8ab	12.5a	16091a	4737a
	Sole Pigeonpea (MD)	524b	470c	11.1b	13.0a	3594b	2087b
	Sorghum/Pigeonpea (LD)	727b	2682ab	13.3a	12.1ab	6680b	1745b
	Sorghum/Pigeonpea (MD)	994b	3551a	11.1b	11.1b	5006b	1501b
Wa	Sole Pigeonpea (LD)	62	49b	9.3a	10.0	1998ab	3750a
	Sole Pigeonpea (MD)	63	41b	7.8a	8.3	2803a	2500b
	Sorghum/Pigeonpea (LD)	72	19b	4.5b	7.8	1927ab	1985b
	Sorghum/Pigeonpea (MD)	50	208a	7.3ab	8.0	1597b	2884ab
	ANOVA						
	Cropping system	0.0006		<.0001		<.0001	
	Site	<.0001		0.0001		0.0025	
	Year	0.2772		0.0039		<.0001	
	Site x Year	0.5687		0.1953		<.0001	
	Cropping system x Year	<.0001		0.4271		0.0006	
	Cropping system x Site x Year	<.0001		0.1017		0.0009	

Table 2.8 (cont'd)

Contrasts			
Intercrop vs sole crop	0.38 (0.5366)	8.33 (0.0046)	20.04 (<.0001)
Pigeonpea LD vs MD	3.36 (0.0693)	10.22 (0.0018)	12.42 (0.0006)

Within a site, cropping system means followed by same letters are not significantly different at $P \leq 0.05$; Grain and biomass data presented here differs from that in chapter 1 in number of plants harvested and harvested area.

Table 2.9 Sowing dates, mean number of days to flowering and physiological maturity of sorghum grown for two years under different cropping system and sites.

Site	Cropping System	Sowing dates		Days to 50% flowering		Days to maturity	
		2015	**2016**	**2015**	**2016**	**2015**	**2016**
SkoLP	Sole Sorghum	07.09.2015	07.08.2016	72a	103a	155a	118
	Sorghum/Pigeonpea (LD)			70b	101b	153b	118
	Sorghum/Pigeonpea (MD)			68c	99c	152c	118
	Mean			86		136	
SkoHP	Sole Sorghum	07.10.2015	07.09.2016	89a	82a	129	2041
	Sorghum/Pigeonpea (LD)			88b	82a	129	202b
	Sorghum/Pigeonpea (MD)			86c	79b	129	201c
	Mean			85		166	
Fko	Sole Sorghum	07.01.2015	07.06.2016	81a	91	123a	115a
	Sorghum/Pigeonpea (LD)			79b	91	122b	113b
	Sorghum/Pigeonpea (MD)			78c	91	120c	112c
	Mean			84		118	
Wa	Sole Sorghum	07.24.2015	07.17.2016	70a	76	105a	107a
	Sorghum/Pigeonpea (LD)			68b	76	105a	105b
	Sorghum/Pigeonpea (MD)			66c	76	104b	104c
	Mean			72		105	
	Mean			82		131	
	CV%			13		24	
	LSD ($P \leq 0.05$)			5		15	

Within a site, means followed by same letters are not significantly different at $P \leq 0.05$.

Table 2.10 Analysis of variance results presented for cropping system, site and season effects on sorghum grain yield, total biomass, and 100-seed weight at final harvesting from SkoLP, SkoHP, Fko and Wa sites for 2015 and 2016 years.

Site	Cropping System	Grain Yield (kg ha^{-1})		100-seed weight (g)		Total Biomass (kg ha^{-1})	
		2015	**2016**	**2015**	**2016**	**2015**	**2016**
SkoLP	Sole Sorghum	734	2345a	2.2	2.1	2726a	6226a
	Sorghum/Pigeonpea (LD)	300	1757b	2.0	2.2	1195b	4310b
	Sorghum/Pigeonpea (MD)	401	1845b	2.2	2.2	1463ab	4500b
SkoHP	Sole Sorghum	5059a	3467a	2.1	2.4	14156a	7952a
	Sorghum/Pigeonpea (LD)	3053b	1798b	2.0	2.3	8467b	4134b
	Sorghum/Pigeonpea (MD)	2489b	1769b	2.0	2.4	7555b	4440b
Fko	Sole Sorghum	1089	1757	2.0	1.9	7723	4743b
	Sorghum/Pigeonpea (LD)	1228	2542	2.0	1.8	5423	7546a
	Sorghum/Pigeonpea (MD)	809	2810	2.3	1.9	4309	8206a
Wa	Sole Sorghum	1569b	1537a	1.6	1.5	8488	9767
	Sorghum/Pigeonpea (LD)	1906ab	489b	1.7	1.5	9046	6497
	Sorghum/Pigeonpea (MD)	2253a	1430a	1.7	1.5	10501	7930
	ANOVA						
	Cropping system	<.0001		0.4800		0.0018	
	Site	<.0001		<.0001		<.0001	
	Year	0.0276		0.7646		0.2687	
	Site x Year	<.0001		0.0017		<.0001	
	Cropping system x Year	0.2256		0.6160		0.2815	
	Cropping system x Site x Year	0.0269		0.7513		0.0038	
	Contrasts						
	Intercrop vs sole crop	3.98 (0.0489)		0.28 (0.5968)		5.25 (0.0242)	

Within a site, means followed by same letters are not significantly different at $P \leq 0.05$; Grain and biomass data presented here differs from that in chapter 1 in number of plants harvested and harvested area.

Table 2.11 Total biomass and grain yield produced by system. For intercrop systems, sorghum plus pigeonpea biomass and yield are presented in combination.

Site	Cropping System	Total Biomass (kg ha^{-1})		Grain Yield (kg ha^{-1})	
		2015	**2016**	**2015**	**2016**
SkoLP	Sole Pigeonpea (LD)	8896a	3050b	69b	33c
	Sole Pigeonpea (MD)	4992ab	1875b	48b	120c
	Sole Sorghum	2726b	6226a	734a	2345a
	Sorghum/Pigeonpea (LD)	1906b	6602a	360ab	1801b
	Sorghum/Pigeonpea (MD)	2783b	5344a	593a	1880b
SkoHP	Sole Pigeonpea (LD)	5332c	5525c	31c	91c
	Sole Pigeonpea (MD)	5633c	5154c	72c	191c
	Sole Sorghum	14156a	7952ab	5059a	3467a
	Sorghum/Pigeonpea (LD)	10620b	9512a	3074b	1869b
	Sorghum/Pigeonpea (MD)	8888b	6489bc	2509b	1987b
Fko	Sole Pigeonpea (LD)	16091	4850b	4050a	1037b
	Sole Pigeonpea (MD)	3594b	1579c	524d	470b
	Sole Sorghum	7723c	4743b	1089cd	1757b
	Sorghum/Pigeonpea (LD)	12103b	9428a	1955b	5224a
	Sorghum/Pigeonpea (MD)	9315bc	9352a	1803bc	6361a
Wa	Sole Pigeonpea (LD)	1998b	3750b	62c	49c
	Sole Pigeonpea (MD)	2803b	2500b	63c	41c
	Sole Sorghum	8488a	9767a	1569b	1537a
	Sorghum/Pigeonpea (LD)	10973a	8481a	1978ab	508b
	Sorghum/Pigeonpea (MD)	12098a	10814a	2303a	1638a

Table 2.11 (cont'd)

ANOVA		
Cropping system	<.0001	<.0001
Site	0.0001	<.0001
Year	<.0001	0.0280
Site x Year	0.0002	<.0001
Cropping system x Year	0.0099	<.0001
Cropping system x Site x Year	<.0001	<.0001
Contrasts		
Intercrop vs sole crop	14.85 (0.0002)	14.20 (0.0002)
Pigeonpea LD vs MD	8.38 (0.0043)	1.94 (0.1656)

Within a site, cropping systems means followed by same letters are not significantly different at $P \leq 0.05$.

Table 2.12 Analysis of variance results presented for cropping system and site effects on relative yield of intercropped (compared to sole crop yield) pigeonpea and sorghum, and land equivalent ratio (LER) estimated for total biomass from SkoLP, SkoHP, Fko and Wa sites averaged over two years (2015 and 2016).

Site	Cropping System	Relative yield		LER
		Sorghum	Pigeonpea	
SkoLP	Sorghum/Pigeonpea (LD)	0.65	0.49	1.14
	Sorghum/Pigeonpea (MD)	0.65	0.45	1.10
SkoHP	Sorghum/Pigeonpea (LD)	0.57	0.72	1.29
	Sorghum/Pigeonpea (MD)	0.55	0.33	0.88
Fko	Sorghum/Pigeonpea (LD)	1.21	0.42	1.63
	Sorghum/Pigeonpea (MD)	1.18	1.18	2.36
Wa	Sorghum/Pigeonpea (LD)	0.98	0.77	1.75
	Sorghum/Pigeonpea (MD)	1.08	0.92	2.00
	ANOVA			
	Cropping system	0.8061	0.2976	0.3312
	Site	0.0208	0.0465	0.0053
	Year	0.1219	0.0874	0.0641
	Site x Year	<.0001	0.0009	0.0378
	Cropping system x Year	0.4903	0.1947	0.8317
	Cropping system x Site x Year	0.9067	0.0002	0.1457

Values larger than 1.0 indicates a greater land use efficiency. LERs are averaged over two years (2015 and 2016).

Table 2.13 Mean number of plants that survived the dry season after ratooning across sites for 2015 and 2016 years.

Site	Cropping system	**2015**	**2016**
SkoLP	Perennial pigeonpea	42	13
	Perennial sorghum	83	-
	Sole pigeonpea (LD), ratooned	50	17
	Sole pigeonpea (MD), ratooned	35	17
	Sole sorghum, ratooned	84	-
	Sorghum/pigeonpea (LD), ratooned	74	29
	Sorghum/pigeonpea (MD), ratooned	75	-
Fko	Sole pigeonpea (LD), ratooned	48	19
	Sole pigeonpea (MD), ratooned	30	26
	Sole sorghum, ratooned	79	29
	Sorghum/pigeonpea (LD), ratooned	72	33
	Sorghum/pigeonpea (MD), ratooned	63	22
Wa	Sole pigeonpea (LD), ratooned	48	20
	Sole pigeonpea (MD), ratooned	31	23
	Sole sorghum, ratooned	96	-
	Sorghum/pigeonpea (LD), ratooned	26	13
	Sorghum/pigeonpea (MD), ratooned	38	26
	Mean	**57**	**22**

Table 2.14 Grain yield, biomass production and plant height of ratooned sorghum grown under different cropping systems at Fko for 2015 and 2016 years.

Cropping system	Grain Yield ($kg\ ha^{-1}$)		Total Biomass ($kg\ ha^{-1}$)		Plant Height (m)	
	2015	**2016**	**2015**	**2016**	**2015**	**2016**
Sole sorghum, ratooned	2307	2800	19081	11346	2.8	2.5
Sorghum/pigeonpea (LD), ratooned	1556	-	14414	-	2.9	
Sorghum/pigeonpea (MD), ratooned	1285	-	17836	-	2.8	

Table 2.15 Grain yield, biomass production and plant height of ratooned pigeonpea grown under different cropping systems from SkoLP, Fko and Wa sites for 2015 and 2016 years. NA = not applicable.

Site	Cropping system	Grain Yield ($kg\ ha^{-1}$)		Total Biomass ($kg\ ha^{-1}$)		Plant height (m)	
		2015	**2016**	**2015**	**2016**	**2015**	**2016**
SkoLP	Perennial pigeonpea	NA	2387		87028a		3.4
	Sole pigeonpea (LD), ratooned		2093		31957b		6.2
	Sole pigeonpea (MD), ratooned		286		2167d		1.0
	Sorghum/pigeonpea (LD), ratooned		2495		26714c		2.9
	Sorghum/pigeonpea (MD), ratooned		-		-		0.8
Fko	Sole pigeonpea (LD), ratooned	677	1590b	15771ab	6756b	3.4a	3.7a
	Sole pigeonpea (MD), ratooned	744	522b	13496b	3397b	1.7b	2.4b
	Sorghum/pigeonpea (LD), ratooned	1043	9321a	27153a	17315a	3.7a	2.7ab
	Sorghum/pigeonpea (MD), ratooned	1888	2416b	10771b	5015b	1.5b	1.6b
Wa	Sole pigeonpea (LD), ratooned			5324	-	3.2a	-
	Sole pigeonpea (MD), ratooned			6115	2159	1.4b	1.3c
	Sorghum/pigeonpea (LD), ratooned			8880	6692	2.6a	2.6a
	Sorghum/pigeonpea (MD), ratooned			5191	4336	0.8b	2.1b
	Mean	2258		15248		2.5	
	ANOVA						
	Cropping system	0.0135		<.0001		<.0001	
	Site	0.1835		<.0001		0.7702	
	Year	0.0137		0.0021		0.4635	
	Site x Year	-		0.0192		0.0919	

*Within a site, means followed by same letters are not significantly different at $P \leq 0.05$.

