EFFECT OF INTERCROPPING SORGHUM WITH COWPEA AND NITROGEN APPLICATION ON GROWTH AND YIELD OF SORGHUM (*Sorghum bicolor* (L.) MOENCH)

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DECLARATION

This thesis is my original work and has not been presented for the award of a degree in any other university**.**

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DEDICATION

To my father, Elia Ramba, who has played an instrumental role in my education, especially during the MSc. degree course and ably provided mental and financial support to enable me complete the programme. My mother, Cicilia Poni, for the continued prayers to see me finish the MSc. degree. Finally, my wife, Poni Rose, for the patience and single-handedly managing the family affairs while I was pursuing this programme.

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LIST OF ABBREVIATIONS AND ACRONYMS

ASALs	Arid and semi-arid lands
CGR	Crop growth rate
CS	Cropping system
DAF	Days after planting
EC50	Time to loss of 50% maximum SPAD (peak leaf greenness)
FAO	Food and Agriculture Organization of the United Nations
GOK	Government of Kenya
HI	Harvest index
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
KALRO	Kenyan Agricultural and Livestock Research Organization
LAI	Leaf area index
LER	Land equivalent ratio
NUE	Nitrogen use efficiency
RUE	Radiation use efficiency
RS	Rate of senescence
SPADmax	Maximum SPAD (peak leaf greenness)
SPADmin	Minimum SPAD
TSP	Triple supper phosphate
UN	United Nations
WAP	Weeks after planting
WUE	Water use efficiency

ABSTRACT

Intercropping is an important sustainable cropping system in which two or more crops are grown in the same piece of land. Despite the development of high yield varieties, sorghum yields have remained low due to low soil fertility, inappropriate cropping practices and limited use of fertilizer nitrogen (N). The integration of cowpea into sorghum-based crop systems and N use are likely to increase yield. However, how sorghum-cowpea compatibility, N use and their interactions impact yield of the companion crops is only partially understood. Further, leaf senescence regulates grain yield and quality in sorghum. However, the effect of intercropping sorghum with cowpea on the patterns of leaf senescence of the former is not known. Therefore, an experiment was conducted in 2018/2019 short rain season at Katumani and Igoji KALRO research stations to: (i) determine the effect of intercropping and nitrogen rates on the growth and yield of selected varieties of sorghum and cowpea; (ii) investigate the effect of intercropping sorghum with cowpea on sorghum time-course of leaf senescence and its association with grain yield. Cropping systems (sole crops of two varieties each of sorghum and cowpea, and cereal-legume intercrop combinations of the two varieties of sorghum and cowpea), and three rates of N (0, 40, and 80 kg N ha^{-1}) were laid out in a randomized complete block design with split plot arrangement, replicated three times. Cropping systems formed the main plots while N rate formed the sub-plots. Sorghum and cowpea growth data were collected every 10 days, which started at 4 weeks after planting throughout physiological maturity while grain yield and yield components data were collected at physiological maturity (harvest). Sorghum leaf senescence was assessed from flowering to maturity at both whole-plant level and flag-leaf level. At the whole-plant level, leaf senescence was scored visually by counting the number of leaves that presented more than 50% green leaf area while the greenness of the flag leaf was tracked using SPAD 502 chlorophyll meter. A logistic function in SigmaPlot was fitted to estimate four parameters of senescence in sorghum, including minimum and maximum SPAD units, time to loss of 50% maximum SPAD (EC50) and the rate of senescence (RS). Data were subjected to analysis of variance using Genstat and means were separated using the least significance difference test ($p \leq 0.05$). Intercropping significantly reduced leaf area index (LAI) of Gadam by 0.53 units but LAI of Serena was not affected by intercropping. Addition of 80 kg N ha^{-1}

increased overall sorghum LAI by 0.08 units (28%) compared with control plots where no fertiliser was applied but no differences were detected between 40 and 80 kg N ha^{-1}. Further, intercropping reduced the number of fertile tillers m^{-2} by 6 tillers but addition of N significantly increased the number of fertile tillers m^{-2} by 1 tiller. Similarly, intercropping significantly reduced CGR of sorghum by 54% for Serena but CGR of Gadam was not affected by intercropping however addition of 80 kg N ha^{-1} increased overall sorghum CGR by 30% but without difference between 40 and 80 kg N ha^{-1}. Grain yield of Gadam exceeded Serena by 1.33 t ha^{-1} but irrespective of the cowpea variety, intercropping significantly reduced the grain yield of sorghum by 53% for Gadam and 42% for Serena in Igoji and by 54% for both varieties in Katumani. Addition of 40 kg N ha^{-1} significantly increased grain yield of sorghum by 0.53 t ha^{-1} (27%) compared with control plots were no fertiliser was applied but no difference was detected between addition of 40 and 80 kg N ha^{-1}. The harvest index (HI) and N uptake of sole sorghum exceeded counterparts in an intercrop with cowpea by 30% and 0.01 kg m^{-2} respectively. Addition of N significantly increased N uptake by 0.006 kg m^{-2} but had no significant effect on HI. Sorghum grain yield was positively and significantly correlated with leaf area index, fertile tillers, panicle weight, harvest index and crop growth rate under sole cropping system however, sorghum grain yield was inconsistently correlated with these traits under intercrop system. Similarly, intercropping significantly reduced the CGR of cowpea by 50% for K80 and 25% for M66 and grain yield of K80 by 54% but grain yield of M66 was not affected by intercropping. On the other hand, addition of N had no significant effect on cowpea growth and yield. The total land equivalent ratio (LER) in both sites was greater unity: 1.4 in Igoji and 1.6 in Katumani. Intercropping reduced the peak leaf greenness (SPADmax) of the flag by 8 SPAD units but delayed leaf senescence at whole plant by 0.2 leaves plant^{-1} day^{-1} compared with sole crop system. On the other hand, fertilizer N delayed leaf senescence at both whole-plant and flag-leaf levels. While EC50 did not correlate with grain yield, sorghum yield was positively and significantly correlated with SPADmax, SPADmin and the rate of leaf senescence. The results therefore suggest that the peak leaf greenness of the flag leaf in the period bracketing flowering determined grain yield but the delay in leaf senescence at whole plant level might have been non-functional. Further, although intercropping reduced sorghum yield, present results show that there is potential to exploit cropping system x N interactions to increase yield, especially in wetter environments than in areas with low rainfall. Lack of significant differences in grain yield between the application of 40 and 80 kg N ha^{-1} suggests that sorghum yield could be maximized at lower N rates. However, further studies are needed to establish the economically optimal N rate in sorghum production. Gadam variety is recommended for commercial production under sole cropping system with addition of N at a rate of 40 kg N ha^{-1} as raw material for making malt and as food security crop in the study areas due to its high yielding traits, short maturity period compared with Serena however the growth and yield performance of Gadam across ecological zones deserve further investigation. Intercropping and N fertiliser application is only recommended for sorghum production to improve household food security since sorghum/cowpea intercropping was more productive than sole (LER>1). Screening and breeding of more cowpea varieties compatible for sorghum intercropping is recommended. The effect of competition for resources in sorghum/legume intercropping system and source-sink relationship on sorghum leaf senescence and yield deserve further investigation.

Keywords: EC50, fertilizer nitrogen, intercrop system, leaf greenness, rate of senescence, SPAD, yield

CHAPTER ONE: INTRODUCTION

1.1. Background

The current population of Africa is 1.2 billion people however, by 2050 Africa's population is estimated to rise to 2.4 billion (UN, 2017). Hence, food production should be improved further without adversely affecting the fertility of the soil and the environment (Layek et al., 2018). However, poor management practices among small holder farmers can not realize a good balance between nutrient supply and plant demand which often causes environmental pollution and low crop yields (Dobermann, 2007). Additionally, yield losses of cereals like sorghum (*Sorghum bicolor* (L.) Moench) are high in dry environments resulting from moisture stress especially at grain filling stage (Kassahun et al., 2010). Land fragmentation practices due to increased population growth have also limited the available land for crop production amidst increasing food demands (Karanja et al., 2014). Therefore, cereal-legume intercropping is considered an appropriate and sustainable practices to increase crop productivity per unit area with reduced external inorganic fertilizer N supply due to the legume ability in the intercrop system to replenish soil nutrients by fixing N in the soil (Ladha and Chakraborty, 2016).

Intercropping system involves growing multiple crops simultaneously in the same piece of land (Iqbal et al., 2019). This practice has been in use for a long time and has contributed to achieve sustainability of the agriculture systems (Layek et al., 2018). Integration of legume such as cowpea into cereal-based cropping systems provides sustainable enrichment of soil physio-chemical properties due to its nitrogen fixing capacity in the soil and helps to stabilize yields by increasing the productivity of land hence protect farmers from the risk of crop failure (Ndiso et al., 2016). The legume improves the nitrogen economy of the cereal by either contributing nitrogen to the soil or removing less amount of soil nitrogen (Layek et al., 2018). Additionally, intercropping contributes to subsequent prevention and reduction of soil erosion and land deterioration through the effective ground cover (Nawal, 1997). Further, intercropping helps to achieve crop diversity in an agricultural system (Baulcombe et al., 2009). The productivity and profitability of intercrop systems can be assessed using various indices including aggressivity ratio, competition ratio, monetary advantage index and using the land equivalent ratio (LER) where yield attained in an intercrop system is expressed relative to yield in a sole crop system (Sibhatu and Belete, 2015).

Sorghum is an essential crop grown globally for food and feed (Deb et al., 2004). The crop is majorly consumed as a grain, but can also be processed into porridges, breads and largely used as raw material for making alcohol (Mundia et al., 2019). Sorghum annual production in Africa is estimated at 20 million metric tonnes representing about 61% of the global total land cultivated and 41%of total global sorghum production (ICRISAT, 2013; Mundia et al., 2019). However, Kenya is among the least sorghum producing countries in Africa where its overall annual production is only 0.6% of Africa's total annual production (Mitaru et al., 2012). Of the total sorghum annually produced in Kenya, 53% is utilised as food (either as grain or flour), 24% is processed to make malt, 11% is lost as waste, 10% for animal feed and 2% used as seed (Kilambya and Witwer, 2013).

Further, Kenya's sorghum productivity remains at 0.8 t ha^{-1} despite development of high yield varieties with expected potential yield of between 2 and 5 t ha^{-1} making Kenya a net importer of sorghum in the region (Ochieng, 2011; Kilambya and Witwer, 2013). This is because of low soil fertility (N deficiency), poor management practices, continuous nutrient mining without replenishment, unpredictably low rainfalls, pests and diseases, birds infestation and weeds such as striga with capacity to cause 40% to 100% crop loss in the Sub-Saharan region (FAO and ICRISAT, 1996; Mitaru et al., 2012). Further, sorghum production is characterized by low use of inputs due to high and unaffordable costs by smallholder farmers (Muui et al., 2013).

Additionally, sorghum inability to meet its nitrogen requirement through own fixation has contributed to major yield constraints (Franzmann, 1993; Dorcas et al., 2019). However, the demand for sorghum has increased in the recent past due to its use as raw material for beer production; however, the current production cannot meet this demand (Kilambya and Witwer, 2013). Therefore, intercropping sorghum with legume like cowpea with effective biological nitrogen fixation (BNF), would increase nitrogen (N) availability through 'N' fixation to be utilized by sorghum hence increasing overall crop productivity (Egesa et al., 2016). Further, integration of fertilizer N at reduced rate to supplement N fixed by the legume symbiotically would help fully meet the N requirements of sorghum, reduce cost of fertilizers N and increase grain yield (Shamme and Raghavaiah, 2016).

Primarily, cereal-legume intercropping aims at increasing productivity of crops per unit land area by ensuring growth resources are efficiently utilized (Layek et al., 2018). The legumes in an intercrop improve soil fertility through BNF and decrease the competition for nitrogen in soil (Egesa et al., 2016). Additionally, soil conservation can be achieved through intercropping due to increased ground cover, thus, will reduce soil erosion and excessive rate of evaporation (Layek et al., 2018).

Despite the wide practice of intercropping, crop yields have remained low. Further, the success of an intercrop system largely depends on the compatibility of the companion crops, cropping density and intensity of competition for growth resources (Vasilakoglou et al., 2008). For instance, sorghum grain yield was significantly reduced in an intercrop system attributed to inter-species competition for growth resources and space (Karanja et al., 2014). Additionally, Sibhatu and Belete (2015) reported that sole sorghum exceeded 31% of the intercropped sorghum yield. Other limitations are attributed to nutrient-depleting nature of cereals like sorghum hence the N symbiotically fixed by the legume in an intercrop system alone may not fully meet its N requirement without external fertilizer N supply (Layek et al., 2018).