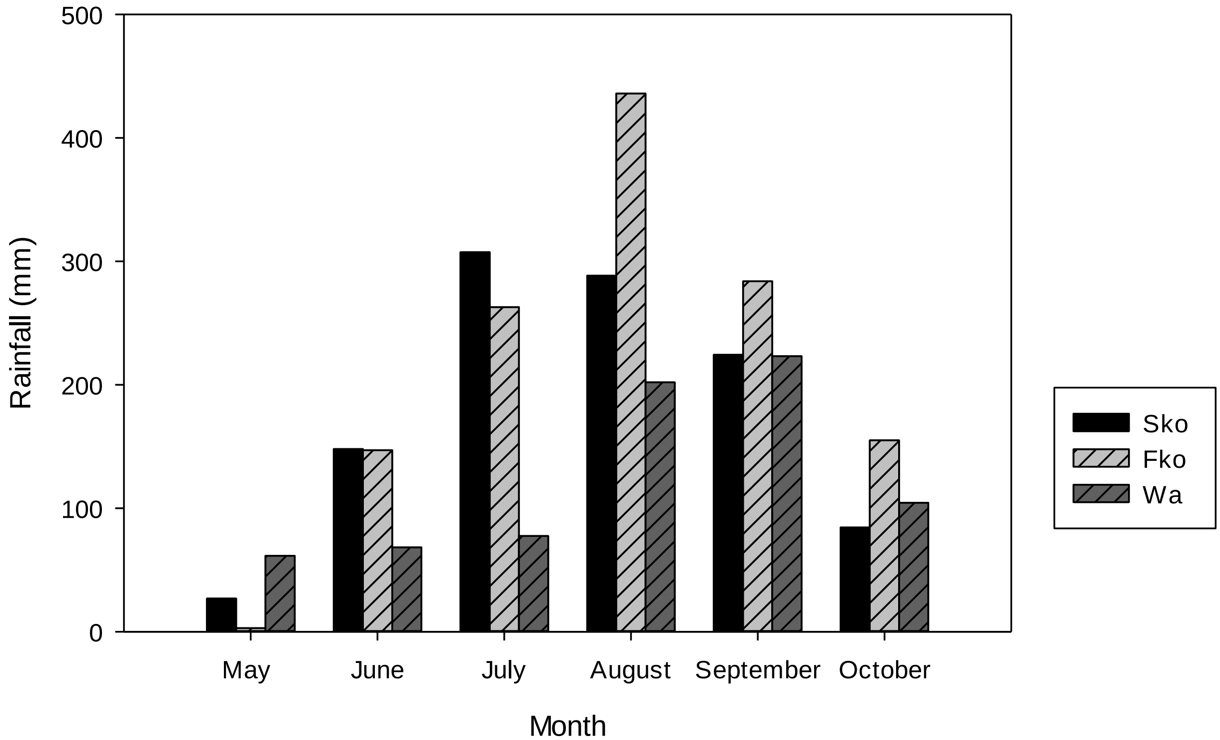

Figure 2.2 Monthly rainfall in mm from May to October during the 2015 growing season for Sko, Fko (both in Mali) and Wa (Ghana). Data recorded on-site using GRWS100 installed in 2014 by ICRISAT.

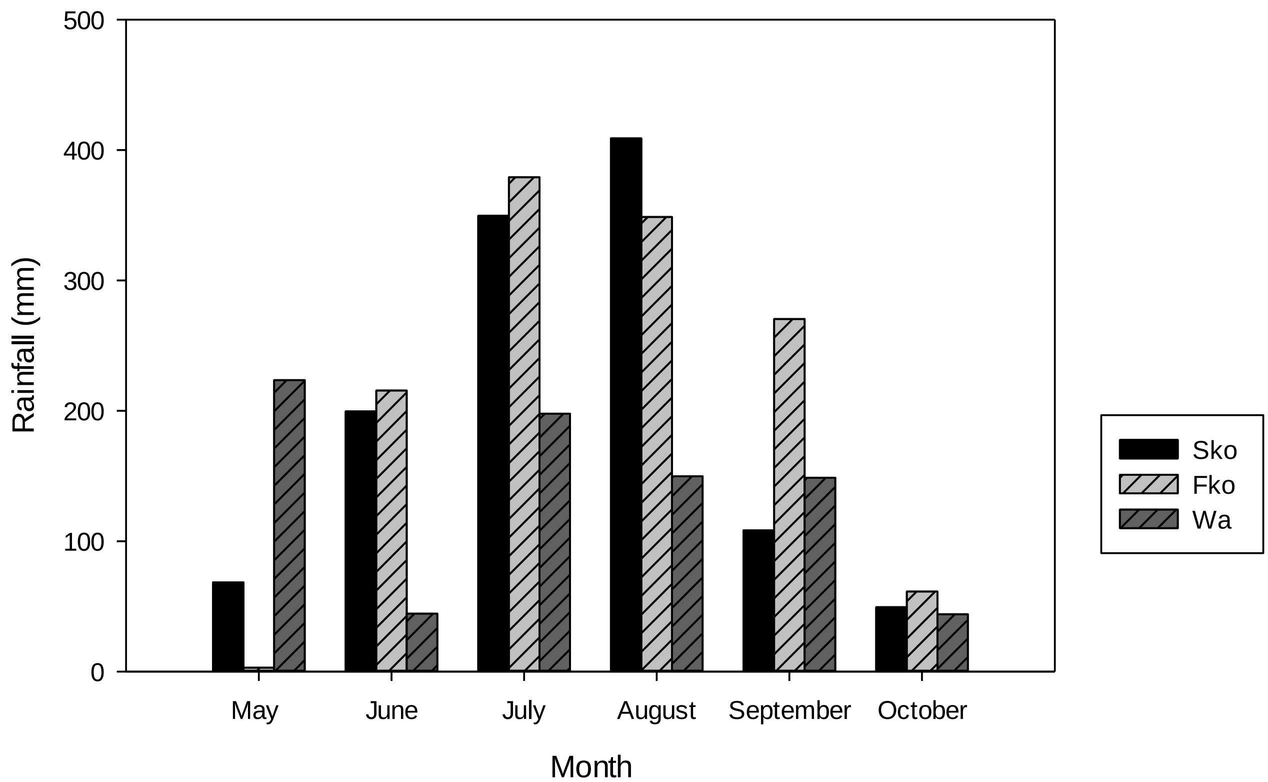

Figure 2.3 Monthly rainfall in mm from May to October during the 2016 growing season for Sko, Fko (both in Mali) and Wa (Ghana). Data recorded on-site using GRWS100 installed in 2014 by ICRISAT.

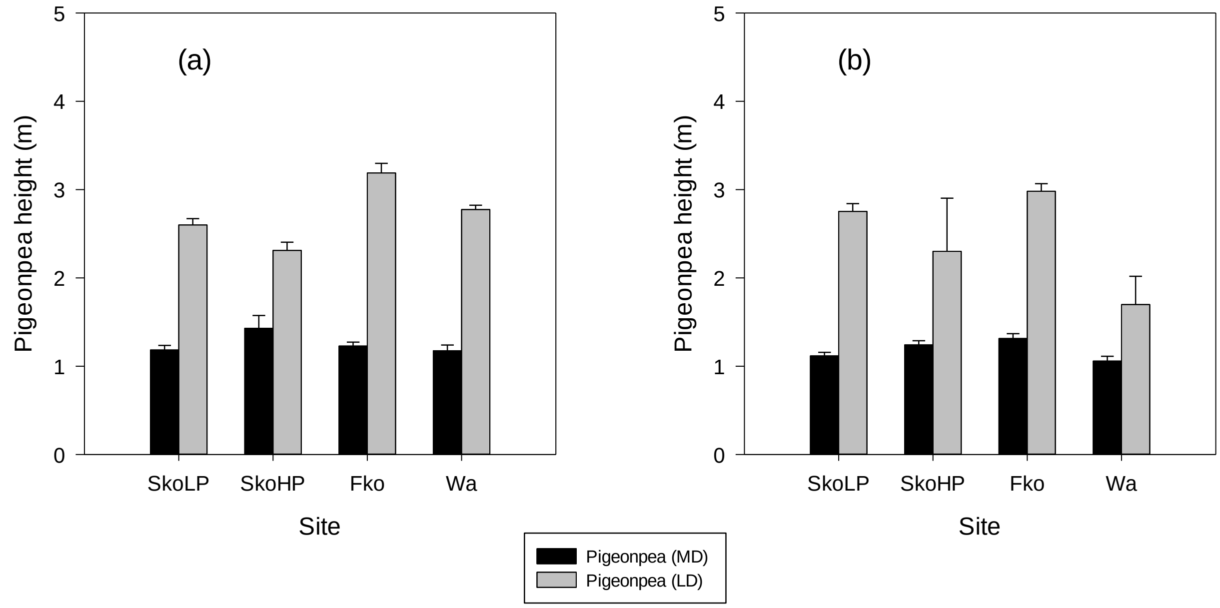

Figure 2.4 Plant height of pigeonpea (MD) and (LD) at maturity across the four sites for (a) 2015 and (b) 2016 years. Error bars represent standard error of cropping system means.

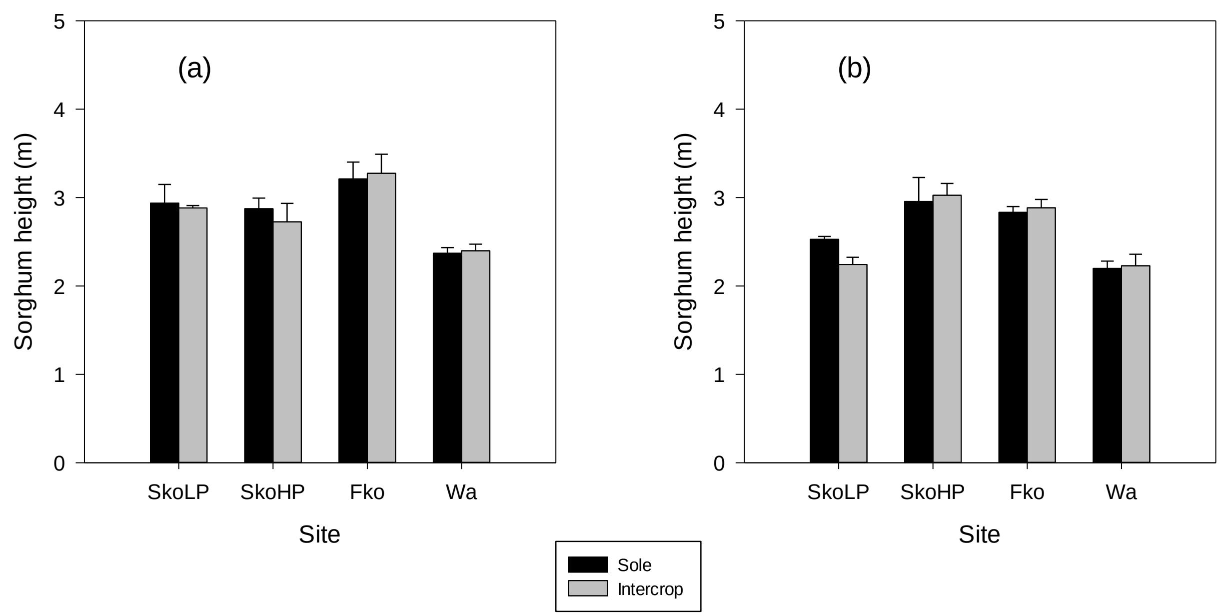

Figure 2.5 Sorghum plant height under sole and intercrop systems at maturity across the four sites for (a) 2015 and (b) 2016 years. Error bars represent standard error of cropping system means.

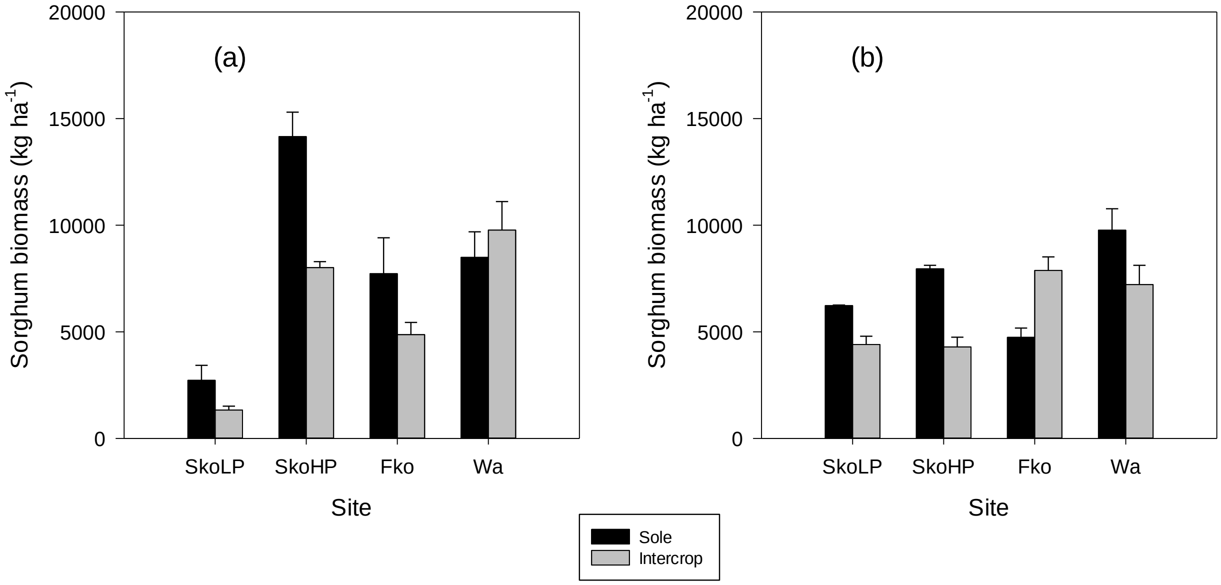

Figure 2.6 Sorghum aboveground biomass under sole and intercrop systems across four sites for (a) 2015 (b) 2016 years. Error bars represent standard error of cropping system means.