Nitrogen (N) is among the most deficient nutrients in many agricultural soils for cereal production on a global basis but is essential in crop growth (Yagoub and Abdelsalam, 2010). Higher crop yields have been attained by increasing N addition and improving fertilizer N efficacy (Dobermann, 2007). Further, increased growth and yield of sorghum with addition of N in the form of urea has been reported (Ahmed and Tanki, 1997). However, N losses remain a challenge in agricultural systems where, 30-50% of the applied nitrogen fertiliser continue being lost through leaching, denitrification and runoff (Shamme and Raghavaiah, 2016). Therefore, agricultural best management practices are required to reduce nutrient losses and prevent negative impact on the environment (Roberts, 2007).

Further, the use of N-fertilizer is expected to rise to match the increasing food demand of a rapidly growing world-wide population hence optimization strategies such as precision application of N-fertilizer practices are required (Sawargaonkar et al., 2013). Additionally, the costs of inorganic fertilizers are continuously rising and unaffordable to most small holder farmers hence integrating legumes like cowpea with effective biological nitrogen fixation (BNF) in sorghum cropping systems could reduce on the amounts of fertilizer N to be externally supplied and will cushion farmers from the high costs (Sibhatu and Belete, 2015). However, information on the appropriate N rates for sorghum production in an intercrop system to improve nitrogen use efficiency (NUE) remains limited (Kanampiu et al., 1997). Further, while previous studies have reported that prolonged leaf greenness has been correlated with higher grain yield in monocarpic crops like wheat (Kitonyo et al., 2017) and maize (Kitonyo et al., 2018), the current knowledge on the effect of sorghum-cowpea intercropping and varying levels of nitrogen application on leaf senescence in sorghum and its association with sorghum grain yield remains limited.

1.2. Problem statement and justification

Sorghum (*Sorghum bicolo*r (L.) Moench) is an essential cereal as a food security crop and a raw material for making malt thus, increasing its productivity could end severe food insecurity and increase incomes of smallholder farmers in the dryland environments due to its unique traits of tolerating moisture stress and high yielding ability in a wide range of soils (Mwadalu and Mwangi, 2013). However, despite the development of improved varieties, the yield of sorghum has remained significantly low in the dryland environments (0.8 t ha^{-1}) in comparison to expected grain yield of between 2 and 5 t ha^{-1} due to soil infertility and inappropriate cropping practices (Kilambya and Witwer, 2013). The former has been attributed to nitrogen deficiency resulting from constant loss of soil nutrients (N) without replenishment and high cost of inputs affecting farmers' ability to apply sufficient N fertilisers to improve soil fertility while the latter results from limited information on appropriate cropping systems for sorghum production and limited skills among smallholder sorghum farmers (Kilambya and Witwer, 2013; Mwadalu and Mwangi, 2013). In Kenya, nitrogen deficiency and late water deficit account for yield losses of 37,000 and 11,000 tonnes per year (T yr^{-1}) respectively (Wortmann et al., 2009; Kassahun et al., 2010). As a result of the low sorghum yields ha^{-1}, most farmers engage in subsistence sorghum production making Kenya a net importer of sorghum to meet increased market demand (Ochieng, 2011). Therefore, in order to increase sorghum productivity to offset the current sorghum deficit, enhance food and nutrition security due to its nutritional importance as well as increase income of sorghum farmers through sale of sorghum as raw material for making malt, its critical to address the challenge of soil infertility in the dryland environments due to N deficiency and inappropriate cropping practices which are the main l root causes of low sorghum grain yield especially in the ASALs.

Intercropping sorghum with cowpea and nitrogen application may have the ability to enhance soil fertility. Additionally, cereal-legume intercropping could be a remedy to address moisture stress in the ASALs through improved land cover by the legumes which leads to retention of moisture and increased crop productivity per unit area of land available (Sibhatu and Belete, 2015). Also, a combination of intercropping and application of varying nitrogen rates would provide information on the appropriate nitrogen rates in an intercropping system that would optimize sorghum yields and ensure improved nitrogen use efficiency and profitability. Further, legume intercropping and fertilizer N application could prolong sorghum leaf senescence which has been reported to profoundly impact grain yield and quality by regulating source-sink relationships for nutrient demand (Feller et al., 2008; Gong et al., 2019). Further, prolonged leaf greenness has been correlated with higher grain yield in sorghum (Kassahun et al., 2010; Christopher et al., 2014), wheat (*Triticum aestivum* L.) (Kitonyo et al., 2017) and maize (*Zea mays* L.) (Kitonyo et al., 2018).

1.3. Objectives

The main objective was to improve the productivity of sorghum through intercropping and nitrogen fertilizer application. The study specific objectives were:

i. To determine the effect of intercropping and nitrogen on crop growth and yield of selected varieties of sorghum and cowpea

ii. To investigate the effect of intercropping sorghum with cowpea and fertilizer nitrogen on the time-course of sorghum leaf senescence

1.4. Hypotheses

i. Intercropping sorghum with cowpea and fertilizer N increases the yield of sorghum.

ii. Intercropping sorghum with cowpea and fertilizer N delays senescence of sorghum plants.

CHAPTER TWO: LITERATURE REVIEW

2.1. Importance and ecology of sorghum

Sorghum (*Sorghum bicolor* (L.) Moench) is an essential cereal worldwide after wheat, rice, barley and maize (Wortmann et al., 2009). Global annual production of sorghum is over sixty million metric tonnes whereby, twenty million metric tonnes are produced in Africa which makes sorghum the second most essential crop produced in the drier zones for the people in Sub-Saharan Africa (ICRISAT, 2013).

Nigeria is the leading sorghum producer in Africa with its total annual production accounting for about 33.8% of Africa's total sorghum production followed by Sudan accounting for about 21.4% (Muui et al., 2013). Ethiopia's sorghum production accounts for about 7.3%, Tanzania accounting for about 3.5 %, Uganda accounting for about 2%, Rwanda accounting for about 0.8% and Kenya accounting for 0.6% of the total Africa's annual production (Mitaru et al., 2012).

Sorghum is the second main food crop after maize in Kenya where it is mainly grown in marginal agricultural areas (Mwadalu and Mwangi, 2013). It is widely found in the dry lands since it has the capacity to produce high grain yield under dry and waterlogging conditions (Mitaru et al., 2012). In the recent years, sorghum production has increased following the development of high yielding, short maturity and drought tolerant germplasm by KALRO and ICRISAT however sorghum yields remain too low in comparison to expected grain yield of between 4 and 5 t ha^{-1} (Mwadalu and Mwangi, 2013). Further, most farmers' yields have remained very low due poor cropping systems, unpredictably low rainfalls, pests and diseases, birds infestation and weeds such as striga with capacity to cause 40% to 100% loss in the Sub-Saharan region (FAO and ICRISAT, 1996; Mitaru et al., 2012).

Sorghum in Kenya is majorly consumed by rural households, processed into flour to make posho (‘ugali’) (Kilambya and Witwer, 2013). Other uses of sorghum include the manufacture of beers, feeds, silage and direct pasture for livestock, textile dyes, ethanol for biofuel and other industrial purposes as well as molasses and syrups from sweet sorghum (Wortmann et al., 2009). Sorghum diseases such as leaf blight, grey leaf, anthracnose and insect pests such as stem borers, head bugs and shoot fly continue to cause high yield losses among rural farmers in Kenya exacerbating the existing problems of continuous depletion of soil nutrients (Mitaru et al., 2012).

Sorghum can resist a range of biotic and abiotic stresses and has a high capacity to produce very high yields in adverse conditions (Mwadalu and Mwangi, 2013). Sorghum grows well in alkaline conditions where the pH ranges from 5.0 to 8.5, it is more tolerant to saline conditions than maize and annual rainfall of 300 - 1200 mm is adequate for its optimal production (Musa et al., 2012). Heavy clay soils (vertisols) are very favourable for sorghum production though sandy soils are as well suitable for sorghum production since they have high drainage capacity and minimize waterlogging (Mwadalu and Mwangi, 2013). Due to its high resistance to drought, sorghum can produce high yield in the dry lands (ASALs) with altitude below 1500 m. Though sorghum can adapt to a range of low and high temperatures, temperatures between 15^{o}C to 35^{o}C are suitable for sorghum production since low temperatures interfere with the early maturity of the crop and impede physiological growth and development (Mwadalu and Mwangi, 2013).

Table 2.1. Area under sorghum cultivation, altitude, temperatures and annual rainfall in selected areas in Kenya where sorghum is mainly produced

Kenya	Area under cultivation, '000 ha^{-yr}	Altitude, m ASL	Average Temperature (^oC)	Annual Rainfall, mm $month^{-1}$
Coast	3	185	24	87
Rift Valley	14	1915	16	75
Western	9	1370	21	174
Eastern-Central	46	1385	21	76
Nyanza	51	1190	22	130

Source: (Karanja et al., 2006)

2.2. Sorghum varieties in kenya

Climate change induced droughts have become more common in Kenya increasing the vulnerability of Kenyan rural smallholder farmers in the ASALs to crop failures (Miano et al., 2010). Development and adoption of drought resistant crop varieties such as sorghum in the ASALs could increase food sufficiency for the smallholder farmers (Mwadalu and Mwangi, 2013). As indicated in Table 2.2, common varieties of sorghum in Kenya mostly introduced by KALRO include, "Serena", "Seredo", "KARI/Mtama1" KARI/Mtama2", "Gadam", "E 1291", "E 6518", "BJ28" which have been recommended for various ecological zones with Gadam being the highest yielding variety with yield potential of up to 4500 kg ha^{-1} (Mwadalu and Mwangi, 2013).

Increasing demand for Gadam sorghum variety due to its high yielding properties, its ability to perform well in marginal agricultural lands and high demand as a raw material for making beer by brewery companies (Mwadalu and Mwangi, 2013). Gadam sorghum variety has been preferred for the dry lands in eastern Kenya, as an important food security crop due its abilities to thrive in harsh conditions and a raw material for making beer by brewery companies (Mwadalu and Mwangi, 2013). The low current sorghum production has been attributed to low adoption of high yielding varieties and inadequate use of fertilizers (Miano et al., 2010).

Table 2.2. Plant height, time to flowering, time to maturity, prospective yield, resistance to biotic and abiotic stress and suitable ecological conditions for Serena, Seredo, Gadam, mtama1 sorghum varieties in Kenya

Variety	Attributes					
	Height of plant (cm)	Time to flowering (days)	Time to maturity	Prospective yield (kg/ha)	Biotic and abiotic stress resistance	Suitable ecological conditions
Serena	150 to160	69 to 78	110 to120	1800 to 2300	Striga, moisture stress	Moist-mid-altitude, Semi-arid low lands, Humid Coast.
Seredo	150 to160	65 to77	110 to120	4000	moisture stress	Moist-mid-altitude, Semi-arid low lands, Humid Coast.
Mtama1	50 to 170	58 to 65	95 to 100	1800 to 4000	moisture stress	Moist-mid-altitude, Semi-arid low lands, Humid Coast.
Gadam	100 to130	45 to 52	85 to 95	1700 to 4500	Pests, moisture stress	Semi-arid low lands and, Humid Coast.

Source: Mwadalu and Mwangi, 2013

2.3. Current status of sorghum production and constraints to sorghum production

Sorghum production in Kenya has experienced volatile trends in the recent years, with the lowest yield recorded in 2008 (Figure 2.1). The reduction in yield was positively correlated with low total area planted due to political instability in 2007 (Kilambya and Witwer, 2013).

Further, sorghum production improved between 2008 and 2010 due to increase in area planted (Figure 2.1). This was attributed to the development of sensitization of small holder farmers about sorghum being a resilient crop to drought in the ASALs, relatively high prices due to high demand for consumption (Kilambya and Witwer, 2013). In 2011, sorghum yield decreased despite an increased in the total area planted which was attributed to low rainfall in the 2011 short rainy season, significantly reducing sorghum production within this period (Figure 2.1). Between 2011 and 2015, the sorghum production increased due to increase in the area planted however the production declined in 2016 which could be attributed to the poor rains due to climate changed induced drought in the horn of Africa region. The sorghum production levels increased between 2016 and 2017 however below the levels that existed in 2015 (Figure 2.1).