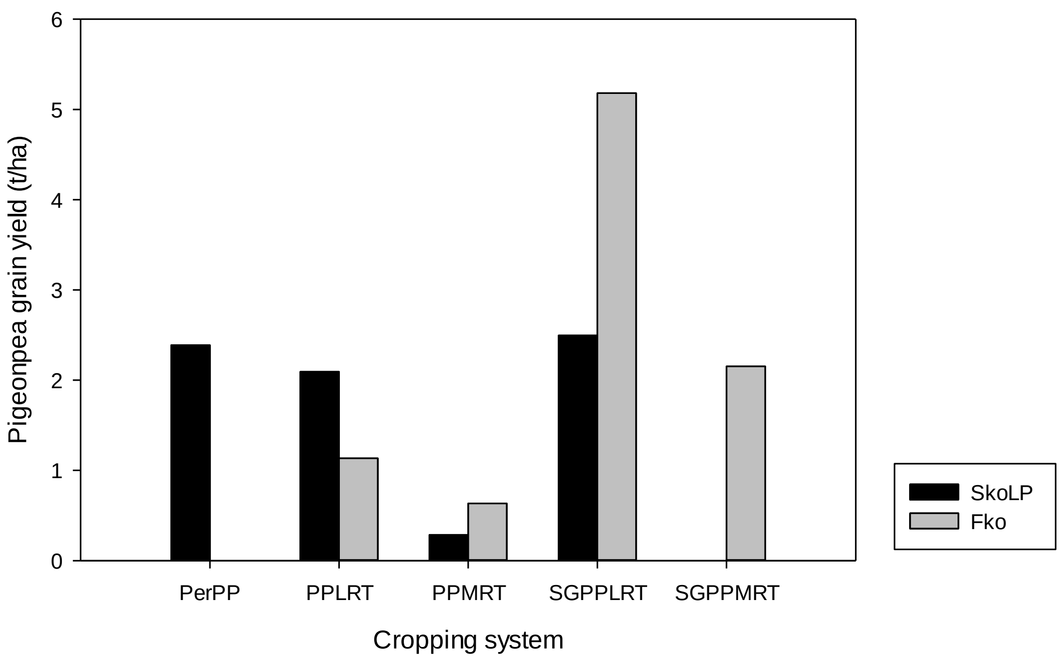

Figure 2.7 Grain yield of second year pigeonpea ratooned in sole and sorghum/pigeonpea intercrop systems at SkoLP and Fko sites for two years. PerPP: perennial pigeonpea; PPLRT: Sole pigeonpea (LD), ratooned; PPMRT: Sole pigeonpea (MD), ratooned; SGPPLRT: Sorghum/pigeonpea (LD), ratooned; SGPPMRT: Sorghum/pigeonpea (MD), ratooned.

Figure 2.8 The podding of the ratooned LD pigeonpea at SkoLP.

Figure 2.9 Ratooned MD pigeonpea at Wa. Note the branching effect from ratooning.

Figure 2.10 A photo of ratooned LD pigeonpea at Fko with thick stem.

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CHAPTER 3

MODELING YIELD AND WATER-USE EFFICIENCY OF SORGHUM AND PIGEONPEA UNDER DIFFERENT CROPPING SYSTEMS

ABSTRACT

Water-use efficiency (WUE) of field crops (cereals, legumes) can be quite variable which complicates the extrapolation of field results to other sites. Crop simulation models (CSM) are useful tools to evaluate the agronomic and environmental performance of farming systems and to extrapolate field experimentation data across environments. One of such CSM is the Agricultural Production Systems sIMulator (APSIM), developed to simulate semi-arid rain-fed cropping systems in Australia, which has since been used extensively in sub-Saharan Africa. It is the only crop simulation model that attempts to address the complexity of tropical cropping systems such as intercropping. In this study, we use APSIM to demonstrate its capacity to simulate WU and WUE in sorghum and pigeonpea cropping systems in West Africa. Data on crop phenology, total soil water, biomass accumulation, yield, water use (WU) and WUE were evaluated from field experiments established over two seasons (2015 and 2016) under rain-fed conditions at three sites: two locations in southern Mali and one in northern Ghana. Daily weather parameters and soil data were used to initialize the model. The SoilP module was utilized in this study to help simulate crop growth on low phosphorus soils. Model calibration was undertaken by using the SkoLP 2015 sorghum yield and pigeonpea biomass dataset. The model was then evaluated with two season's data from SkoLP, SkoHP and Wa under sole and intercrop systems. Model evaluation was done by comparing observed data for phenology, total biomass, yield, WU and WUE with simulated outputs. The performance of the model was assessed with statistical indices

such as coefficient of determination (R^2), root mean squares error (RMSE), relative RMSE (RRMSE), and linear regression (1:1) plot.

The simulation of phenology by the model across sites and under different cropping systems was good for sorghum (flowering: R^2 = 0.82, RMSE = 11 days, RRMSE = 12%; maturity: R^2 = 0.67, RMSE = 19 days, RRMSE = 15%) and satisfactory for pigeonpea (flowering: R^2 = 0.73, RMSE = 15 days, RRMSE = 14%; maturity: R^2 = 0.61, RMSE = 33 days, RRMSE = 19%). Simulation of total soil water by the model was satisfactory, even though there was overestimation of about 22% by the model. Pigeonpea grain yield was overestimated while that of sorghum was underestimated. Prediction of total biomass by the model was underestimated for pigeonpea but was simulated satisfactorily for sorghum (R^2 = 0.73, RMSE = 1262 kg ha^{-1}, RRMSE = 28%). The model simulated WU for both sole and intercrop systems very good for sorghum (R^2 = 1.0, RMSE = 82 mm, RRMSE = 9%) and pigeonpea (R^2 = 1.0, RMSE = 91 mm, RRMSE = 10%). Finally, pigeonpea WUE was underestimated by the model but simulated well for sorghum. The results of the study showed that APSIM is capable of predicting growth, plant biomass, yield, WU and WUE of sorghum and pigeonpea under variable soil and weather conditions. But, there is the need to improve the prediction of grain and total biomass for both crops.

INTRODUCTION

Agriculture is a major economic sector and the one most vulnerable to climate change due to its subsistence nature in West Africa (Jarvis et al., 2011; Roudier et al., 2011). Rainfall in the region depends on the West African monsoon (WAM) which exhibits considerable variability on inter-annual and inter-decadal timescale (Haussmann et al., 2012; Roudier et al., 2011). Crop yields are highly dependent on climate fluctuations as agriculture is mostly rain-fed. Additionally, the use of fertilizers, pesticides and modern cultivars remain low. The predicted impact is large, about 10-15% losses on staple cereal crops such as sorghum and millet (Haussmann et al., 2012; Roudier et al., 2011). This highlights how adverse changes in weather can impact directly on agricultural systems, thereby threatening food security and economic growth. Intercropping systems are complex but highly efficient in resource use leading to overall yield increase (Kimaro et al., 2009; Tobita et al., 1994; West and Griffith, 1992; Zhang and Li, 2003). Numerous studies have outlined their effects on soil fertility improvement, yield stability, improved diet, food security and income (Chikowo et al., 2004; Adjei-Nsiah et al., 2007; Kerr et al., 2007, Zhang et al, 2008, Myaka et al., 2006, Ghosh et al, 2006). This makes intercropping systems a sustainable cropping system option for farmers to sustain crop production especially under highly variable rainfall and soil environment.

Water-use efficiency of field crops (cereals, legumes) can be quite variable due to seasonal variability and distribution in total amount of rainfall; the diversity in soil and crop types; and the interaction between crop, soil and climate in relation to water use (Asseng et al, 2001). This variability complicates the extrapolation of field results to other sites. Crop simulation models (CSM) are useful tools to evaluate the agronomic and environmental performance of farming systems, and have been identified as one of the more appropriate approaches to explore climate change production risk (Bergez et al., 2014; Miglieta, 1993).

Models have been used to assess the impact of changes in weather on crop production in both on-farm and on-station trials (Asseng et al., 2014; Bergez et al., 2010; Keating et al., 2003; Ollenburger and Snapp, 2014; Wang et al., 2009). Also, CSMs have been used by researchers to extrapolate field experimentation data across environments (Bergez et al., 2010; Malézieux et al., 2009). One of such CSM is the Agricultural Production Systems sIMulator (APSIM), developed to simulate semi-arid rain-fed cropping systems in Australia, which has since been used extensively in sub-Saharan Africa (Keating et al., 2003). APSIM have been used by researchers to extrapolate field experimentation data across environments and explore the dynamics between climate, soil type, and plant characteristics on cropping system (Asseng et al., 2004; Bergez et al., 2014; Keating et al., 2003; Ollenburger and Snapp, 2014; Wang et al., 2009). Considerable experimental work has been done on simulating WU and WUE in APSIM. Asseng et al. (2001) through a scenarios analysis simulated potential yield, WUE and nutrient use efficiency (NUE) of wheat crops using APSIM. They found that the greatest potential for increasing yield, WUE and NUE exists in high rainfall zones on soils with high water-holding capacity. Response to fertilizer and yields were higher on sandy soils than on clay soils in low rainfall years and in low rainfall zone. Ncube et al. (2009) simulated the impact of legumes on sorghum grown under rotation systems in south-western Zimbabwe and reported that APSIM can predict well both sorghum and legume yield and water use in the rotation system. Also, the residual benefit of legumes to subsequent sorghum is mainly nitrogen, and not water under semi-arid conditions. Chimonyo et al. (2016) reported that APSIM has capability of predicting the growth, yield and WU of a sorghum-cowpea intercrop system under varying water regimes in South Africa, however the model is still limited with regards to rain-fed conditions since it overestimated biomass, yield and WU, and underestimated biomass WUE. In another study under rain-fed conditions at Iowa, APSIM simulated soil water content satisfactorily, capturing the general pattern of soil water fluctuations under a continuous corn and corn-soybean rotations. Water use efficiency was observed to vary across years with greatest WUE in wet years and lowest in dry years (Dietzel et al., 2016). The prediction ability of APSIM in simulating soil water dynamics is good, however uncertainty always exists in water retention parameters due to soil spatial variability (Archontoulis et al., 2014).

In this study, APSIM was used to simulate crop performance and WUE of sorghum and pigeonpea cropping systems under variable weather and soil conditions over time. The objective of the study was to simulate WUE in a sorghum-pigeonpea cropping system. Few studies have been conducted that model West African sorghum-based cropping systems. Further, pigeonpea is a novel crop in West Africa, and simulation modeling is well suited to investigate suitability of different types of pigeonpea in sole and intercrop systems. Water use efficiency is also understudied in this context, and crop modeling can provide important insights.

Modeling intercropping systems

One challenge to using crop models in developing countries is that mixed cropping systems such as intercropping are widely used. It is challenging to predict growth, productivity and efficiency of cropping systems that involve two or more species grown simultaneously. One aspect that sets APSIM apart from other process-based crop simulation models is its capacity to simulate intercrop systems. Intercropping and interspecific competition in APSIM is simulated using the canopy module (Anon, 2016). The module uses a routine that defines soil water and nutrient supply for each species component in a daily alternating manner. Various canopy layers are defined starting at the top of the tallest canopy which is equal to the plant height of the dominant species in the system. The fraction of light transmitted out of the top layer can be calculated using Beer's law and this in turn is the fraction entering the next layer below. To account for daily radiation of each canopy, the total radiation intercepted in a layer is divided among the canopies occupying the layer. This approach ignores the possibility of different leaf area distribution within a layer, as it considers the distribution between canopy layers on the assumption that LAI (Leaf Area Index) increases exponentially with crop height. Belowground resource competition is predicted by using the rotating call system of resource allocation. Here, the simulation of water and nitrogen extraction between the component species is done in turns, with the order of extraction alternated between crops each day. Thus, crop A is allowed first use of resources in a given day, then crop B is given the opportunity the next day and vice versa (Anon, 2016; Carberry et al.,1996).

This modeling approach has been critiqued as not being able to simulate crop performance adequately in intercropping systems. Knörzer et al. (2011) pointed out that the assumption that competing species share a common pool of resources could lead to underestimation of crop growth. Also, the canopy module ignores the spatial heterogeneity of plant mixtures; since the model assumes that both aboveground and belowground stand components are horizontally homogeneous. This is not a true reflection of the process and pattern of resource partitioning in multispecies mixtures (Malézieux et al., 2009). However, it is the only crop simulation model that attempts to address this complexity of tropical cropping system, intercropping. APSIM has been used to test interspecific competition in wheat-lucerne (*Medicago sativa*) and canola-lucerne (*Brassica napus*) companion farming (Robertson et al., 2004), maize-cowpea intercropping (Carberry et al., 1996; Adiku et al., 1995), and maize-legume pasture and sorghum-legume pasture systems (Carberry et al., 1996). These studies have reported a good model fit between simulated and observed yields. The simulation of either intercropping or sole cropping systems require robust and carefully evaluated and validated models, which makes APSIM the best modeling tool to use for this research despite its shortcomings.

APSIM Model description

The Agriculture Production Systems sIMulator (APSIM) interface has the crop and soil modules linked by a central simulation engine and controlled by management modules that allow the user to establish rules that control the biophysical modules (Keating et al., 2003). The system runs on a daily time step and requires daily climate data, soil properties and crop variety information as inputs. The Manger module allows the user to set management practices and specific operations for the specific scenario modeled. It provides control over individual components and the overall simulation. The Crop modules simulate key physiological processes, describing plant growth, development and yield. APSIM divides crop phenology into subphases and the duration of each phase is primarily based on temperature, light, water, and nutrient-availability.

The Soil modules consist of several in-built systems (SoilWat, SoilN, SoilpH, and SoilP) that simulate water and nutrient availability for the crop (Keating et al., 2003). The APSIM SoilWat is a cascading layer model used to describe movement of water and solutes within the soil system. Soil water characteristics are specified in terms of the lower limit (LL15), drained upper limit (DUL) and saturated (SAT) volumetric water contents. SoilN module simulates the mineralization of nitrogen and the N supply available to the crop from the soil and residues/roots from previous crop. This also accounts for C and N in different soil organic matter pools. The SoilpH module provides representation of the acidification of the soil and how pH changes are distributed through the soil profile. It is a tool that can be used for reducing the effect of liming (Keating et al., 2003). SoilP module describes the transformation of P in the soil. This module is useful in simulating crop growth and development under P limiting conditions. Also, it simulates crop response to added P fertilizers under different soil conditions (Delve et al., 2009).

Apart from the science and infrastructure elements of APSIM simulator, the framework also includes various user interfaces for model construction, testing and application, database tools for visualization and further analysis of simulation output and a web-based user and developer support facility that provides documentation, distribution and defect/change request tracking capability (Keating et al., 2003).

MATERIALS AND METHODS

Site description

Field experiments were conducted under rain-fed conditions at three sites: two locations at Samanko (Sko), ICRISAT-Mali; and one location at Wa, SARI-Ghana. The climate at Sko is typical of a Sudanean climate characterized by a unimodal rainy season (June-October), followed by a long dry period of and cooler (December-February) and warmer (from March) months. Wa climate on the other hand, is typical of Sub-humid tropics with a relatively longer rainfall season (May-November) (Table 3.1) and shorter dry season.

Table 3.1 Geographical description of the study sites.

Location	Soil type	Latitude (S), Longitude (E), Elevation (m asl)	Mean annual rainfall (mm)	Growing-season (May-Oct) mean rainfall (mm)	
				2015	2016
Sko	Sandy loam (Acidic acrisol)	12.58S, -8.61E, 328	1029	1080	1184
Wa	Sandy loam (Ferric Lixisols and Luvisols)	10.07S, -2.5E, 319	1055	727	851

Soils at Sko are a light sandy loam of a tropical ferruginous washed-type (Sivakumar et al., 1984) and are well drained. These soils are very low in soil organic carbon (Table 3.2), and hence, soil N supply, but are also characterized by low P availability. Because of management history, two sites at Sko were selected that varied in soil P status - one low phosphorus (LP) and the other high phosphorus (HP) (Table 3.2). The SkoLP site was chosen for soils that are representative of on-farm environments in Mali, which are highly nutrient depleted.

The Wa experimental site was characterized as a well-drained sandy loam soil with higher levels of SOC compared to Sko and a P status similar to the HP site.

Table 3.2 Soil profile parameters measured from experimental fields and used to parameterize the model.

Depth (cm)	% Sand	% Silt	% Clay	% C	FBIOM* (0-1)	FINERT* (0-1)	pH (1:5)	Labile P (mg kg^{-1})
SkoLP								
0-15	71	10	20	0.3	0.02	0.45	6.5	5.0
15-30	53	25	22	0.3	0.01	0.55	6.5	1.0
30-60	48	15	37	0.3	0.01	0.85	6.5	1.0
60-90	53	10	37	0.2	0.01	0.90	6.5	1.0
90-120	58	12	30	0.2	0.01	0.95	6.5	1.0
SkoHP								
0-15	74	22	5	0.3	0.03	0.40	6.0	10.0
15-30	73	19	9	0.3	0.02	0.55	6.0	2.0
30-60	71	20	8	0.3	0.01	0.75	6.0	1.0
60-90	66	17	16	0.2	0.01	0.80	6.0	1.0
90-120	63	17	20	0.2	0.01	0.85	6.0	1.0
Wa								
0-15	78	15	7	0.7	0.03	0.40	7.0	10.0
15-30	76	12	12	0.4	0.02	0.55	7.0	1.0
30-60	61	15	25	0.3	0.01	0.75	7.0	1.0
60-90	66	5	30	0.2	0.01	0.80	7.0	1.0
90-120	41	5	55	0.3	0.01	0.85	7.0	1.0

*Estimates of APSIM input variables used in SoilN module; Finert is the proportion of soil organic matter assumed not to decompose; Fbiom is the proportion of decomposable soil organic matter in the more rapidly decomposing pool.

Field experiments

All three experiments were laid out in a randomized complete block design with 4 replications. The treatments consisted of sole and intercropped cropping systems with sorghum and pigeonpea (Table 3.3). Two varieties of pigeonpea were planted; ICEAP 00557 (medium, 153days) and ICEAP 00982 (long duration, 207days). The sorghum variety planted was Fadda, a photoperiod sensitive, dual purpose (grain and biomass) and tall growing (2 m in height) and of medium duration (131 days). The plant population density used for sole sorghum and pigeonpea was 88,000 and 44 000 per ha, respectively. The intercrop system was a 2:1 in-row substitutive design with 44 000 and 22 000 per ha, for sorghum and pigeonpea respectively (Table 3.3).

Table 3.3 Cropping systems and plant population density examined in the study.

Treatment No.	Treatment ID	System description	Sorghum plants/m^2	Pigeonpea plants/m^2
1	SG	Sole sorghum	8.8	
2	PPM	Sole pigeonpea (MD)		4.4
3	PPL	Sole pigeonpea (LD)		4.4
4	SG/PPM	Sorghum/pigeonpea intercrop (MD)	4.4	2.2
5	SG/PPL	Sorghum/pigeonpea intercrop (LD)	4.4	2.2

Land preparation was done manually for the SkoLP site (hand-hoe ridges) and Wa site (hand-hoe flat). SkoHP was ploughed to approximately 25 cm depth with a tractor. The Sko trials were planted 8 and 9th of July in 2015, and 9 and 10th of July in 2016. Wa was planted later, 17 and 24th of July in 2015 and 2016 respectively. Sole sorghum and pigeonpea were planted at a spacing of 30 cm x 75 cm and 60 cm x75 cm, respectively with two plants per hill. Pigeonpea in intercropped plots were thinned to one plant per hill at all locations.

Weeds were controlled by using a hand hoe at three different times after planting. Insect pest damage on pigeonpea plants were controlled at 2-week intervals from the start of flowering to maturity by using K-optimal, a systemic insecticide (Lambda-cyhalothrine 15g/l +Acetamipride 20g/l; EC) in spraying the plants. A basal dose of diammonium phosphate (DAP) at 100 kg fertilizer/ha to supply 18 kg of N and 46 kg of phosphate-P was applied to the plots at Wa and SkoHP. In addition, a side-dress of urea was applied at 50 kg/ha (23% N) after the second weeding at these sites. The SkoLP field was supplied with compost at 3 tons/ha, on dry weight basis.

To monitor soil water, fifteen access tubes were installed in each of the three sites, SkoLP, SkoHP and Wa respectively. Access tubes were installed in each treatment plot for three replications. Soil water content were measured at incremental depths of 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-60 cm, and 60-100 cm using the Time domain reflectometry (TDR) profile probe type PR2 (Delta-T Devices Ltd, Cambridge, UK). The TDR technique was used based on the detailed description given by Dalton (1992) and Zegelin et al. (1992). Measurement started at planting through to the end of the crop cycle. The profile probe determined soil water content in volumetric %. It was then converted to soil water content in mm^{-1} mm^{-1} by dividing each meter reading by 100 (i.e. thickness of soil depth). Soil water content measurements were used to estimate water use (WU) and water use efficiency (WUE) of total biomass. Data on crop phenology, biomass accumulation and yield were collected as described in chapter 1. Water use was measured by the difference between the amount of water in the soil at the beginning and end of growing season under each cropping system, and then added to seasonal rainfall (Chirwa et al., 2007). The estimation of WUE was given as the ratio of total aboveground biomass to WU of each cropping system (Katerji et al., 2008).

$$\text{WU (mm)} = (\text{R}) + (\text{SW}_{\text{start}}) - (\text{SW}_{\text{end}}) \qquad \text{Equation 1}$$

$$\text{WUE (kg ha}^{-1}\text{mm}^{-1}) = \frac{\text{Total biomass}}{\text{WU}} \qquad \text{Equation 2}$$

where WU = crop water use; R= seasonal rainfall; SWstart = soil water content of the root zone at the start of the growing season; and SWend= soil water content of the root zone at the end of the growing season.

Model parameterization

The APSIM version 7.7 was used on a daily time step to simulate crop growth and development and soil water use of sorghum and pigeonpea cropping system. To achieve this, the required input data for APSIM was configured for the following modules: SoilWat (soil water), SoilN (SOC, NO_3 and NH_4), SoilP (available inorganic P extracted by Mehlich III and then correlated to and reported as Bray P), SurfaceOM (OM type was manure; fraction of surface residue incorporation was 1 with a depth of 100 mm), Sorghum (sorghum crop) and Pigeonpea (pigeonpea crop).

Weather parameters: Daily maximum (Tmax) and minimum (Tmin) air temperature (°C), solar radiation (Radn, MJ/m^2), and rainfall (mm) for the 2015-2017 years were recorded using General Research-Grade Weather Station (GRWS100, Campbell Scientific, Inc.), installed by ICRISAT-Mali in 2014. The raw data was converted to the APSIM format (.met) using tav_amp. The tav_amp calculates values of average ambient temperature (TAV) and annual amplitude in mean monthly temperature (AMP) for use in the soil T routines of the SoilN module.

Soil parameters: The SoilWat module in APSIM describes the movement of water and solutes within the soil system. APSIM requires estimates of LL and DUL determined under field conditions (Dalgliesh and Foale, 2005). We used Littleboy et al. (1999) equations to estimate values of soil water properties for each layer from soil texture data. Soil textural properties and bulk density measured at each site were used to estimate lower limit (LL15), drained upper limit (DUL) and saturated (SAT) volumetric water contents for soil layers using equations described in Littleboy et al. (1999) (Table 3.4). The soil moisture limit to which soil can dry by evaporation (Airdry) was estimated as 0.5 x LL15 in 0 to 15 cm soil layer (Cresswell et al., 2009), and layers below 30 cm are set equal to LL15. The crop lower limit (CLL) was assumed to be equal to LL15. Initial water was set to LL15 in mid-May 2015 (to coincide with manure application at SkoLP site) across the sites. Initial plant available water capacity (PAWC) was changed by adjusting the DUL values of the soil layer to minimize the difference between simulated and observed values.

Measured soil organic carbon was used to initialize the SoilN module and all other inputs were estimated following consultation with an experienced APSIM user. The SoilP module was included to enable simulation of crop growth under low phosphorus soil conditions. Soil P inputs for SkoHP and Wa were assumed to be equal (15 mg kg^{-1}) and a lower amount of P (9 mg kg^{-1}) was used for the SkoLP site. In addition to lower P status, initial inorganic N (4 kgN/ha cf. 10 kgN at other sites) and Fbiom and Finert inputs (Table 3.2) were calibrated to the low yield levels observed at the SkoLP site following consultation with an experienced APSIM user (John Dimes, personal communication).

The soil/root water extraction coefficient (KL, d^{-1}) and root penetration parameter (XF, 0-1) for sorghum and pigeonpea were set to default values of 0.08 and 1.00, respectively as there were no observed values. The soil evaporative coefficient CONA (6 mm $d^{-0.5}$) and U (4 mm) values were input to the model. APSIM uses the curve number method to calculate runoff and bare soil runoff curve was set at 85, diffusivity constant and diffusivity slope at 256 and 26, respectively, and then soil albedo at 0.2. Soil water conductivity was set to 0.55 for all layers across soil descriptions. The initial root weight was set to 300kg/ha for all soils to estimate the residual root from previous weed and crop growth.