Sorghum productivity is estimated to be below potential and major problems facing sorghum production include low input utilization, neglect of the sector and access to market and information (Mwadalu and Mwangi, 2013). Additionally, diseases and pests have also contributed to low sorghum yield (Miano et al., 2010).

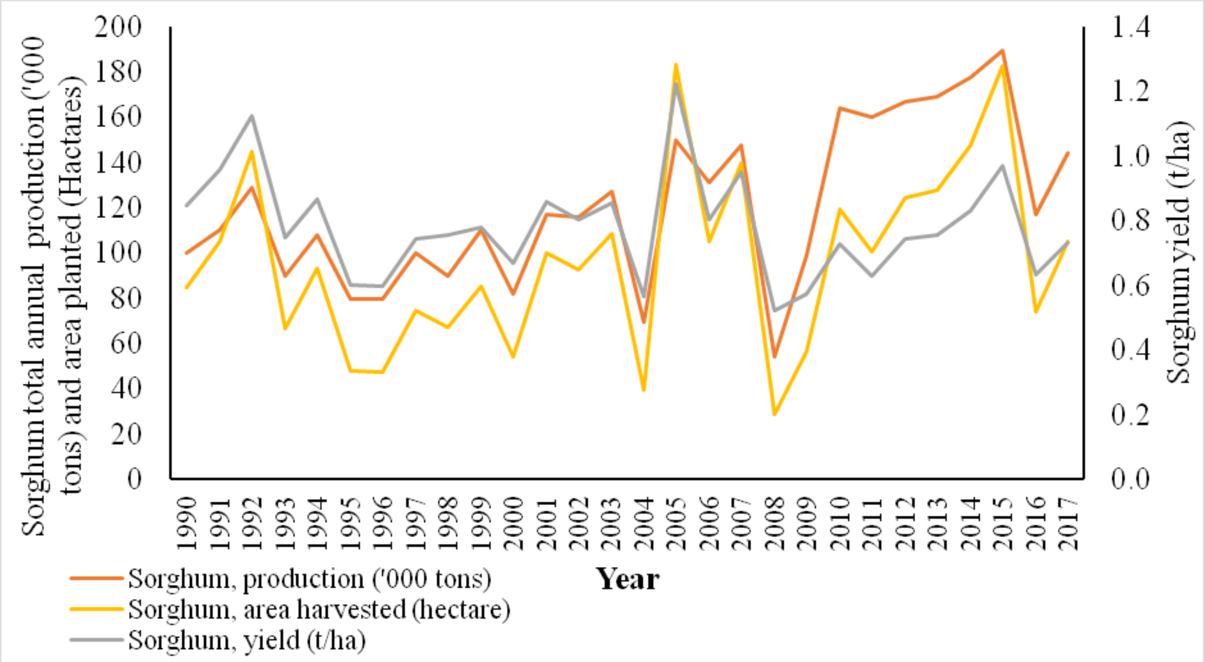

Figure 2.1. Sorghum production, area harvested and grain yield in Kenya, 1990-2017. Source: MoA, 2017

2.4. Consumption of sorghum in kenya and the region

More than half of the sorghum grain supply in Sub-Saharan Africa either through own production or imports is consumed in various forms including being processed to sorghum flour used mainly to produce foods such as for *ugali, nshima, sadza,* and *uji*, and for *injera* in Ethiopia. Also, sorghum is used for brewing but little is fed to livestock while stover use accounts for 26% of the value of the sorghum crop in most African countries and f37% of the value in Ethiopia (Wortmann et al., 2009). Specifically, in Kenya, overall sorghum consumption was reported to have increased by 36% and per capita consumption by 46% from 2004 to 2008 (Mwadalu and Mwangi, 2013). Further, 53% of the total annual sorghum supply in Kenya through own production and imports is consumed as food (flour or grain), 24% utilised for making malt, 11% lost as waste, 10% for animal feed and 2% for seed for subsequent planting seasons (Kilambya and Witwer, 2013). With more than half of the total sorghum being consumed as food, this suggests that sorghum has the potential as a main food security crop despite low adoption of improved germplasm (Mwadalu and Mwangi, 2013). Further, despite a general increase in the sorghum production in in the East African region between 2016 and 2019, the local production doesn’t meet the demand as shown by the negative net trade balance especially in Kenya and Rwanda making these countries net importers of sorghum while Uganda and Tanzania within the same period realized positive net trade balance (Table 2.3) (MoA, 2019).

Table 2. 3. Sorghum trade and production in Kenya, Uganda, Tanzania and Rwanda 2016-2019 (tonnes).

Country	**Kenya**				
	Unit	2016	2017	2018	2019
Production	Tonnes	117,000	144,000	189,000	288,000
Imports	USD	29,251,859	31,069,883	39,550,872	48,265,513
Exports	USD	17,811,777	16,379,523	20,943,690	19,815,073
Trade Balance	USD	(11,440,082)	(14,690,360)	(18,607,182)	(28,450,440)
countries		**Uganda**			
Production	Tonnes	365,622	410,597	371,517	400,000
Imports	USD	11,137	2,575,679	2,471,281	12,438,574
Exports	USD	3,682,294	50,258,893	66,476,619	574,288
Trade Balance	USD	3,671,157	47,683,214	64,005,338	(11,864,286)
Country		**Tanzania**			
Production	Tonnes	743,487	755,041	672,235	731,877
Imports	USD	949,023	674,718	122	-
Exports	USD	127,120	23,067,552	221,741	-
Trade Balance	USD	(821,903)	22,392,834	221,619	-
Country		**Rwanda**			
Production	Tonnes	163,832	151,447	159,972	159,626
Imports	USD	1,632,968	4,858,719	8,438,227	4,829,873
Exports	USD	2,475,846	14,726	8,223	3,427
Trade Balance	USD	842,878	(4,843,993)	(8,430,004)	(4,826,446)

Source: MoA-ERA, 2019

2.5. Importance and ecology of cowpea

Cowpea (*Vigna unguiculata* (L.) Walp) ranks the second most essential pulse in tropical Africa after common beans (*Phaseolus vulgaris*) (FAO, 2004). The crop is an essential legume grown mainly for food (Sanginga et al., 2002). Cowpea contributes significantly to food security in developing countries and especially in Africa, it is valued for the high protein content of its grains, which is about 25% (Ndiso et al., 2015; Wamalwa et al., 2016). Therefore due to its high protein content, cowpea complements foods such as maize, sorghum and cassava which have high starch content contributing to the improvement of the nutritional status of the low income rural households in the dry lands in Africa (Phiri et al., 2018).

Global annual cowpea production is estimated at 3 million metric tonnes under 12.5 million hectares (FAO, 2004). As an indigenous crop in many African countries, its production is mainly for food, livestock feed and as well as cash crop hence cowpea production acts as a source of livelihoods to many rural populations in Africa (Phiri et al., 2018). Cowpea can withstand various types of soil and drought hence its integration in cereal inter-cropping systems, has the potential to improve soil physico-chemical properties, replenish depleted soil nutrients and reduce soil erosion (FAO, 2004). Current yield of cowpea in many developing countries is approximately 240 kg ha^{-1} instead of 2,500 to 3,000 kg ha^{-1} especially for short to medium maturity period cowpea varieties when grown under controlled conditions (Iqbal et al., 2019).

Well drained fertile soils at an average altitude of 1,600 m above sea level (asl), optimum temperature ranges of 23–35^{o}C, alkaline soils with a 6.0 - 7.5 pH range and minimum annual rainfall of between 300 - 650 mm are favourable conditions for cowpea production to obtain optimum yields (FAO, 2004). The crop is grown throughout the world especially in the tropical and sub-tropical regions, with low rainfall between 300 mm and 600 mm per annum and it is highly adaptable to variable moisture regimes and more tolerant to drought, extreme temperatures, pests and diseases than most legumes and cereals (Ndiso et al., 2015).

Cowpea also produces high yields in various soil textures ranging from well-drained heavy clays to sandy soils and grows best in slightly alkaline soils (pH 5.5 – 6.5) and in Kenya, varieties such as Machakos (M66), Katumani 80 (K80) and KVU27-1 have been developed for the semi-arid areas with potential yields of between 800 and 1,800 kg ha^{-1} (Karanja et al., 2006).

Cowpea has deep roots that offer assistance in stabilizing soil, high ground that conserves moisture which is an important character particularly in the areas which receive limited rainfall and ability to improve the yields of intercrops especially when integrated in cereal based cropping system or when grown in rotation (FAO, 2004). While cowpea is drought tolerant, severe moisture stress has been reported to reduce its yield by more than 63% and by between 43% to 66% under medium water stress (Abayomi and Abidoye, 2009). Therefore, agronomic practices like intercropping which contribute to moisture retention is important in the improvement of cowpea yield (Ndiso et al., 2015). Further, use of cowpea varieties which are highly resistance to dry environments, heat and other stresses are recommended for adoption in the dry environments to optimise yield (Anyia and Herzog, 2004).

Table 2.3. Time to maturity, growth conditions and estimated grain yield of Machakos 66 (M66), Katumani 80 (K80) KVU 27-1 cowpea varieties in the ASALs of Kenya

Variety	Time to maturity (days)	Required conditions for production	Estimated grain yield (kg/ha)
"Machakos 66 (M66)"	85 to 95	Medium to high altitude 1200-1500 m asl	800-1700
"Katumani 80 (K80)"	75-85	Semi-arid and arid areas with altitude of 1500 m asl and average rainfall of200 mm per season	800-1800
"KVU 27-1"	70-90	Altitude 600 - 1200 m asl	800-1800

Source: Karanja et al., 2006

Like sorghum, cowpea is drought tolerant and its integration into sorghum based cropping system is likely to increase productivity of sorghum in the dry environments due to its ability to effectively fix more than 150 kg ha^{-1} of Nitrogen (N) in a cowpea-rhizobium symbiosis (Alghali, 1993). While contrasting results have been reported on the benefits of cowpea when integrated in cereal-based cropping systems including reduced cereal yields because of competition for growth resources (moisture, nutrient, light, space) between the companion crops, previous studies on cowpea-maize intercropping reported positive impact of intercropping on weed reduction thus, reducing cost of labour for weed control, increasing land productivity and enhancing nutritional benefits for the communities in the ASALs (Takim, 2012).

2.6. Nitrogen nutrition of sorghum

Nitrogen is a key element for growth and development of sorghum and despite its abundance on earth, it’s always deficient in plants especially cereals due to high uptake and losses through leaching, volatilization and denitrification (Davis et al., 1991). Nitrogen in sorghum production contributes to high biomass yields, protein content and better milling properties of the sorghum grain (Blumenthal et al., 2008). Nitrogen presence in plants is reflected by the energetic and health growth and the dark green leaves and stems (Davis et al., 1991).

Sorghum has been reported to positively respond to addition of N. For instance, Shamme and Raghavaiah (2016) reported that addition of N increased sorghum plant height, tillers, grain yield and N uptake. Further, Sibhatu and Belete (2015) reported that sorghum plant height, dry biomass, leaf area index (LAI) and grain yield proportionally increased with an increase in N fertilizer.

2.7. Nitrogen nutrition of cowpea

Nitrogen is important in cowpea production, since its availability in high quantities contributes to lush vegetative growth but excess nitrogen quantities delay maturity, reduce seed yield and impede nitrogen fixation (Davis et al., 1991). Before cowpea fixes nitrogen symbiotically, mobilization of the cotyledonary reserves occur during the growth of its hypocotyl and the shedding of its cotyledons after two days of emergence (Abayomi et al., 2008). Therefore, before cowpea can fix its own nitrogen, external supply of starter nitrogen is recommended (Keerio and Wilson, 1998).

Earlier study by Abayomi et al. (2008), found that N addition increased cowpea plant height, leaves plant^{-1} and yield but reduced root nodules plant^{-1}. Additionally, Sibhatu and Belete (2015), found that cowpea LAI and grain yield were significantly enhanced with addition of N fertiliser.

2.8. Nitrogen use efficiency in intercrop systems

Nitrogen use efficiency (NUE) refers to yield unit^{-1} of nitrogen (N) available in the soil (Worku et al., 2007). Nitrogen is mostly deficient in most soils hence additional N through external supplies is recommended to meet plant demand for optimum growth (Masclaux-Daubresse et al., 2008).

The efficiency with which N is used in intercrop systems is important due to high costs of fertilizer and environmental concerns since nitrogen is easily lost through leaching, volatilization and denitrification (Kanampiu et al., 1997). Nutrient depletion is a major contributor to the low crop yields in most African developing countries and the poor management practices contribute to significant losses of nitrogen in agricultural production hence failure to balance between nitrogen supply and crop demand (Dobermann, 2007).To maximize the nutrient use by plants, nutrient budgeting is required to account for the nutrient input, storage and export processes. It is estimated that nutrient surplus or deficit is determined by the net nutrient reduction (output greater than input) or enhancement (output less than input) of the system (Dobermann, 2007).

2.9. Water use efficiency in intercrop systems

Water use efficiency (WUE) refers to grain produced per unit of water used by the crop (Hatfield and Dold, 2019). It can also be expressed as: $WUE = \frac{\text{Above ground biomass}}{\text{Water use}}$ (Bramley et al., 2013). Water use efficiency under plant canopy can be enhanced by intercropping, mulching and irrigation to reduce soil water loss through evaporation component and enhances transpiration (Hatfield and Dold, 2019). For instance, a study by Franco et al. (2018), revealed that an intercrop system of peanut, watermelon, okra, cowpea, and pepper showed, peanut increased WUE by 46% (from 0.00015 to 0.00022 kg plant^{-1} mm^{-}

[1]) and similar results were recorded with watermelon and okra. Therefore, this suggest that, grain yield can be improved in dry environments through proper management of the relationship between photosynthesis and transpiration (Bramley et al., 2013).

2.10. Radiation use efficiency in intercrop systems

Radiation-use efficiency (RUE), refers to the biomass produced per unit of photosynthetically active photons absorbed by plants (Keating and Research,1993). Radiation plays a vital role in photosynthesis and in water use through its effects on evaporation. Further, RUE varies among plant species as well as cropping systems. However, intercrops have a higher RUE than monocrop because of the effect of light diffusion and little saturation of light (Liu et al., 2017).

Further, independent plant species coefficient of extinction and leaf area index (LAI) determines the absorption of radiation efficiency in intercropping canopy (Karimian et al., 2015). Therefore, it’s essential to understand the light changes within a plant canopy in any cropping system (sole or intercrop) before choosing crops for intercropping as the efficient use of radiation impact growth and the final total crop yields (Biosci et al., 2014).

One of the most important parameters in determining RUE is leaf area distribution which helps in describing the crop cover structure and plays a vital role in regulating energy and mass balance in soil to vegetation and then to atmosphere in an energy transfer system (Xie et al., 2016). The leaf geometry also determines how the incident solar radiation influences the energy balance between the surface of the soil and the top of any plant canopy layer (Kucharik et al., 1998). Further, leaf angle distribution affects vegetation reflectivity (Norman, 1985).

2.11. Compatibility of intercrop systems

The most essential factor to consider in any intercropping system is crop compatibility which determines the feasibility of a successful intercropping system where competition for light, moisture, space and nutrients needs to be minimized (Fukai et al., 1993). Intercropping challenges however lie in the identification of compatible crops with abilities to sustain their potential yield when intercropped with other crops (Mead and Willey, 1980). When intercropping, enough space is required to maximize cooperation and minimize competition for growth resources between the companion crops (Nawal, 1997). This can be achieved if attention is given to; spatial arrangements, plant density and maturity dates of the companion crops in an intercrop system (Sullivan, 2001).

2.12. Intercropping effects on growth and yield of sorghum and cowpea

Intercropping involves growing two or more crops on the same land (Iqbal et al., 2019). In an intercrop system, the crops may necessarily not be planted at precisely the same time and may be of different maturity periods (Mead and Willey, 1980). Sorghum-cowpea intercropping is considered to be one of the best management practices for subsistence farmers in the ASALs of sub-Saharan Africa (Karanja et al., 2014).

Further, the integration of cowpea in sorghum based intercropping system increases sorghum yields especially in the dry lands partially due to more efficient use of ecological resources which include but not limited to light, nutrients and water in an intercropping system than in a sole crop system (Sibhatu and Belete, 2015). The choice of the intercrops is mainly determined by the growth period of the crop and their environmental stress (biotic and abiotic stresses) adaptability (Yang and Udvardi, 2018).

Cowpea generally contributes to soil fertility enhancement on lands with low fertility levels through fixing atmospheric nitrogen (FAO, 2004). Cowpea deep roots help to stabilize soil and preserves moisture through its ground cover hence important characters for the dry lands (FAO, 2004). Intercropping sorghum with cowpea results into significant sorghum grain yield attributed to the nitrogen fixed under cowpea intercropping system as well as the ability of cowpeas to control weeds through inhibiting the propagation of seeds of noxious weeds such as *Striga* in the sorghum rhizosphere (Matusso et al., 2014).

Biological Nitrogen Fixation (BNF) facilitates leguminous plants to rely on nitrogen from the atmosphere which is imperative in a cereal-legume intercropping systems and when nitrogen fertilizers are restricted (Matusso et al., 2014). Another advantage of intercropping over sole cropping is that different rooting habits of intercrops result in efficient soil moisture and nutrient utilization from various soils depths (Adam and Mohammed, 2012).

Intercropping effects on sorghum growth and yield has been established in previous studies. For instance, Ibrahim (1994), reported that intercropping increased sorghum plant height compared with sole crop. However, Karanja et al. (2014), found sorghum/cowpea intercropping at high crop density reduced sorghum plant height. Conversely, Farist et al. (1983), reported insignificant effect of intercropping on sorghum plant height. Additionally, Nyambo et al. (1980), reported intercropping significantly reduced fertile tillers of sorghum in sorghum/legume intercropping. Further, Sibhatu and Belete (2015) reported that dry biomass of Sole sorghum exceeded the dry biomass of counterparts in an intercrop with cowpea.

Other studies reported that the sorghum and cowpea grain yield in sole cropping system exceeded grain yield of counterparts in an intercrop system (Oseni, 2010). Further, Karanja et al. (2014) found sole sorghum grain yields exceeded yield of sorghum in an intercrop system while Sibhatu and Belete (2015), reported sole sorghum grain yield exceeded counterparts in an intercrop system by 31%.

Likewise, intercropping effect on legumes has been reported in earlier studies. Farist (1983) reported common beans produced significantly more pods/plant in intercrop systems compared with sole. Ibrahim (1994) reported that intercropping significantly increased cowpea dry biomass. However, Karanja et al. (2014) found that intercropping reduced cowpea plant height, dry biomass and grain yield. Additionally, Sibhatu and Belete (2015) reported intercropping effect was insignificant on cowpea plant height. The same study however reported that the highest harvest index (HI) was attained by sole cowpea while the lowest HI was recorded with cowpea in an intercrop with sorghum and intercropping reduced the grain yield of intercropped cowpea yield by 58%.

2.13. Patterns of leaf senescence in sorghum

Leaf senescence involves a steady loss of green leaf area especially in the mature leaves and then the whole plant during the crop development process and determines the crop grain yield (Kitonyo et al., 2018). Stay-green is an essential trait in sorghum breeding for high yield (Kassahun et al., 2010). This is because, stay-green is influenced by the balance between source-sink relation during grain filling and it is highly associated with grain yield (Borrell et al., 2000b).

Moisture stress triggers various responses in sorghum and one of its effects is leaf senescence, where it reduces losses of water in the whole sorghum plant and allows translocation of photosynthates from the senescing leaves to other parts such as the sink organs or young leaves hence ensuring plant survival at critical times (Gong et al., 2019). Long periods of sorghum exposure to moisture stress result in sugar accumulation and a reduction in the nitrogen content of the leaf which causes Carbon/Nitrogen imbalance (Masclaux-Daubresse et al., 2008). Further, addition of N effects on leaf senescence in maize confirmed a linear correlation between the senescence rate with nitrogen remobilization efficiency (NRE) and grain yield (Kitonyo et al., 2018).

A delayed N-remobilization in vegetative or senescing organs contributes in maintaining prolonged photosynthetic capacity hence increasing carbohydrate supply for grain development (Kassahun et al., 2010). Positive correlation between sorghum leaf senescence and grain yield has been reported in water stress environments during grain filling (Borrell et al., 2001). Delayed leaf senescence in crops prolongs duration of photosynthesis resulting into high grain weights and yields (Li et al., 2018).

2.14. Assessment of the productivity of intercrop systems

The productivity of intercropping systems can be evaluated using a number of indices including: aggressivity ratio, competition ratio, monetary advantage index and land equivalent ratio (Sibhatu and Belete, 2015). Specifically, land equivalent ratio (LER) is a useful index to determine compatibility and evaluate the biological efficacy of an intercropping system (Jan et al., 2014).

To determine LER, the yields of crops in intercropping system are divided by the yields of crops in sole cropping and the LER is obtained from the sum of the two figures (Mead and Willey, 1980). If the land equivalent ratio measures 1.0, it means that there is no advantage of intercropping over sole cropping. Land equivalent ratio values above 1.0 show benefit of intercropping while below 1.0 they show a disadvantage (Nawal, 1997). For instance, LER of 1.2 implies that sole cropping requires 20 % more area planted to achieve the combined yield (Sibhatu and Belete, 2015). The total LER values for a number of cowpea-sorghum intercropping studies conducted for various varieties is found to be above 1.0 (Galwey et al., 1986). This therefore suggests that a higher combined grain yield of sorghum and cowpea can be obtained through intercropping than through sole cropping hence confirms sorghum-cowpea compatibility in intercropping system.

CHAPTER 3: EFFECT OF SORGHUM-COWPEA INTERCROPPING AND FERTILIZER NITROGEN ON GROWTH AND YIELD OF THE ASSOCIATED CROPS

3.1. Abstract

Despite the development of improved yield varieties, sorghum grain yields have remained low due to reduced soil fertility, inappropriate cropping practices and limited use of fertilizer nitrogen (N). The integration of cowpea into sorghum-based cropping systems and N use are likely to increase yield. However, the understanding of the effect of sorghum-cowpea intercropping, N use and their interactions on the performance of the companion crops remains limited. The effect of sorghum-cowpea intercropping and three N rates on growth and yield of two sorghum varieties (Gadam and Serena) and two cowpea varieties (K80 and M66) was investigated in RCBD with a split-plot arrangement, replicated three times. Intercropping significantly reduced CGR of sorghum by 54% for Serena but CGR of Gadam was not affected by intercropping. Application of 80 kg N ha^{-1} increased overall sorghum CGR by 30% but no difference was detected between 40 and 80 kg N ha^{-1}. Grain yield of Gadam exceeded Serena by 1.33 t ha^{-1} but irrespective of the cowpea variety, intercropping significantly reduced the grain yield of sorghum by 53% for Gadam and 42% for Serena in Igoji and by 54% for both varieties in Katumani. Addition of 40 kg N ha^{-1} significantly increased grain yield of sorghum by 0.53 t ha^{-1} (27%) compared with control plots but no difference was detected between addition of 40 and 80 kg N ha^{-1}. Intercropping reduced cowpea grain yield by 50% for K80 but M66 grain yield was not affected by intercropping. Sorghum grain yield was positively correlated with harvest index, fertile tiller m^{-2}, leaf area index, panicle weight and CGR. Sorghum/cowpea intercropping was more productive than sole (LER >1). Gadam was superior to Serena in terms of growth and yield hence recommended to farmers for commercial production. Therefore, sole cropping system and N addition was effective in enhancing growth and grain yield of sorghum and cowpea hence recommended for commercial production of Gadam. Intercropping is only recommended for sorghum production to improve household food security since it improved land productivity (LER >1). Application of 40 kg N ha^{-1} is recommended as economically optimum rate for sorghum production in the study areas. Screening and breeding of cowpea varieties compatible for intercropping with sorghum is recommended.

Keywords: Cropping system, crop growth rate, land equivalent ratio, drylands, interactions

3.2. Introduction

Cereal-legume intercropping is a common practice in the tropics (Layek et al., 2018). The practice involves growing two or more crops in the same piece of land (Musa et al., 2012). Often, intercropping has advantages over sole cropping in terms of improved crop productivity, land sustainability, dietary diversity and higher incomes (Sibhatu and Belete, 2015). For instance, an earlier study on cereal-legume intercropping found that the combined grain yield of cereal/legume was higher by 20 - 67% compared with sole crops and saved 38% more farm land (Takele et al., 2017). This was attributed to efficient utilization of water, radiation and nutrients in crop mixtures (Liu et al., 2017). Further, increased diversity of crops in an agricultural system and enhanced moisture conservation and weed management can be achieved through intercropping (Dariush et al., 2006).