Crop parameters: To accurately simulate the phenology of a crop, there is a need for adjustments in the APSIM crop files as some crop cultivars may have variety-specific trait such as the photoperiod sensitivity of West African sorghum. Cultivar phenological parameters for sorghum and pigeonpea were developed based on observed data. These crop coefficients were used to modify sorghum and pigeonpea files to get predicted crop stages closer to observed. The Fadda cultivar was created by modifying the sorghum medium duration cultivar in APSIM.

The APSIM long duration and short duration cultivars of pigeonpea were modified to create the long and medium duration cultivars used in the study respectively (Table 3.5). Observations on crop phenology were recorded in calendar days and later converted to thermal time using method 2 as described by (Mcmaster and Wilhelm, 1997).

$$GDD = \left[\frac{T_{max} + T_{min}}{2}\right] - T_{base} \quad \text{……Equation 4}$$

where GDD = growing degree days (°C-d), Tmax and Tmin = maximum and minimum temperatures, respectively, and Tbase = base temperature. If Tmax < Tbase then Tmax = Tbase and if Tmin < Tbase then Tmin = Tbase.

Table 3.4 Soil water characteristics used for model parameterization.

Depth (cm)	Bulk density (g/cm^3)	Airdry (mm/mm)	LL15 (mm/mm)	DUL (mm/mm)	SAT (mm/mm)	PAWC (mm)
SkoLP						
0-15	1.214	0.081	0.162	0.240	0.472	11.7
15-30	1.322	0.161	0.178	0.225	0.440	7.1
30-60	1.280	0.173	0.173	0.210	0.475	11.1
60-90	1.169	0.175	0.175	0.240	0.514	19.5
90-120	1.210	0.162	0.162	0.232	0.488	21.0
SkoHP						
0-15	1.232	0.075	0.150	0.210	0.443	9.0
15-30	1.359	0.127	0.141	0.190	0.409	7.4
30-60	1.255	0.160	0.160	0.180	0.441	6.0
60-90	1.245	0.120	0.120	0.171	0.456	15.3
90-120	1.142	0.093	0.093	0.145	0.495	15.6
Wa						
0-15	1.232	0.074	0.148	0.210	0.447	9.3
15-30	1.359	0.125	0.138	0.200	0.413	9.3
30-60	1.255	0.150	0.150	0.175	0.466	7.5
60-90	1.245	0.112	0.112	0.177	0.476	19.5
90-120	1.142	0.072	0.072	0.155	0.551	24.9

Table 3.5 Crop coefficients for sorghum and pigeonpea based on observed results from 2015 and 2016 growing years.

Parameter name	Explanation	Unit	Sorghum	Pigeonpea (MD)	Pigeonpea (LD)
Tbase	Base temperature	°Cd	8[b]		
tt_emerg_to_endjuv	Thermal time from emergence to end of the juvenile phase	°Cd	301		
photoperiod_crit1	Day length photoperiod to inhibit flowering	H	12.8[c]		
photoperiod_crit2	Day length photoperiod for insensitivity	H	13.2[c]		
photoperiod_slope	Photoperiod slope	°C/H	600[c]		
tt_endjuv_to_init	Thermal time from end of juvenile to floral initiation	°Cd	124		
tt_flag_to_flower	Thermal time from flag leaf to flowering	°Cd	176		
tt_flower_to_start_grain	Thermal time from flowering to start of grain fill	°Cd	80[a]	100[a]	746
tt_flower_to_maturity	Thermal time from flowering to physiological maturity	°Cd	898		
tt_emergence	Thermal time to emergence	°Cd			400
y_tt_end_of_juvenile	Thermal time from end of juvenile to floral initiation	°Cd		630	
y_tt_floral_initiation	Thermal time from initiation to flowering	°Cd		300	203
y_tt_start_grain_fill	Thermal time to start grain fill	°Cd		470	746
tt_end_grain_fill	Thermal time to end grain fill			30	34

[a] Default values in APSIM; [b]value obtained from Hodges (1990); [c]values obtained from Akinseye et al, 2017; MD medium duration; LD long duration.

Management: Management input variables such as sowing date, sowing density, sowing depth, fertilizer application were set based on field experiment data. For the intercropping simulation, the component crop specific coefficients with the sole crop system were used. The two crops were sown at the same time and linked through the canopy module without changing soil, weather or management input. Within the management node, sowing date was set to fall in between 14 May 2015 - 30 May 2017. Sorghum and pigeonpea were sown when at least 30 mm of rainfall was received, and topsoil water content was at least 50%. Sowing depth for both sorghum and pigeonpea was set at 0.05 m. Sowing densities were set to reflect densities in the experiment with the exception of sorghum which was modified to 5.0 plants/m as actual density was not yielding any biomass results. Also, row spacing was same as on the field (0.75 m). An application of 100 kg/ha DAP (starter, 12 DAS) and 50 kg/ha Urea (top-dress, 23 DAS) fertilizers was added 35 days after planting to sorghum and pigeonpea at SkoHP and Wa sites. Compost (888 kg/ha dry weight) was added to the crops at SkoLP.

Model calibration was performed on a specific planting density (5 000 plants/hill), then evaluated with different density. The use of same plant population densities in calibration and validation can reduce model estimation errors for total biomass and grain yield

Calibration

Model calibration was undertaken by matching the 2015 observed sorghum yield and pigeonpea biomass data from the SkoLP site with simulated outputs. To achieve this, the model was first calibrated by calculating crop coefficients describing the varieties in this study by using a combination of measured and literature data (Table 3.5).

Secondly, calibration for soil N and P inputs for the SkoLP soil, this led to better predict the observed sorghum and pigeonpea yield at the site. The pH at SkoLP was adjusted from 5 to 6.5 to avoid any effect of nitrification, which was occurring at this site based on soils data. Calibration was completed when a balance was achieved between observed and simulated parameters using statistical indices described below.

Model evaluation and validation

Data collected during the 2015 and 2016 growing season were used to test the performance of the model from the SkoLP, SkoHP and Wa sites. APSIM does not calculate WUE directly; however, it is able to simulate biomass and soil water inputs. These simulated outputs were used to calculate WU and WUE. In APSIM WU is estimated as:

WU = (in-crop rainfall) + (SWS) – (SWH)…………………………………………..Equation 5

WUE $(\text{kg ha}^{-1}\text{mm}^{-1}) = \frac{\text{Total biomass}}{\text{WU}}$………………………………………………Equation 2

where in-crop rainfall = rainfall between sowing and crop harvest; SWS = soil water at sowing; SWH = soil water at harvest (harvest here refers to the physiological maturity stage).

Statistical indices for model performance

Model performance in simulating crop phenology, total soil water, biomass, yield, WU and WUE of sorghum and pigeonpea cropping systems was evaluated by statistically analyzing simulated (model-estimated) output against observed data using One-way ANOVA. The goodness of fit was assessed by comparing simulated with observed data using the following statistical indices:

(1) Root Mean Square Error (RMSE) reflects a magnitude of the mean difference between observed and simulated results (Willmott, 1981).

$$\text{RMSE}=\left[n^{-1}\sum\left(\text{simulated-observed}\right)^{2}\right]^{0.5} \text{......................................Equation 6}$$

(2) Relative RMSE (RRMSE) gives a measure (%) of the relative difference between simulated and observed data. The performance of the model is very good if the RRMSE < 10%, good if RRMSE ≈ 15%, and satisfactory if RRMSE ≈ 20% (Ma et al., 2011).

$$\text{RRMSE}=\left[n^{-1}\sum\left(\text{simulated-observed}\right)^{2}\right]^{0.5}\times\frac{100}{M} \text{..............................Equation 7}$$

where, n is number of observations, M is the mean of observed variable.

(3) Linear regression (1:1) plot was conducted between simulated and observed data to inform whether the model under or over-predicted measured yields, i.e. the direction and magnitude of bias. It provides a visual assess of how well the model is performing – if all on the 1:1 line, then perfect prediction, the scatter above/below gives an idea of the bias tendency in the predicted, relative to the observed.

(4) Coefficient of determination (R^2) was calculated between observed and predicted. Note that this does not account for model bias. The R^2 value ranges from 0 and 1. $R^2 = 1$ indicates a perfect correlation between observed and simulated results, and $R^2 = 0$ means no correlation between the two results (Ma et al., 2011).

RESULTS

Crop phenology

APSIM simulated the days to flowering and maturity of pigeonpea across all sites with an overall RMSE estimate of 15 and 33 days, respectively (Figure 3.1). There was agreement between the observed and simulated days to flowering and physiological maturity, with overall correlation coefficient (R^2**)** values of 0.73 and 0.61, respectively. The performance of the model was good with RRMSE of 14% and 19%, respectively. Also, there was no significant difference of mean between observed and simulated values across sites.

The model simulated sorghum days to flowering and physiological maturity very good with RRMSE of 12% and 15%, respectively. The overall RMSE estimate for days to flowering and maturity was 11 and 19 days, respectively (Figure 3.2). The model overestimated sorghum days to physiological maturity. There was significant difference of mean between the simulated and observed number of days to maturity (*P value* = 0.0018).

Total soil water

The model overpredicted total soil water across sites, relative to observed total soil water. The model simulated total soil water dynamics with R^2 of 0.51, RMSE 60 mm and RRMSE 40% (Figure 3.3). Initial simulation showed higher total soil water across sites compared to the observed data.

Grain yield

The model overestimated pigeonpea grain yield for all three sites, except SkoLP (RMSE = 128 kg ha^{-1}) (Figure 3.4). There was a significant difference of mean between observed and simulated grain yield. For sorghum, APSIM underestimated grain yield (Figure 3.5). Grain yield was simulated relatively better at SkoHP (RMSE = 604 kg ha^{-1}) than SkoLP (RMSE = 739 kg ha^{-1}) and Wa (839 kg ha^{-1}) sites. There was no correlation between observed and simulated values for sorghum grain yield.

Total aboveground biomass

Pigeonpea total biomass was underestimated by the model (RMSE = 1611 kg ha^{-1}, RRMSE 48% and R^2 = 0.07). The observed total biomass was significantly different from simulated (*P value = 0.0101*). The RMSE across sites was 2403 kg ha^{-1}, 2565 kg $ha^{-1}$and 1795 kg ha^{-1}, respectively for SkoLP, SkoHP and Wa (Figure 3.6). Simulation of sorghum total biomass on the other hand, matched observations closely with an average R^2 of 0.73 (Figure 3.7; RMSE = 1262 kg ha^{-1}, RRMSE = 28%).

Water use under sole crop systems

APSIM simulated WU under sole pigeonpea very good across sites (overall RMSE = 82 mm, R^2 = 1.0, RRMSE = 9% (Figure 3.8). The Wa site had the least RMSE estimate of 38 mm compared to SkoHP (83 mm) and SkoLP (109 mm).

Model simulation of sole sorghum WU across sites was comparable with observed values (Figure 3.9; RMSE= 104 mm, R^2 = 0.9, RRMSE= 12%). The Wa site had the lowest RMSE estimate of 80 mm. The SkoHP and SkoLP sites had RSME of 109 mm and 120 mm, respectively.

Water use in intercrops

Simulation of WU under intercropped pigeonpea systems matched closely with observed values. The overall performance of the model was very good with RRMSE of 11%, RMSE = 94 mm, R^2 = 1.0 (Figure 3.10). Numerically, simulated WU under sole crop stands seem higher but was not significantly different from the observed values (*P value = 0.5285*).

Water use under intercropped sorghum was also simulated very well by the model (Figure 3.11; RRMSE of 10%, RMSE = 91 mm, R^2 = 1.0).

Water use efficiency

Under sole cropped system, the model simulated pigeonpea WUE with an average RSME of 1.86 kg mm^{-1}, R^2 = 0.53, RRMSE = 48%. The intercropped system also had RSME estimate of 2.0 kg mm^{-1}, R^2 = 0.36, RRMSE = 69% (Figure 3.10). The performance of the model in predicting pigeonpea WUE was poor.

Simulation of sorghum WUE under both sole and intercrop systems was done very well by the model (Figure 3.11). The simulated values are in agreement with observed values. Sole crop system WUE had RMSE estimate of 2.33 kg mm^{-1}, R^2 = 0.76 and RRMSE = 36%. Intercropped system WUE also had RMSE = 1.06 kg mm^{-1}, R^2 = 0.91 and RRMSE = 20%.

DISCUSSION

Crop phenology

The APSIM model was able to simulate crop growth duration of both sorghum and pigeonpea with good accuracy. In both field experiments and model simulation, cropping system did not influence on days to flowering in either species. This result is similar to that reported by (Akinseye et al., 2017; Hammer et al., 2010). Both studies found good fit with observed and simulated sorghum phenology following the use of calculated crop specific coefficients. In contrast, Ncube et al., (2009) reported that the use of existing cultivar parameters in APSIM led to a good prediction of the phenology for pigeonpea, cowpea and sorghum. In their study, they used short duration pigeonpea and early sorghum variety.