Nonetheless, intercropping has its limitations. For instance, a study on sorghum-cowpea intercropping in the arid and semi-arid lands (ASALs) in Kenya reported a decrease in sorghum yield at higher cowpea density (Karanja et al., 2014). Other limitations of intercropping include cereal-legume compatibility challenges and inability of the legume to sufficiently meet the all the cereal N requirements without external N supply (Layek et al., 2018). One of the most essential tool to evaluate productivity of an intercropping systems is the land equivalent ratio (LER) which expresses yields obtained in an intercrop system relative to the yield from a crop in sole cropping system (Beets, 1982; Sibhatu and Belete, 2015).

Sorghum (*Sorghum bicolor* (L.) Moench), is an important cereal grown globally for food and feed (Deb et al.,2004). Therefore, increasing sorghum productivity will likely reduce severe food insecurity in the arid and semi-arid lands (ASALs) due to its ability to produce high yields under moisture stress and various soil conditions compared with other cereal crops like maize (Mwadalu and Mwangi, 2013). Although mainly consumed as grain, sorghum is also used for manufacture of beers, feeds, silage and direct pasture for livestock (Mundia, et al., 2019; Wortmann et al., 2009). Sorghum annual production in Kenya remains low representing only 0.6 % of the total Africa's annual production (Mitaru et al., 2012; ICRISAT, 2013; Mundia, et al., 2019). The low total annual production could be due to the low yield per hectare: 0.8 t ha^{-1} despite the development of new seed varieties with the potential to yield 2 to 5 t ha^{-1} (Kilambya and Witwer, 2013). The main drivers of yield decline are poor management practices, unpredictably low rainfalls, pests and diseases, birds infestation and striga weed (Mitaru et al., 2012).

Additionally, the use of fertilisers remains limited among smallholder farmers mainly caused by high and unfordable cost of fertilisers (Muui et al., 2013). However, the demand for sorghum has increased in the recent past within the brewing industry due to its use as raw material in alcohol production (Kilambya and Witwer, 2013). Therefore, improving sorghum productivity through practices such as application of N and intercropping could not only address food insecurity but also increase household incomes of rural populations in the ASALs.

Previous studies found that addition of N in urea form enhanced growth and yield of sorghum (Ahmed and Tanki, 1997). Further, Uchino et al. (2013), observed that sorghum performed poorly in the dry environments without addition of N. However, while Nitrogen (N) is an essential nutrient which plays crucial functions in plant growth and development, increasing nitrogen use efficiency remains a challenge (Yagoub and Abdelsalam, 2010). This is due to excessive use of nitrogen in agricultural systems (Dobermann, 2007). Therefore, adoption of best management practices of establishing a balance between nutrient supply and demand as well as the use of appropriate placement method and correct rate of nutrient supply at the right time required to enhance optimum production potential, input efficiency and environmental protection is important (Roberts, 2007; Shamme and Raghavaiah, 2016). Further, meeting sorghum N requirements through a combination of symbiotic N fixation by the legume in an intercrop system and minimal external synthetic N supply would help attain high yields at low cost and minimum environmental pollution from N losses.

The objective of the study was to determine the effect of cropping system and N rate on sorghum growth and yield. The study hypothesized that intercropping sorghum with cowpea and N-fertilizer application increases growth and yield of sorghum.

3.3. Materials and methods

3.3.1. Sites

Two field experiments were concurrently conducted under rain-fed conditions at Katumani and Igoji KALRO research stations during the 2018/2019 short rain season. Katumani is 575 meters above sea level (masl) and located 01º 35'S, 37º 14'E while Igoji is 1770 masl and located 0°11'13" S, 37°40'10" E and 1770 masl. Katumani lies in upper midland zone four (UM4) while Igoji lies in the upper midland zone two (UM2) (Njiru et al., 2010). Annual mean temperature in Katumani and Igoji is 21.0ºC and 19.7°C, respectively (Jaetzold and Schmidt, 1983). The soils of Katumani are classified as *ferral chromic luvisols* (Kinama et al., 2007). Soils in Igoji are deep well-drained volcanic dusky red to dark reddish brown (Jaetzold & Schmidt, 1983). Rainfall distribution in both sites is bimodal where long rains fall between March and May while short rains are received from October to December (Huho, 2017). In the short rain season, Katumani receives 288 mm of rainfall while Igoji receives 370 mm which suggests that Katumani is drier than Igoji as it receives 82 mm of rainfall less than Igoji (Jaetzold and Schmidt, 1983).

3.3.2. Treatments and experiment design

Experimental treatments consisted of cropping systems (intercrops and sole crops of two crop varieties each of sorghum and cowpea) and three fertilizer N rates (0, 40 and 80 kg N ha^{-1}). Under intercrop system, a row of cowpea was sown between two rows of sorghum. Gadam and Serena sorghum varieties and Machakos 66 (M66) and Katumani 80 (K80) cowpea varieties, which are adapted to the ecological conditions of the study areas were used as test crops for this study. The potential yield of Gadam ranges between 1,700 and 4,500 kg ha^{-1} and Serena between 1,800 and 2,300 kg ha^{-1} while both M66 and K80 have potential yield range of between 800 and 1,800 kg ha^{-1} (Karanja et al., 2006). The seeds for all the sorghum and cowpea varieties were sourced from the Seed Unit of KALRO Katumani research station.

Fertilizer N was supplied from urea (46% N) which was applied to the side bands of the planting rows of both crops where a third (1/3) was applied at sowing and the remaining two-thirds (2/3) was applied at tillering stage by top dressing. All treatment plots received 60 P kg ha^{-1} applied at planting in form of triple super phosphate (TSP) in the side bands of the planting rows of both crops. Experiments were laid out in a RCBD with a split-plot arrangement, replicated three times. Factorial combinations of sorghum-cowpea intercropping or sole crop formed the main plots while N rate formed the sub-plots. The main plots measured 25.7 m x 8.5 m and sub-plots were 12.6 m x 4 m. The main plots were separated by 1 m path and the sub-plot by 0.5 m path while treatment blocks were separated by 2 m.

3.3.3. Experiment management

Primary tillage was done a week prior to the onset of the rains followed by secondary tillage during the 2018/2019 short rains season in both sites. The planting was manually done by placing seeds in holes of 5 cm deep opened using a machete. Sorghum and cowpea were planted at 10 kg ha^{-1} seed rate at the start of the rains. In the sole crop system, a spacing of 75 cm and 20 cm between rows and within plants respectively was used for sorghum while cowpea was sown 60 cm and 30 cm between rows and within plants respectively. In the intercrop system, sorghum was sown at 90 cm and 20 cm spacing between rows and within plants respectively and a row of cowpea was sown between two rows of sorghum with a spacing of 30 cm from plant to plant. In both crops, three seeds were planted in each hole and later thinned to one plant per hole to achieve a sorghum density of 6.7 plants m^{-2} in the sole crop system and 5.6 plants m^{-2} in the intercrop system. Cowpea plant density was 5.6 plants m^{-2} in the sole crop system and 3.7 plants m^{-2} in the intercrop system.

Pre-emergence weed control was done using Roundup® (glyphosate) immediately after sowing. Experiments were kept weed free through hand weeding. Insect pests, mainly thrips and aphids in cowpea and stem borers in sorghum, were controlled with Thunder® (Imidacloprid 100 g / L + Betacyfluthrin 45 g/L) at 120 mL acre^{-1}. Sorghum was guarded against birds feeding on the grains at grain filling until harvesting.

3.3.4. Data collection

3.3.4.1. Initial soil analysis

Soil samples were collected from the experimental sites in Igoji and Katumani using a soil auger prior to sowing. The samples were collected from a 0 - 30 cm depth in five spots per replicate in each site in a zigzag pattern. The collected soil samples were mixed and composited into one sample. Soil samples were air dried, mixed, ground and sieved to pass through a sieve of 2 mm before complete soil fertility analysis was done at the KALRO National Laboratory in Nairobi. A Mehlich double acid method was used to analyze the soils for Phosphorus, potassium, Sodium, Calcium, Magnesium, Manganese, Iron, Zinc and Copper. The total organic carbon (C) was analyzed using calorimetric method (Shamme and

Raghavaiah, 2016), while the total nitrogen was analysed using Kjeldahl method (Ghosh, 2004). A digital pH meter was used to measure the soil pH in a ratio of 1:1 soil-water suspension (w/v) (Mehlich et al., 1962). Ammonium acetate method was used to analyse for cation exchange capacity (CEC) (Shamme and Raghavaiah, 2016).

Table 3.1 presents initial soil fertility analysis prior to establishment of the experiments. Analysis of the soil fertility data showed, total nitrogen, total organic carbon and phosphorus level in both sites were low however, potassium, Calcium, Manganese, magnesium, copper, iron, zinc and sodium were adequate for sorghum and cowpea production in both sites. Potassium, Calcium and copper were adequate in Katumani however were low in Igoji. Further, N and P were supplied externally however other deficiencies were kept constant across the experimental plots.

Table 3.1. Soil chemical properties at depth of 0 – 30 cm before planting at Igoji and Katumani KALRO research stations during 2018/2019 short rain season

Soil fertility results	Units	Igoji	Katumani
pH	-	4.64^{sa}	5.9^{ma}
Total N	%	0.1^{*}	0.1^{*}
Total organic carbon (C)	%	0.93^{*}	0.82^{*}
Phosphorus (P)	ppm	13.33^{*}	18.33*
Potassium (K)	me%	0.26^{*}	0.91^{**}
Calcium (Ca)	me%	1.07*	2.9^{**}
Magnesium (Mg)	me%	2.48^{**}	2.35^{**}
Manganese (Mn)	me%	0.58^{**}	0.5^{**}
Copper (Cu)	ppm	0.55^{*}	1.26^{**}
Iron (Fe)	ppm	18.46^{**}	11.77^{**}
Zinc (Zn)	ppm	7.08^{**}	1.88^{*}
Sodium (Na)	me%	0.15^{**}	0.16^{**}

* is Low, ** is Adequate, sa is strong acid, ma is medium acid

3.3.4.2. Weather data

Readily available daily minimum and maximum temperature and daily rainfall data consistently collected by staff at Igoji and Katumani KALRO research stations from October, 2018 to April, 2019 bracketing the experimental period was obtained for respective experimental sites. The mean monthly rainfall and temperature data were computed. Analysis of the rainfall and temperature during the 2018/2019 short rain season is shown in Figure 3.1. Rainfall started in early October at land preparation and increased until December at sorghum tillering stage however decreased in January towards flowering and grain filling. As the crop matured, rainfall significantly reduced however, the temperature increased (Figure 3.1).

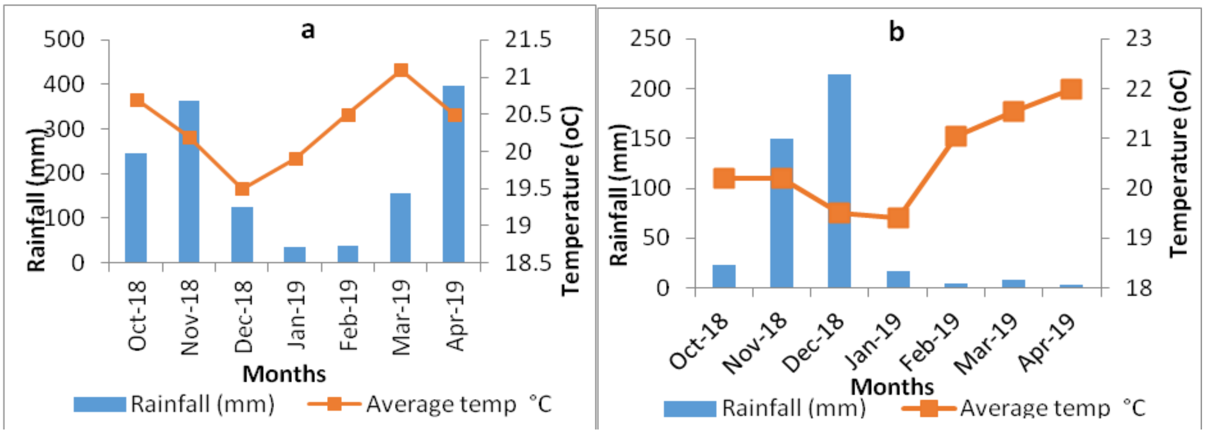

Figure 3.1. Weather conditions from sowing to physiological maturity of sorghum at Igoji (a) and Katumani (b) Kenya Agricultural and Livestock Research Organization research stations during 2018/2019 short rain season

3.3.4.3. Sorghum phenology and growth parameters

The phenology of sorghum was regularly scored from emergence to physiological maturity. Emergence was visually scored and the duration from sowing to emergence were recorded in days. The duration to 50 % flowering was recorded (in days) at the time of sowing until 50 % of the plant populations in each plot had flowered. Further, the duration from 50% flowering to 90% physiological maturity was recorded in days. Further, the duration to physiological maturity was recorded as the time of sowing until 90% of the plant leaves had turned yellow and the base of most panicles had started drying (Shamme and Raghavaiah, 2016).