The model simulated time to flowering in pigeonpea with minimized RMSE compared to time to physiological maturity. The ability of APSIM to predict well flowering in pigeonpea has been reported previously (Robertson et al., 2001). Overprediction of pigeonpea date to maturity (about 22 days late) compared to actual observed date has also been reported, and this deserves attention by model developers (Ncube et al., 2009). One challenge that has been highlighted by Robertson et al. (2001) is the difficulty in determining physiological maturity in the field due to the occurrence of multiple flushes of pods in this indeterminate plant.

Overall, the model simulated the growth duration of both sorghum and pigeonpea in a satisfactory manner. However, the results obtain also suggests further improvement in the calibration process is needed to fully capture the growth duration of pigeonpea and sorghum with the minimum possible RMSE estimate. This is in line with the observation of Ncube et al. (2009) that the crop growth parameters in APSIM describing the pigeonpea cultivars need improvement.

Total soil water

The prediction of changes in soil water and nitrogen with sufficient accuracy is important in simulating production systems credibly in the APSIM model (Probert et al., 1998). In general, simulation of total soil water by the model was good, even though there was overestimation of about 22% by the model. The over-prediction could be attributed to the incompatibility of observed data with estimated soil water values, or the inherent variability in the observed soil water data. Across sites, total soil water varied considerably, and this was captured well by the model. In the absence of experimental data for LL, DUL and SAT, there is no certainty that the parameter values we used are the correct match. The prediction ability of APSIM in simulating soil water dynamics under continuous corn and corn-soybean rotations has been reported previously (Archontoulis et al., 2014; Dietzel et al., 2016). However, uncertainty in water retention parameters due to soil spatial variability is a continuing challenge (Archontoulis et al., 2014). Likewise, there are often substantial discrepancies between observed and simulated soil water with APSIM (Ncube et al., 2009).

Grain yield

The model predicted pigeonpea grain yield under low P conditions reasonably well at the SkoLP site. The same observation has been made by (Delve et al., 2009). They observed a good fit between observed and simulated maize and bean crop yields grown in rotation on different rates and sources of P. However, there was significant overestimation of pigeonpea grain yield at the other two sites. This was expected as model calibration was done with dataset from the SkoLP site. In this study, crop failure with regards to pigeonpea grain yield was observed on the field. Also, the growth and performance of pigeonpea was variable across sites. Given the variability that existed in the measured pigeonpea grain yield, the crop model was not altered much to influence the prediction. The model was unable to capture the low grain yield of pigeonpea leading to the overestimation of pigeonpea grain yields. The overestimation can also be attributed to the difficulty in simulating crop failure due to the presence of pests which is not included in the model. The APSIM crop model assumes a disease-free crop and this often create large discrepancies between simulated and observed yields (Asseng et al., 1998).

The overall simulation of sorghum grain yield was good. This result agrees with Akinseye et al. (2017) and Ncube et al. (2009) reporting good prediction of sorghum grain yield by APSIM. However, there was a significant overestimation at the Wa site. APSIM was not able to capture fully the effect of delayed sowing at Wa, which has been shown to be associated with low yields (Farré et al., 2007; Kumar et al., 2008).

Total aboveground biomass

Pigeonpea total biomass was under-predicted by the model. The same under-prediction of pigeonpea total biomass is reported in an earlier study (Ncube et al., 2009). The difficulty in gaining good agreement between simulated and observed total biomass at maturity is due, in part, to the issue of variable leaf loss in pigeonpea (Robertson et al., 2001). Notwithstanding these simulation issues, APSIM still had overall satisfactory predictive capability for pigeonpea phenology, biomass and grain yield (RRMSE of 14 - 47%).

The slight underestimation of sorghum biomass and yield can be related to the low plant density and the default APSIM radiation use efficiency (RUE of 1.25 g/MJ) value used. The modification of plant population density in the model to capture effects of aphid damage or poor plant stand on sorghum observed total biomass production led to good prediction (Ncube et al., 2009).

Potential biomass production in APSIM requires reliable values of leaf area index (LAI), radiation extinction coefficient and RUE (Archontoulis et al., 2014; Robertson et al., 2001). These two parameters have great influenced on biomass production. We maintained the default APSIM values for RUE and this may have influenced simulation of total biomass production. The dataset used for calibration was under limiting soil nutrient conditions and this may have affected the simulation of response at the other two sites.

Water use (WU) and water use efficiency (WUE)

Water use in this study was calculated as rainfall during the crop growth (in-crop rainfall) plus changes in soil water content as measured by access tubes. The model simulated WU under both sole and intercrop systems of sorghum and pigeonpea very well. This agrees with findings of other studies on sorghum and legume rotations (Ncube et al., 2009) and sorghum-cowpea intercrop systems (Chimonyo et al., 2016). In this study, WU was influenced more by changes in soil water content over the growing season than the amount of rainfall. This was captured well by the model.

There was poor prediction of pigeonpea WUE by the model under both sole and intercrop systems. This could be attributed to the inability of the model to simulate of pigeonpea total biomass, as the observed biomass was substantially higher than predicted. However, the general performance of the model in simulating WUE of sorghum and pigeonpea under intercrop systems was satisfactory. The results in this study confirms earlier findings that APSIM is able to simulate WU and WUE for a range of cropping systems, although pigeonpea simulation under

West Africa conditions requires further calibration (Asseng et al., 2001; Chimonyo et al., 2016; Dietzel et al., 2016).

CONCLUSION

The APSIM model was used to simulate growth and productivity of sorghum and pigeonpea grown under different cropping systems, sites and with varying soil P. The model captured well the effect of low P on crop growth at the SkoLP site. The study thus highlights how the P routines in APSIM can be specified to produce output that matched field observations. The performance of the model in predicting crop phenology was good; however this was not the case for several other parameters including pigeonpea biomass which was underestimated. APSIM is also not an appropriate model to simulate the effect of pests on pigeonpea, thus it would need to be linked to a pest prediction model to represent the field situation with a pest-susceptible crop such as pigeonpea. As pigeonpea is a novel crop to be grown in Ghana, adaptation of the crop to the environment needs work, and this poses a challenge to model parameterization as well. Overall, APSIM performance was robust considering these challenges, and it provided some insights into the potential for gains in water use efficiency through growing mixed cropping systems of pigeonpea-sorghum, relative to sole crop systems. As pigeonpea varieties were not adapted to this environment grain yields were very low in our field experiments, but the high biomass produced and the APSIM modeled grain yields shown here both point to the benefit possible from this alternative crop, if adapted varieties of pigeonpea could be identified.

APPENDIX

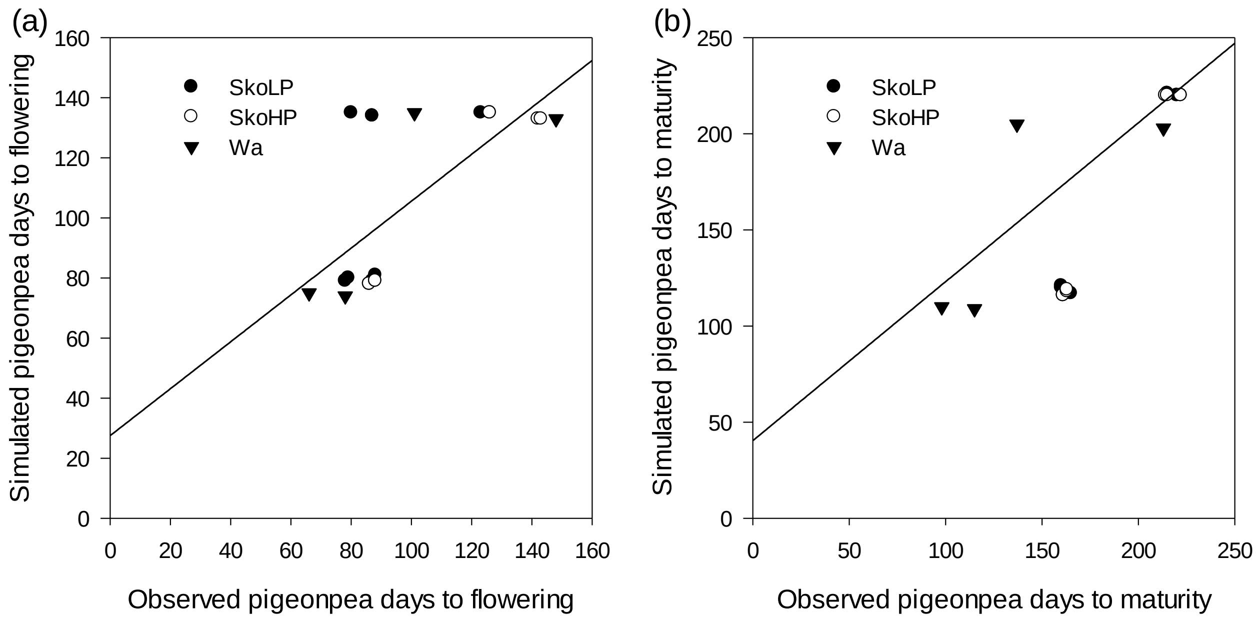

Figure 3.1 Simulated pigeonpea phenology and observed values for all cropping systems across sites for two growing seasons (2015 and 2016). (a) Flowering: R2 = 0.73, RMSE = 15 days, RRMSE = 14%; (b) Maturity: R2 = 0.61, RMSE = 33 days, RRMSE =19%.

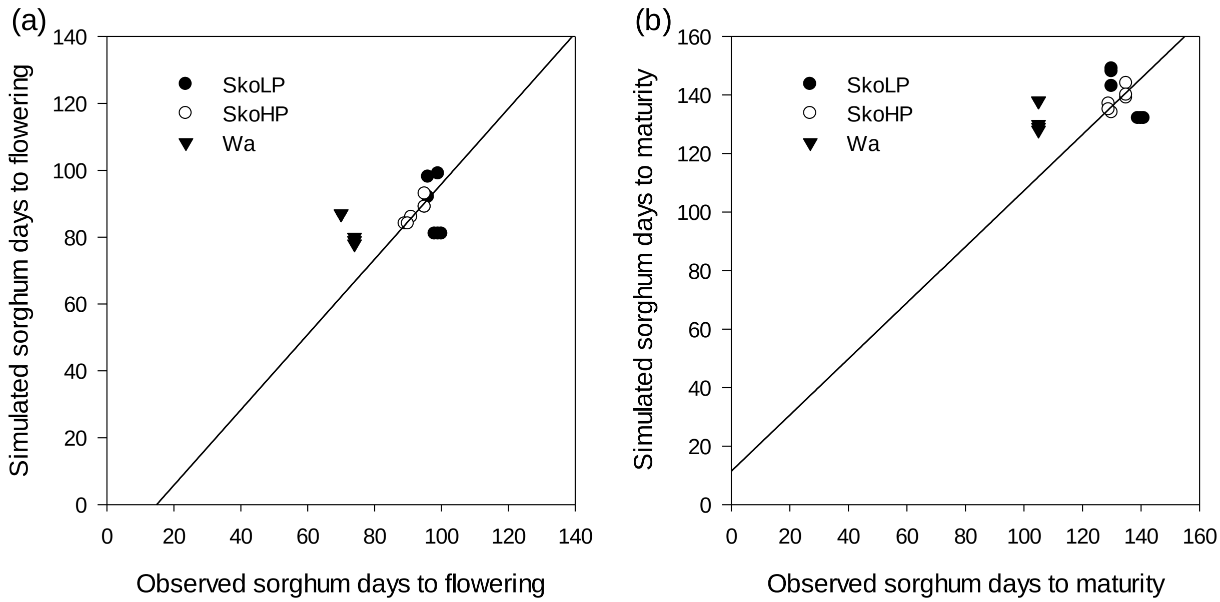

Figure 3.2 Simulated sorghum phenology and observed values for all cropping systems across sites for two growing seasons (2015 and 2016). (a) Flowering: R2 = 0.82, RMSE = 11 days, RRMSE = 12%; (b) Maturity: R2 = 0.67, RMSE = 19 days, RRMSE =15%.

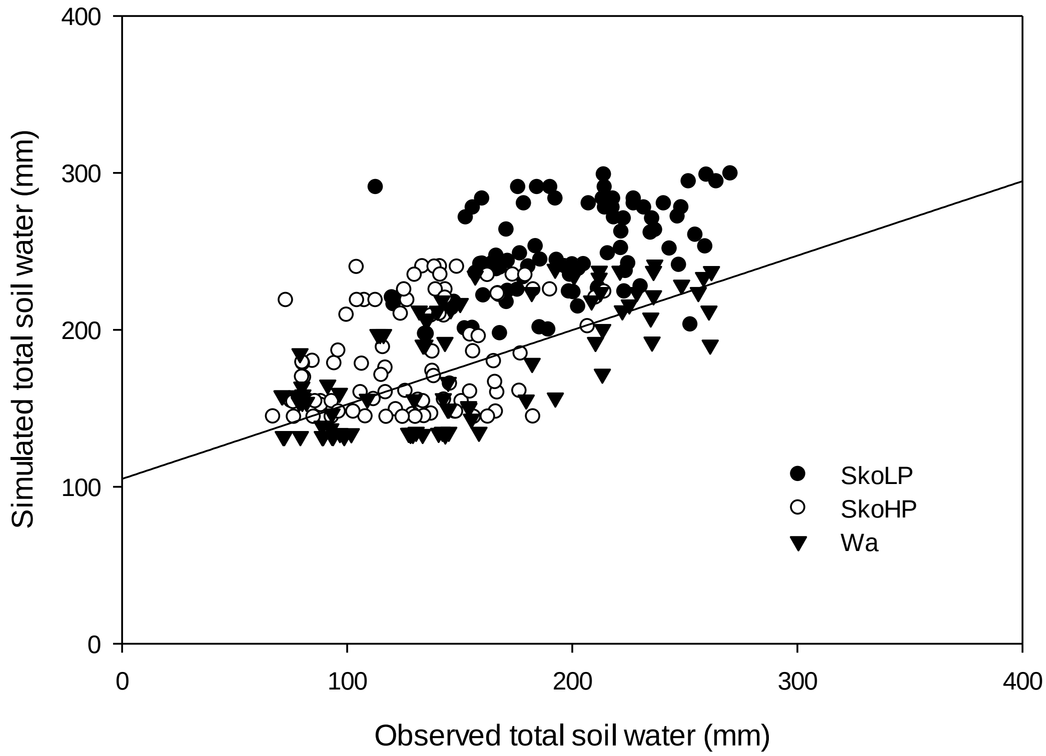

Figure 3.3 Simulated and observed total soil water under all cropping systems across sites for two growing seasons (2015 and 2016), R2 = 0.51, RMSE = 60 mm, RRMSE = 40%.

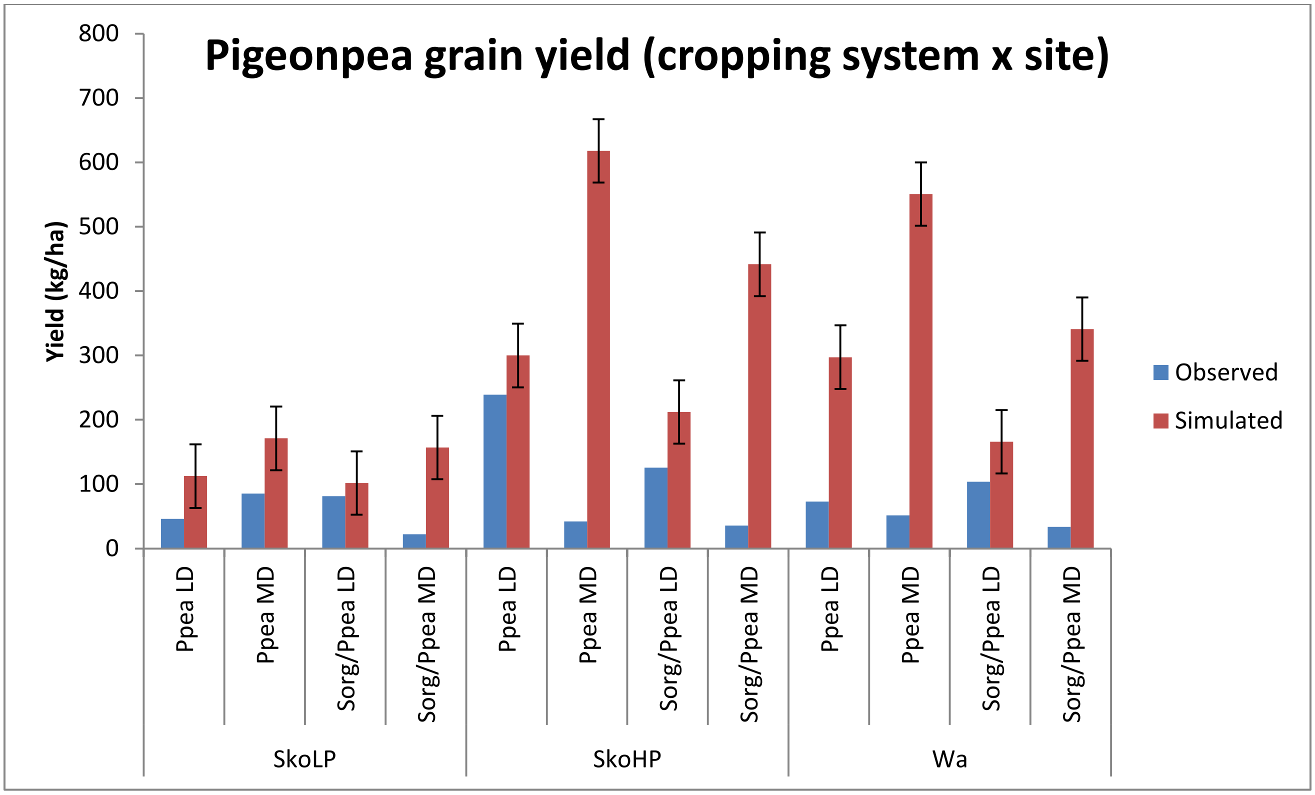

Figure 3.4 Simulated and observed pigeonpea grain yield for all cropping systems and sites for two growing seasons (2015 and 2016). Error bars represent standard error of cropping system means.

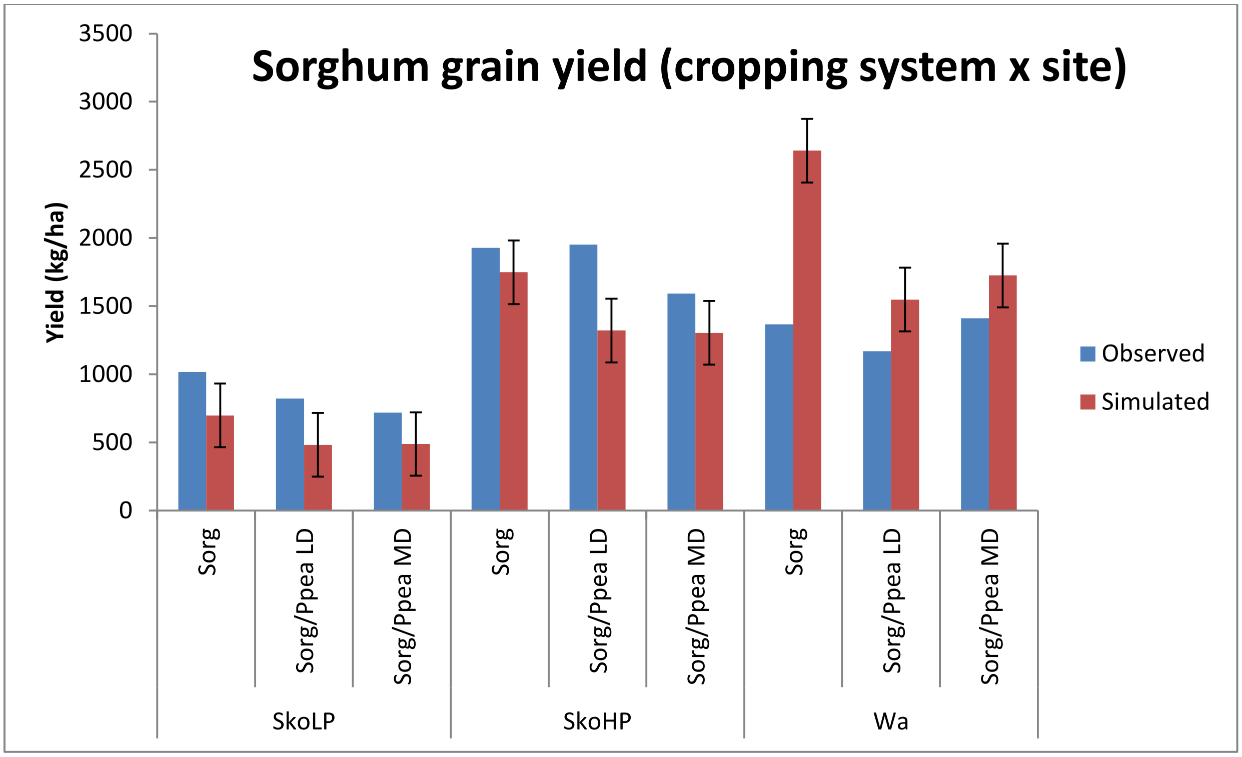

Figure 3.5 Simulated and observed sorghum grain yield for all cropping systems and sites for two growing seasons (2015 and 2016). Error bars represent standard error of cropping system means.

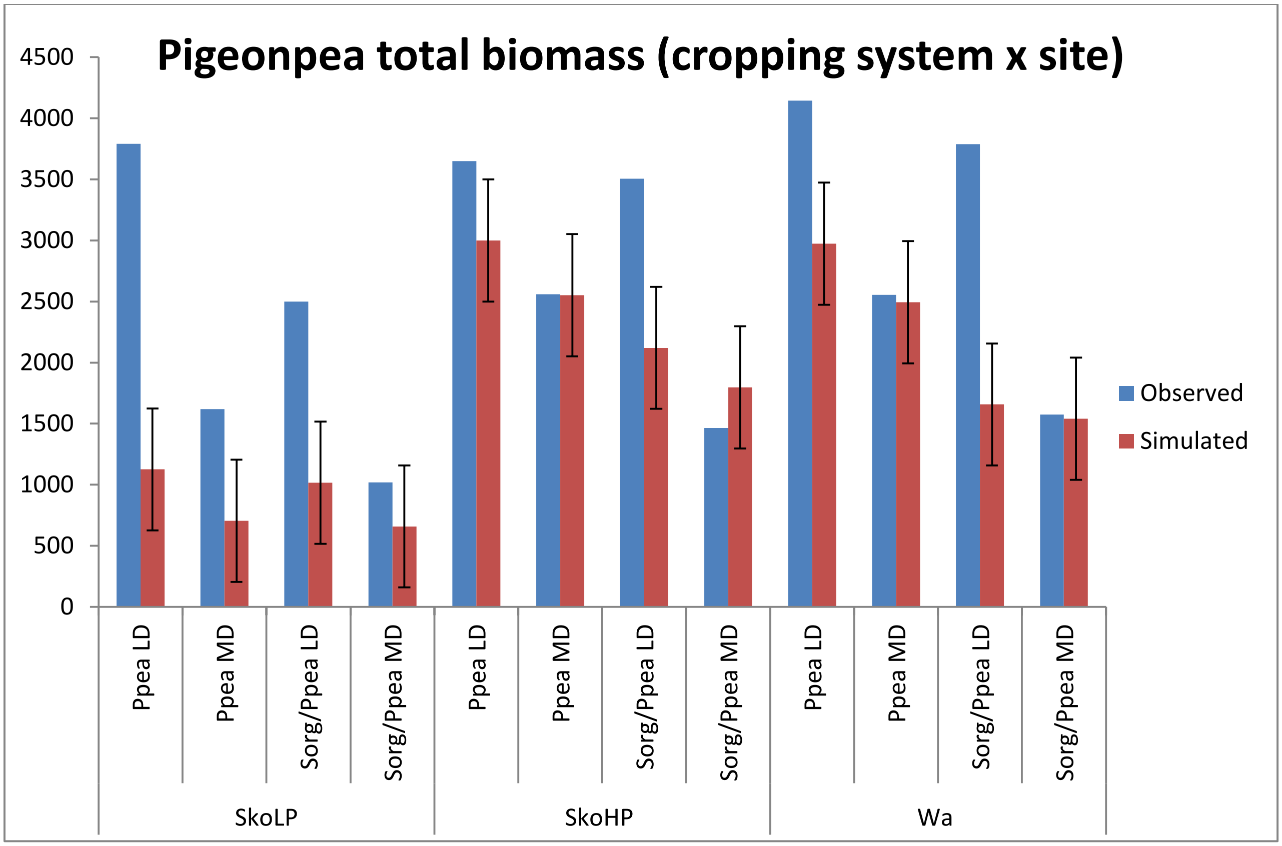

Figure 3.6 Simulated and observed pigeonpea total biomass for all cropping systems and sites for two growing seasons (2015 and 2016). Error bars represent standard error of cropping system means.