Five sorghum plants randomly selected from the central part of a net plot (4 m x 4 m) were tagged for repeated measurements of growth parameters. Plant height (cm) of the tagged plants was consistently measured using a standard tape at 4, 6, 8 and 10 weeks after planting (WAP) while the number of leaves plant^{-1} at 4, 6, 8 and 10 WAP were manually counted. The average plant height and number of leaves plant^{-1} of the five tagged plants collected at each of the sampling period was computed.

Further, the leaf length and width of three randomly selected leaves plant^{-1} from the tagged plants was measured at 50% flowering and means computed for each plant and plot. The means of the leaf length and width were used to calculate the leaf area (cm^2):

A_L = L x W; where, A_L is the leaf area (cm^2), L is leaf length (cm), W is maximum leaf width (cm) and 0.75 is sorghum leaf correction factor (Sibhatu and Belete, 2015). Leaf area index (LAI) was calculated using the plant population per plot (p), average number of leaves plant^{-1} at 50% flowering (n), leaf area (A_L) and the area of each plot (PA) hence, LAI = p x n x A_L x (PA)$^{-1}$ (Sibhatu and Belete, 2015).

The number of fertile tillers plant m^{-2} was counted and means computed to represent each plot. Further, the above ground dry biomass was measured at 50% flowering and 90% physiological maturity. Samples were oven-dried at 70°C for three days and dry weight measured using a weighing scale in grams/plant. The dry matter was then converted to kg m^{-2} using the plant population of 6.7 and 5.6 plants m^{-2} in sole and intercrop systems, respectively. Crop growth rate from flowering to physiological maturity was determined using equation 3.1.

$$\text{Sorghum crop growth rate} = \frac{\text{Dry mass at maturity - Dry mass at flowering}}{\text{Days between two stages}}\ \text{kg m}^{-2} \qquad (3.1)$$

Further, a rotor mill was used to grind the oven dried samples collected at maturity to pass through a 0.5 mm sieve and a sample of 10 g was prepared. Nitrogen concentrations were analysed using Kjeldahl method from the sub-samples from each plot separately (Shamme and Raghavaiah, 2016). Nitrogen uptake in sorghum shoot and grain was computed using equation 3.2.

$$\text{Sorghum N uptake} = \frac{\%\text{N concentration x dry mass at maturity}}{100} \quad \text{kg m}^{-2} \qquad (3.2)$$

3.3.4.4. Sorghum yield and yield components

Panicles of each sorghum variety were harvested using a knife at physiological maturity in a net plot area of 4 m x 4 m and air-dried. Weight of 10 air-dried sorghum panicle plot^{-1} was measured using a weighing scale in grams and means computed. The number of spikelets for the 10 panicles plot^{-1} were manually counted and means computed to represent spikelets panicle^{-1}. Panicle length and width were measured using a tape measure in centimeters. The air-dried panicles were then threshed and cleaned. The grain moisture content was measured consistently during the air drying period using a grain moisture meter and the grain weight was adjusted to 12.5% (Sibhatu and Belete, 2015). One thousand (1000) sorghum seeds from each experimental plot were counted using a seed counter and the weight measured using a weighing scale. Harvest index of sorghum was determined using equation 3.3

$$\text{Sorghum harvest index} = \frac{\text{Grain yield}}{\text{Above ground dry biological yield}} \text{X} \, 100\% \qquad (3.3)$$

3.3.4.5. Cowpea phenology and Growth Parameters

The phenology of cowpea was regularly scored from emergence to physiological maturity. Emergence was visually scored and the number of days from sowing to emergence were recorded. The duration to 50% flowering was recorded at the time of sowing until 50% of the plant populations in each plot had flowered (days). Further the duration from 50% flowering to 90% physiological maturity was recorded in days. Five cowpea plants randomly selected from the central part of a net plot (4 m x 4 m) were tagged for the repeated measurement of growth parameters. Plant height (cm) of the tagged plants was consistently measured using a standard tape at 4, 6 and 8 weeks after planting (WAP) and the means computed. For the same plants, the number of leaves plant^{-1} was recorded at 4, 6 and 8 WAP and means computed. The effective root nodules number plant^{-1} was determined at 4, 6 and 8 WAP by digging. One plant was dug in each plot, soil removed from the roots and nodules pinched and counted. Nodules with pink or reddish colouration were considered effective (Sibhatu and Belete, 2015).

Cowpea leaf length and width were measured at 50% podding at the central part of the leaf. Leaf area plant^{-1} (cm^{2}) was calculated as: LA = 2.325 x L x W (Olusanya et al. 2016). Where, LA = leaf area, L = cowpea leaf length, W = Maximum cowpea leaf width and 2.325 is the correction factor for cowpea leaf. The cowpea leaf area, plant population plot^{-1}, average number of leaves plot^{-1} and the area of each plot were used to determine the leaf area index (LAI) as described for sorghum in subsection **3.3.4.3** above.

The above ground dry biomass of was measured at branching and 90% physiological maturity. The samples were oven-dried at 70°C for a period of three days and dry weight measured in grams/plant. The dry matter was then converted to g m^{-2} using an average of 5.6 and 3.7 plants m^{-2} in sole and intercrop systems. The growth rate from branching to physiological maturity was determined using equation 3.4.

$$\text{Cowpea growth rate} = \frac{\text{Dry mass at maturity} - \text{Dry mass at branching}}{\text{Days between two stages}} \qquad (3.4)$$

3.3.4.6. Cowpea yield and yield components

Cowpea pods were harvested at physiological maturity manually by hand picking from a net plot area of 4 m x 4 m and air-dried. Number of air-dried pods plant^{-1} in each plot was determined by dividing the total number of pods harvested from a net plot by the final plant count plot^{-1} at harvest. Number of cowpea seeds pod^{-1} was determined by counting the seeds pod^{-1}from 10 pods taken from the net plot (4 m x 4 m) and means computed. The air-dried pods plot^{-1} were then threshed and cleaned. The moisture content of cowpea grain was consistently measured during the air drying period using a grain moisture meter and cowpea grain weight was adjusted to 10.5% (Sibhatu and Belete, 2015). The grain weight plot^{-1} was then measured using a weighing scale in grams and then converted to t ha^{-1}. One hundred (100) cowpea seeds from each plot were counted using a seed counter and weight determined using a weighing scale in grams.

3.3.4.7. Land equivalent ratio

The efficiency of the intercrop system compared with sole cropping was evaluated using the land equivalent ratio (LER). The LER constituted the sum of partial LER of the companion crops. As shown in equation 3.5, partial LER was computed as the ratio between intercrop and sole crop yield for each component (Mead, and Willey,1980).

$$\mathrm{LER} = \frac{\mathrm{Yis}}{\mathrm{Yss}} + \frac{\mathrm{Yic}}{\mathrm{Ysc}} \qquad (3.5)$$

Yis is yield of intercrop sorghum, Yss is yield of sole crop sorghum, Yic is yield of intercrop cowpea and Ysc is yield of sole cowpea.

3.3.5. Data analysis

All data were subjected to the analysis of variance (ANOVA) using GenStat 14th Edition. The treatment structure in a split plot design comprised the cropping system and N rates. The data was normally distributed and transformation was not required. The mean separation was carried out using the least significant difference (LSD) test at 5% probability level (Gomez and Gomez, 1984). Average values of the yield and yield parameters of the 3 blocks were computed in each experimental site and the relationship between the yield and yield parameters were examined by correlation analysis using SigmaPlot version 10.0 (www.systatsoftware.com) (Kitonyo et al., 2018).

3.4. Results

3.4.1. Effect of cropping system and nitrogen rates on sorghum phenology

Sorghum varieties differed in phenology whereby Gadam flowered 11 days earlier than Serena in sole cropping system and 8 days in intercrop system with cowpea. Similarly, Gadam variety matured earlier than Serena by 24 days in both cropping systems. However, intercropping sorghum with cowpea had no significant effect on the duration from sowing to 50% flowering and from flowering to 90% physiological maturity of sorghum (Figure 3.2).

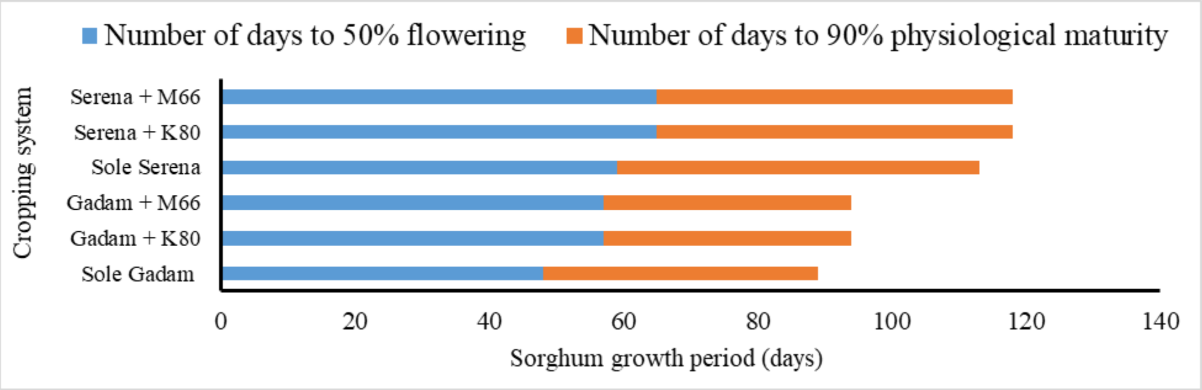

Figure 3.2. Phenology of two sorghum varieties (Gadam and Serena) grown in an intercrop system with two varieties of cowpea (K80 and M66) at Igoji and Katumani KALRO research stations during 2018/2019 short rain season

3.4.2. Effect of cropping system and nitrogen rate on sorghum growth parameters

The plant height did not significantly differ between Gadam and Serena in both experimental sites throughout the sampling period. Similarly, cropping system, N rate and cropping system x N rate effect on sorghum plant height was insignificant throughout the sampling period (Figure 3.3).

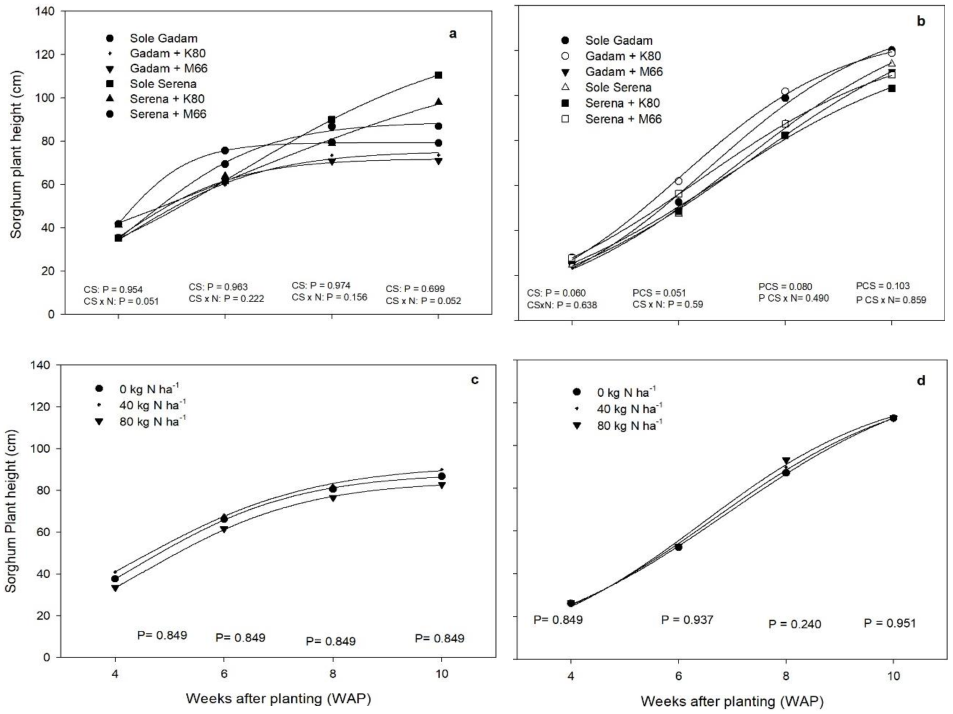

Figure 3.3. Plant height at 4, 6, 8 and 10 WAP of two sorghum varieties (Gadam and Serena) at three N rates (0,40,80 kg N ha^{-1}) at Igoji (a, c) and Katumani (b, d) KALRO research stations during 2018/2019 short rain season

The leaf area index (LAI) did not significantly differ between Gadam and Serena in both sites. However, cropping system (P = 0.05), N rates (P = 0.039) and the cropping system x N rate (P = 0.006) effects on LAI were significant in Katumani but insignificant in Igoji (Table 3.2). In Katumani, irrespective of the cowpea variety, intercropping reduced the LAI of Gadam by 0.53 units, while application of 80 kg N ha^{-1} increased sorghum LAI by 0.08 units (28%) compared with control plots where no fertiliser was applied but no difference was detected between application of 40 and 80 kg N ha^{-1} (Table 3.2). Nonetheless, intercropping had no effect on the LAI of Serena sorghum variety in Katumani experimental site (Table 3.2). Cropping system x N rate effect was only significant in Katumani (P = 0.006) whereby N increased LAI of sorghum in intercrop with cowpea however sorghum in grown as sole did not respond to addition of N (Figure 3.4).