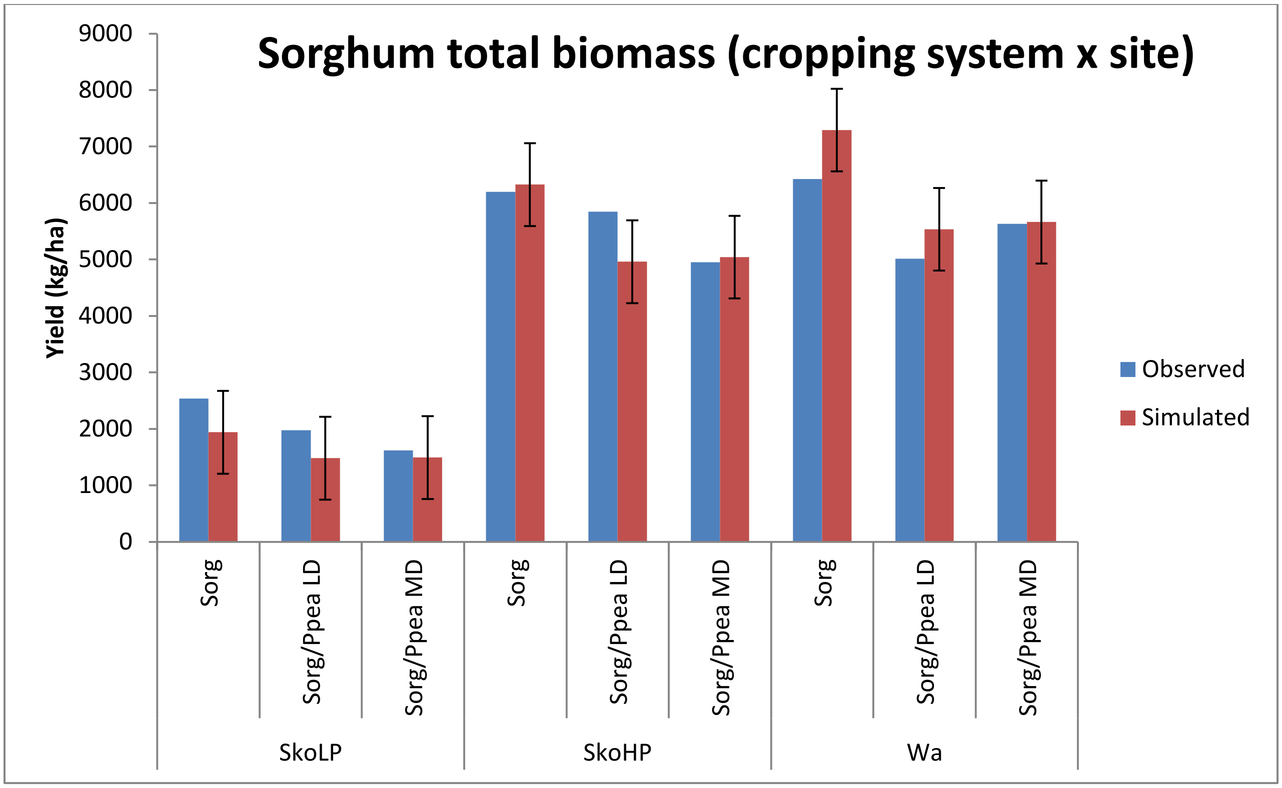

Figure 3.7 Simulated and observed sorghum total biomass for all cropping systems and sites for two growing seasons (2015 and 2016). Error bars represent standard error of cropping system means.

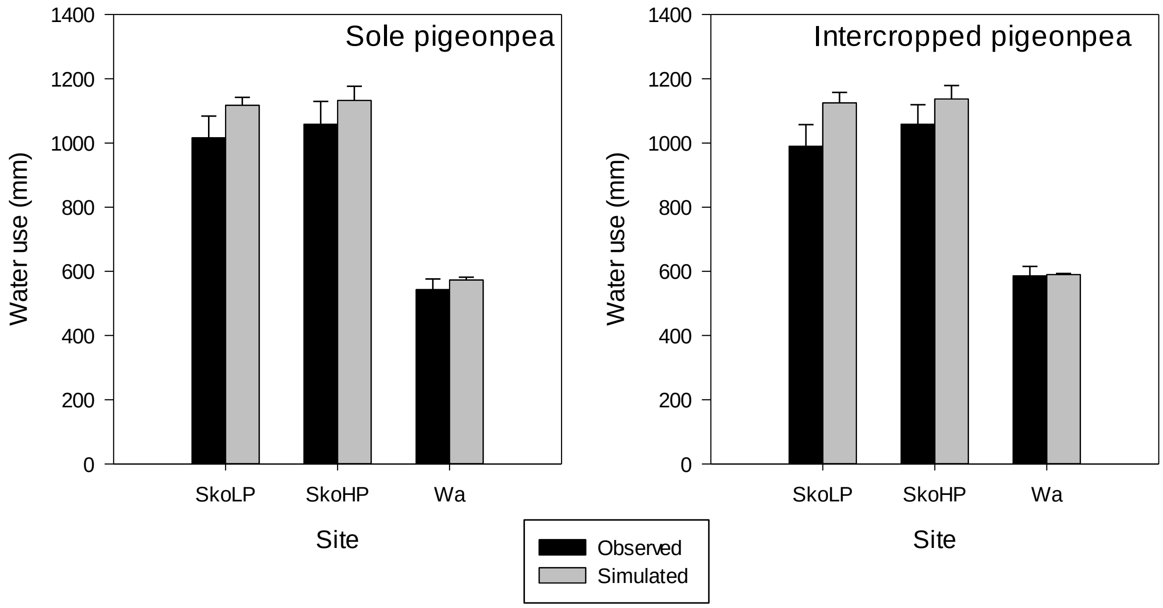

Figure 3.8 Simulated and observed pigeonpea water use under sole and intercrop cropping systems across sites for two growing seasons (2015 and 2016). Error bars represent standard error of cropping system means.

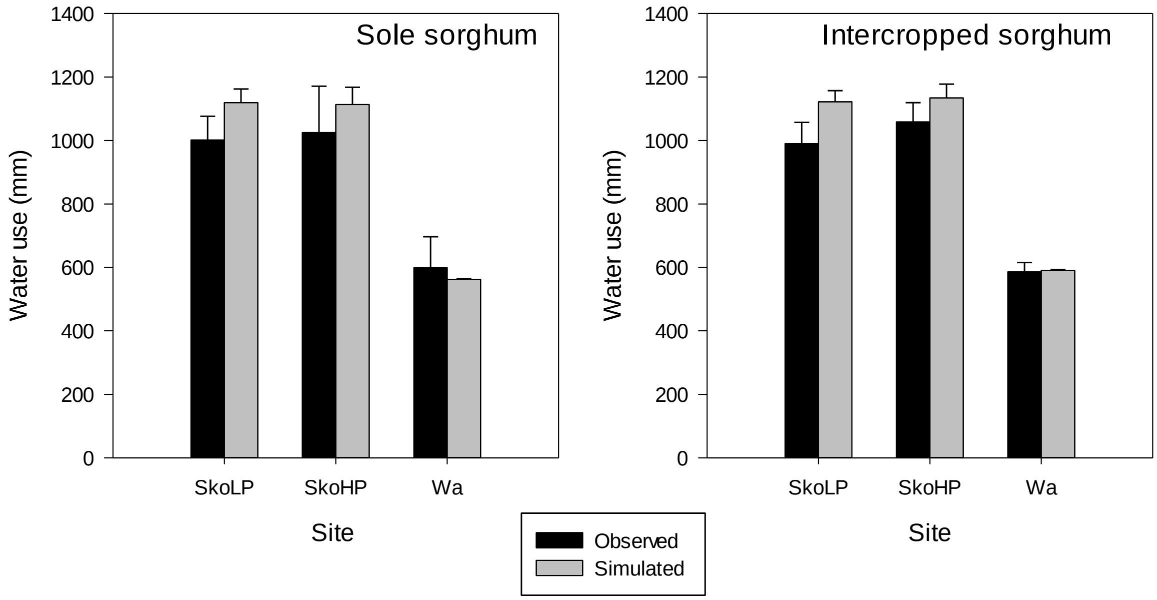

Figure 3.9 Simulated and observed sorghum water use under sole and intercrop cropping systems across sites for two growing seasons (2015 and 2016). Error bars represent standard error of cropping system means.

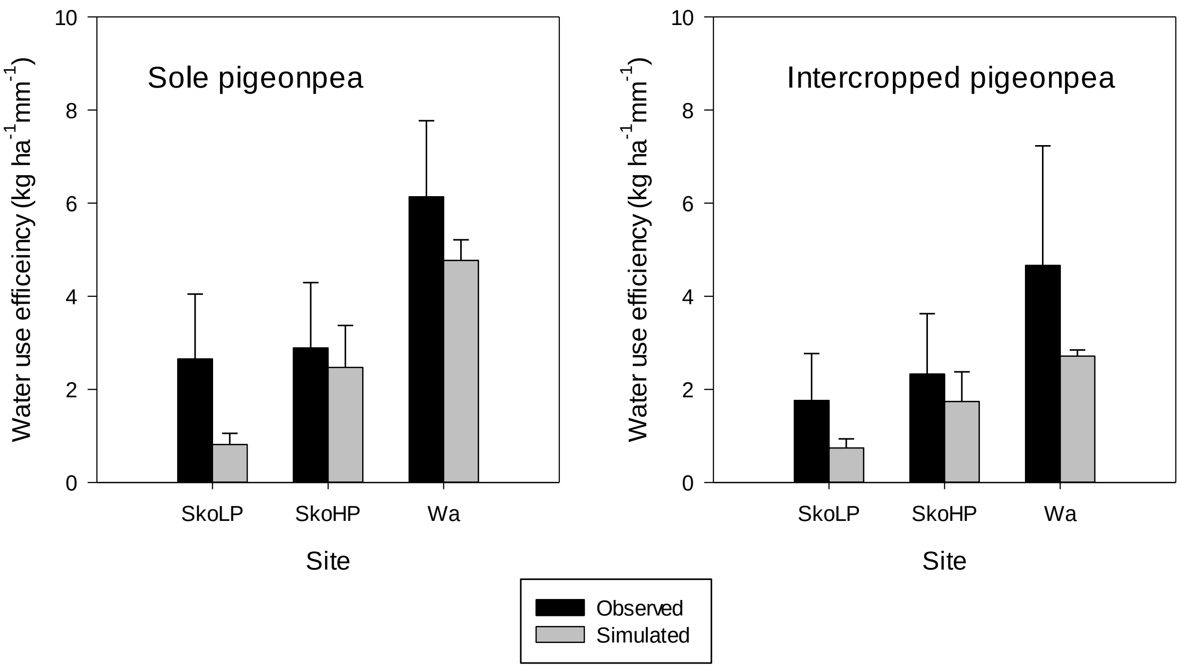

Figure 3.10 Simulated and observed pigeonpea WUE under sole and intercrop cropping systems across sites for two growing seasons (2015 and 2016). Error bars represent standard error of cropping system means.

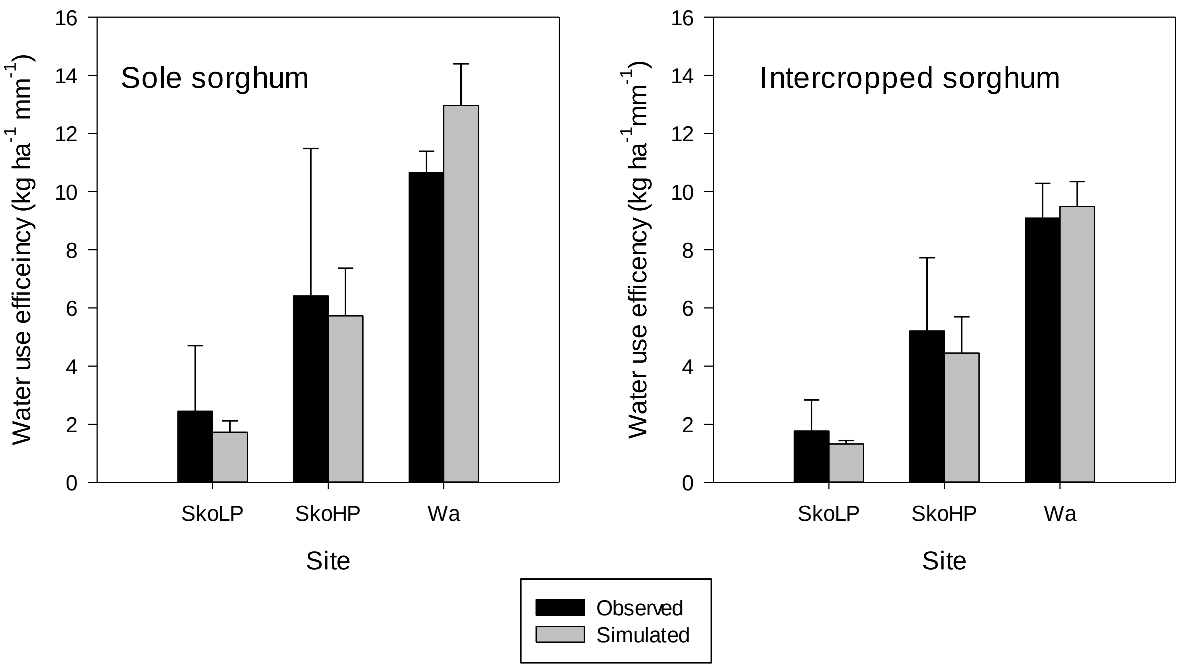

Figure 3.11 Simulated and observed sorghum WUE under sole and intercrop cropping systems across sites for two growing seasons (2015 and 2016). Error bars represent standard error of cropping system means.

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