Dry biomass at 50% flowering differed between Gadam and Serena in both experimental sites whereby Gadam yielded more biomass than Serena by 0.056 kg m^{-2} in Igoji however the reverse was true in Katumani whereby Serena yielded more biomass than Gadam by 0.048 kg m^{-2} (Table 3.2). Cropping system ($P < .001$) and N rates ($P < .001$) had significant effect on the above ground dry biomass at 50% flowering in Igoji and Katumani experimental sites (Table 3.2). In Igoji, irrespective of the cowpea variety, intercropping reduced the dry biomass of Gadam by 0.131 kg m^{-2}. On the other hand, dry biomass of Serena was reduced by 0.061 kg m^{-2} when intercropped with K80 however, intercropping Serena with M66 had no significant effect on dry biomass (Table 3.2). Further, sorghum dry biomass at 50% flowering increased with addition of N whereby, addition of 40 kg N ha^{-1} increased dry biomass by 0.197 kg m^{-2} and application of 80 kg N ha^{-1} increased dry biomass by 0.182 kg m^{-2} compared with control plots but no significant difference was detected between 40 and 80 kg N ha^{-1} (Table 3.2). In Katumani, irrespective of the cowpea variety, intercropping reduced the dry biomass of Gadam at 50% flowering by 0.156 kg m^{-2} while dry biomass of Serena at 50% flowering was reduced by 0.240 kg m^{-2} when intercropped with K80 and by 0.136 kg m^{-2} when intercropped with M66 compared with sole crops (Table 3.2). Application of 80 kg N ha^{-1} increased dry biomass of sorghum at 50% flowering by 0.066 g m^{-2} compared with control plots however no difference was detected between addition of 40 kg N ha^{-1} and control plots (Table 3.2).

Cropping system × N rate had significant effect on the dry biomass of sorghum at 50% in Igoji ($P < .001$) and Katumani ($P = 0.002$) (Table 3.2). In Igoji, addition of N significantly increased dry biomass of sorghum in sole and intercrop system except for Gadam intercropped with M66 where biomass in control plots exceeded biomass of in plots supplied with N fertilizer but no difference was detected between 40 and 80 kg N ha^{-1} (Figure 3.4).

Similarly, in Katumani addition of N increased biomass of sorghum in sole and intercrop system except for Serena grown as sole and Serena in an intercrop with M66 (Figure 3.4).

The above ground dry biomass at 90% physiological maturity did not significantly differ between Gadam and Serena in both sites but cropping system significantly affected this trait in Igoji (P = 0.007) and Katumani (P <.001) (Table 3.2). In Igoji, intercropping Gadam with K80 significantly reduced dry biomass by 0.19 kg m^{-2} and by 0.121 kg m^{-2} when intercropped with M66 (Table 3.2). Likewise, dry biomass of Serena was significantly reduced by 0.132 kg m^{-2} due to intercropping with M66 but no effect was observed when Serena was intercropped with K80 (Table 3.2). In Katumani, intercropping Gadam with K80 significantly reduced dry biomass by 0.279 kg m^{-2} however no effect was detected when Gadam was intercropped with M66 (Table 3.2). Irrespective of the cowpea variety, intercropping significantly reduced the dry biomass of Serena by 0.29 (Table 3.2). Addition of N significantly affected sorghum dry biomass at 90% physiological maturity in Igoji (P <.001) and Katumani (P = 0.009). In Igoji, addition of 40 kg N ha^{-1} increased dry biomass by 0.121 kg m^{-2} compared with control plot (0 kg N ha^{-1}) but dry biomass attained with addition of 80 kg N ha^{-1} was statistically similar to dry biomass obtained in control plots (Table 3.2). In Katumani, addition of 80 kg N ha^{-1} significantly increased dry biomass by 0.122 kg m^{-2} compared with control plots but no effect detected between addition of 40 kg N ha^{-1} and control plot (Table 3.2).

The cropping system x N rate effect on dry biomass was significant in Igoji (P <.001) and Katumani (P = 0.04). At 90% physiological maturity, dry biomass of sorghum increased with addition of N in both sole and intercrop systems (Figure 3.4). However, Gadam intercropped with M66 in Igoji did not respond to addition of N. Generally, dry biomass of sole crops exceeded those in in an intercrop system (Figure 3.4)

Crop growth rate (CGR) did not significantly differ between Gadam and Serena in both sites (Table 3.2). Cropping system significantly affected sorghum growth rate in Igoji ($P = 0.002$) and Katumani ($P = 0.016$). In Igoji, intercropping Serena with M66 significantly reduced growth rate by 2.38 g m^{-2} day^{-1} but no significant effect of intercropping Serena with K80 was observed. Further, intercropping had no significant effect on CGR of Gadam irrespective of the cowpea variety (Table 3.2). In Katumani, intercropping Gadam and Serena with cowpea had no effect on the CGR of both varieties. (Table 3.2). Addition of N significantly increased sorghum growth rate over control plots in Igoji ($P = 0.002$) whereby, addition of 80 kg N ha^{-1} increased overall sorghum growth rate by 1.6 g m^{-2} day^{-1} (30%) compared with control plots but without significant differences between 40 and 80 kg N ha^{-1} (Table 3.2). Nonetheless, no effect of N on the CGR was observed in Katumani experimental site.

Additionally, cropping system x N rate effect on crop growth rate (CGR) was significant in Igoji ($P <.001$) and Katumani (0.042) (Table 3.2). In Igoji, CGR of Gadam and Serena was insensitive to addition of N whereby, crops fertilized with N had lower CGR compared with unfertilized crops. However, the reverse was true for both sorghum varieties in Katumani (Figure 3.4). In Igoji, CGR of Gadam in an intercrop system with K80 and M66 significantly increased with addition of N where the highest CGR was attained with addition of 80 kg N ha^{-1}. However, the CGR of Serena in an intercrop with K80 did not respond to addition of N whereby crops in control plot had higher growth rate (Figure 3.4). Further, addition of 80 kg N ha^{-1} increased the growth rate of Serena intercropped with M66 but the effect of addition of 40 kg N ha^{-1} on CGR was insignificant. Similarly, in Katumani, addition of N increased CGR of Gadam intercropped with M66 and Serena intercropped with K80; however, addition of N did not cause any significant growth response for Gadam intercropped with K80 and Serena intercropped with M66 (Figure 3.4).

Correlation analysis revealed CGR was positively and significantly correlated with sorghum grain yield under sole cropping system (Igoji: R^2 = 0.95, Katumani: R^2 = 0.83) but was weakly and insignificantly correlated with grain yield under intercrop system in both experimental sites (Table 3.10)

Table 3.2. Leaf area index, dry biomass (DM) at flowering and harvest and crop growth rate (CGR) of two sorghum varieties (Gadam and Serena) grown in sole and intercrop system with two varieties of cowpea (K80 and M66) and at three N rates (0, 40 and 80 kg N ha^{-1}) at Igoji and Katumani KALRO research stations during 2018/2019 short rain season

	Igoji				Katumani			
Treatments	Leaf area index	DM flowering (kg m^{-2})	DM harvest (kg m^{-2})	CGR (g m^{-2} day^{-1})	Leaf area index	DM flowering (kg m^{-2})	DM harvest (kg m^{-2})	CGR (g m^{-2} day^{-1})
Cropping system (CS)								
Sole Gadam	0.86a	0.472a	0.690a	5.32ab	0.68a	0.394b	0.634ab	5.86ab
Gadam+K80	0.40a	0.326c	0.518cd	5.19ab	0.15b	0.217de	0.355d	3.74bc
Gadam+M66	0.25a	0.341c	0.569bcd	6.17a	0.14b	0.238d	0.522bc	7.69a
Sole Serena	0.81a	0.416b	0.651ab	4.35b	0.34ab	0.442a	0.674a	4.31bc
Serena+K80	0.21a	0.355c	0.614abc	4.88ab	0.08b	0.202e	0.384d	3.44bc
Serena+M66	0.28a	0.415b	0.519d	1.97c	0.12b	0.306c	0.409cd	1.94c
P-value	0.469	<.001	0.007	0.002	0.05	<.001	<.001	0.011
LSD$_{p\leq0.05}$	ns	0.045	0.090	1.54	0.39	0.031	0.118	2.71
N rates								
0 kg N ha^{-1}	0.50a	0.261b	0.493c	3.67b	0.21b	0.283b	0.436b	3.60a
40 kg N ha^{-1}	0.43a	0.458a	0.614b	5.00a	0.26ab	0.267b	0.495ab	5.11a
80 kg N ha^{-1}	0.47a	0.443a	0.493c	5.27a	0.29a	0.349a	0.558a	4.77a
P-value	0.747	<.001	<.001	0.002	0.039	<.001	0.009	0.157
LSD$_{p\leq0.05}$	ns	0.020	0.028	0.88	0.06	0.034	0.074	ns
P-value CS x N	0.503	<.001	<.001	<.001	0.006	0.002	0.040	0.042
LSD$_{p\leq0.05}$	ns	0.057	0.101	2.23	0.40	0.073	0.182	4.060

Within a column, means followed by the same alphabets are not significantly different, CS x N is cropping system and N rate interactions, ns is not significant

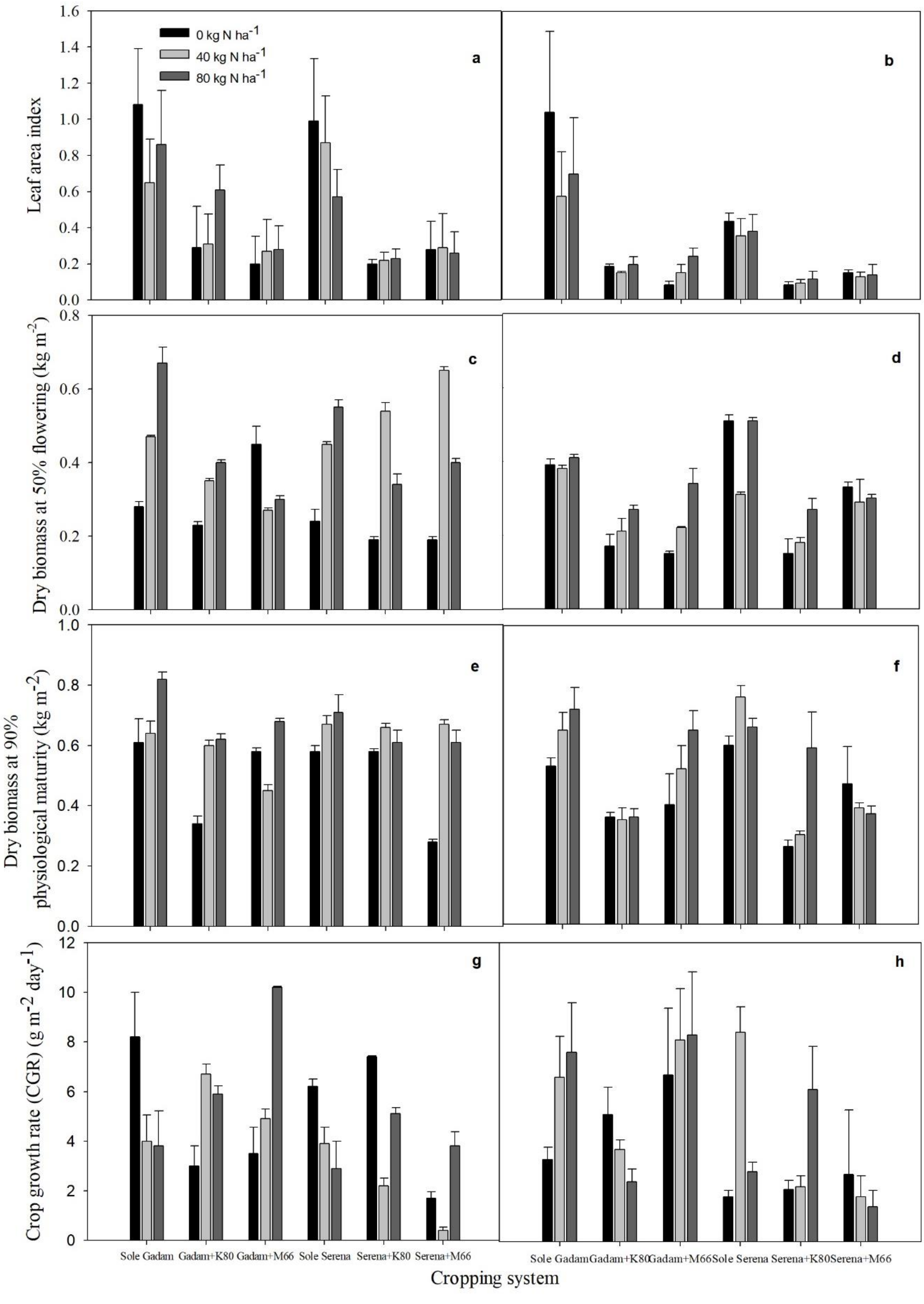

Figure 3. 4. Leaf area index, dry biomass at flowering and maturity and crop growth rate (CGR) of two sorghum varieties (Gadam and Serena) grown under sole and intercrop system with two varieties of cowpea (K80 and M66) and in interactions with 0, 40 and 80 kg N ha^{-1} at Igoji (a, c, e, g) and Katumani (b, d, f, h) KALRO research stations during 2018/2019 short rain season

3.4.3. Effect of cropping system and nitrogen rate on sorghum yield and yield components

Sorghum grain yield was significantly affected by cropping system (P <.001) in both sites, N rate in Igoji (P <0.01) and Katumani (P = 0.013) and cropping system x N rates only in Igoji (P <0.01) (Table 3.3). Under sole crop system, Gadam sorghum out-yielded Serena by 1.33 t ha^{-1} in Igoji and but the grain yield difference between the two varieties was insignificant in Katumani. In Igoji, irrespective of the cowpea variety, intercropping significantly reduced sorghum grain yield by 1.67 t ha^{-1} (53%) for Gadam while intercropping Serena with M66 significantly reduced the grain yield of Serena by 0.87 t ha^{-1} (42%) compared with yield of sole crops (Table 3.3). In Katumani, Intercropping Gadam with K80 significantly reduced grain yield by 2.2 t ha^{-1} (71%) and by 1.66 t ha^{-1} (54%) when intercropped with M66 compared with grain yield of sole crops. On the other hand, irrespective of the cowpea variety, intercropping significantly reduced the grain yield of Serena by 1.49 (54%) compared with grain yield of sole crops (Table 3.3). Conversely, sorghum grain yield increased with addition of N whereby in Igoji, addition of 80 kg N ha^{-1} increased overall grain yield by 0.38 t ha^{-1} (21%) compared with control plots but no difference was detected between sorghum grain attained with addition of 40 kg N ha^{-1} and grain yield in control plots where no fertiliser was added (Table 3.3). In Katumani, addition of 40 kg N ha^{-1} significantly increased grain yield of sorghum by 0.53 t ha^{-1} (27%) compared with control plots were no fertiliser was added but no difference was detected between addition of 40 and 80 kg N ha^{-1} (Table 3.3). Cropping system × N rate interaction effect on sorghum grain yield in Igoji (P <0.01) revealed that while sorghum grain yield increased with the addition of N under the sole crop system, higher N rates only marginally increased yield under the intercropping system (Table 3.3; Figure 3.5). Further, the study revealed positive and significant correlation between sorghum grain yield and LAI, number of fertile tillers, panicle weight, harvest index (HI) and growth rate under sole cropping system in both experimental sites; however, these traits were weakly and insignificantly correlated with sorghum gran yield (Table 3).

Further, the study revealed positive and significant correlation between sorghum grain yield and LAI, number of fertile tillers, panicle weight, harvest index (HI) and growth rate under sole cropping system in both experimental sites however, these traits were weakly and insignificantly correlated with sorghum gran yield (Table 3.10).

The harvest index (HI) of Gadam and Serena did not differ significantly between the two varieties in both sites however, cropping system effect on HI was significant in Igoji ($P = 0.014$) and Katumani ($P <.001$) (Table 3.3). In Igoji, intercropping Gadam and Serena with M66 significantly reduced the HI by 42% and 14%, respectively, but no significant effect on HI was observed when both varieties were intercropped with K80 (Table 3.3). In Katumani, intercropping Gadam with K80 significantly reduced the HI by 30% but HI of Gadam was significantly reduced by 44% when intercropped with M66. Additionally, intercropping Serena with K80 significantly reduced the HI by 36% and HI of Serena was reduced by 38% when intercropped with M66 (Table 3.3). Nonetheless, N effect on HI of both varieties was insignificant in Igoji and Katumani (Table 3.3). However, the cropping system x N rates significantly affected HI in Katumani ($P <.001$) but there was no significant effect of the interaction on HI in Igoji. As illustrated in Figure 3.5, HI of Gadam increased with addition of N in both sole and intercrop systems in Igoji. A similar trend was observed in Katumani where HI of Gadam increased with N, however, under sole cropping, Gadam only responded to addition of 80 kg N ha^{-1} where maximum HI was attained. However, 40 kg N ha^{-1} was the optimum N rate for Gadam intercropped with M66 where the highest HI was attained. At Igoji, addition of N affected Serena intercropped with K80 but marginal effects of N were observed on HI of sole Serena and Serena intercropped with M66.

Sorghum panicle width significantly differed between Gadam and Serena only in Igoji whereby panicle width of Serena exceeded Gadam by 1.7 cm (Table 3.3). Cropping system significantly affected panicle width both in Igoji (P <.001) and Katumani (P = 0.013). In Igoji, intercropping Gadam with K80 and M66 significantly reduced panicle width by 6.8 cm and 8.5 cm, respectively. Likewise, intercropping Serena with K80 significantly reduced the panicle width by 9.4 cm and by 8.8 cm when Serena was intercropped with M66. However, only little effect was observed when both sorghum varieties were intercropped with either K80 or M66 in Katumani (Table 3.3). On the other hand, addition of N had not significant effect on sorghum panicle width in both experimental sites (Table 3.3). Cropping system x N rate effect on panicle width was significant in Igoji (P = 0.034) but no effect was observed in Katumani (Table 3.3). As illustrated in Figure 3.5, panicle width of Gadam and Serena under sole cropping system was significantly higher than counterparts in an intercrop with cowpea. Gadam grown as sole crop in Igoji did not respond to addition of N as indicated by the low panicle width; however, Gadam grown in an intercrop with K80 and M66 significantly responded to N addition whereby panicle width of N fertilized crops was significantly higher than panicle width of crops that did not receive N fertilizer (Figure 3.5). Serena grown as a sole crop in Igoji responded well to addition of N where the highest panicle width was attained with addition of 40 kg N ha^{-1}; however, marginal effects of N were observed in the panicle width of intercropped crops (Figure 3.5).

The panicle length did not differ between Gadam and Serena in both experimental sites however, cropping system significantly affected sorghum panicle length in Igoji (P = 0.002) and in Katumani (P = 0.017) (Table 3.3). In Igoji, intercropping Serena with K80 significantly reduced panicle length by 13.8 cm. Likewise, in Katumani, the panicle length for Gadam was reduced by 1.5 cm due to intercropping with M66; however, intercropping

Serena with K80 or M66 did not significantly affect panicle length. Nonetheless, sorghum panicle length was not significantly affected with addition of N (Table 3.3).

The effect of cropping system × N rate on panicle length was significant in Igoji ($P = 0.01$) but not in Katumani (Table 3.3). Addition of N increased panicle length across cropping systems except for sole Gadam in Igoji where addition of N had no effect on panicle length. Further, the panicle length of both sorghum varieties in sole cropping system exceeded panicle length of counterparts in an intercrop system (Figure 3.5).

Nitrogen uptake in sorghum shoot and grain at physiological maturity significantly differed between Gadam and Serena in Katumani whereby N uptake of Serena was 0.01 N kg m^{-2} higher than Gadam but no difference detected in Igoji (Table 3.3). Further, cropping system effect on N uptake was significant in Igoji ($P = 0.008$) and Katumani ($P = 0.001$) (Table 3.3). In Igoji, intercropping Gadam with M66 significantly reduced Gadam N uptake by 0.003 kg m^{-2} while in Katumani, intercropping reduced the N uptake of Serena by 0.01 kg m^{-2}, irrespective of the cowpea variety (Table 3.3). Significant increase in N uptake with increasing rate of N application was observed only in Igoji ($P = 0.001$) whereby addition of 80 kg N ha^{-1} significantly increased N uptake by 0.006 kg m^{-2} compared with control plots and by 0.003 kg m^{-2} compared with addition of 40 kg N ha^{-1} (Table 3.3).

The cropping systems x N significantly affected N uptake only in Igoji ($P < .001$) but the interactions had no effect on N uptake in Katumani (Table 3.3). Addition of 80 kg N ha^{-1} significantly increased the N uptake of Gadam grown in sole and in intercrop with K80 and M66; however, the effect of 40 kg N ha^{-1} was only marginal (Figure 3.6). Addition of 40 and 80 kg N ha^{-1} significantly increased N uptake in Serena in both cropping systems.

Table 3.3. Sorghum grain yield, harvest index (HI), panicle width and panicle length, and N uptake of two sorghum varieties (Gadam and Serena) grown under sole and intercrop system with two varieties of cowpea (K80 and M66) and at three N rates (0, 40 and 80 kg N ha^{-1}) at Igoji and Katumani KALRO research stations during 2018/2019 short rain season

	Igoji					Katumani				
Treatments	Grain yield (t ha^{-1})	HI (%)	Panicle width (cm)	Panicle length (cm)	N uptake (kg m^{-2})	Grain yield (t ha^{-1})	HI (%)	Panicle width (cm)	Panicle length (cm)	N uptake (kg m^{-2})
Cropping system (CS)										
Sole Gadam	3.15a	43.4a	13.6b	19.6ab	0.011ab	3.09a	43.2a	6.3ab	7.9a	0.010b
Gadam+K80	1.48bc	29.4ab	6.8c	17.8ab	0.011a	0.89c	30.1b	6.8a	8.0a	0.007b
Gadam+M66	1.27bc	25.1b	5.1d	15.0b	0.008b	1.43b	24.1c	5.1b	6.4b	0.010b
Sole Serena	1.82b	31.1ab	15.3a	21.3a	0.011ab	2.76a	41.4a	6.7a	8.5a	0.020a
Serena+K80	1.06bc	30.0ab	5.9cd	7.5c	0.011ab	1.10bc	26.4bc	6.5ab	7.5ab	0.010b
Serena+M66	0.95c	26.9b	6.5c	16.8ab	0.013a	1.27bc	25.5bc	5.9ab	8.6a	0.007b
P-value	<.001	0.014	<.001	0.002	0.080	<.001	<.001	0.013	0.017	<.001
LSD$_{p\leq0.05}$	0.75	14.0	0.99	5.0	0.003	0.42	4.6	1.4	1.2	0.003
N rates										
0 kg N ha^{-1}	1.46b	28.8a	8.7a	15.4b	0.008c	1.43b	31.9ab	6.1a	7.7a	0.01a
40 kg N ha^{-1}	1.57b	31.0a	8.7a	16.5ab	0.011b	1.96a	33.6a	6.0a	7.9a	0.01a
80 kg N ha^{-1}	1.84a	33.1a	9.3a	17.1a	0.014a	1.88a	29.8b	6.7a	7.9a	0.01a
P-value	0.015	0.128	0.207	0.076	<.001	0.013	0.0082	0.089	0.725	0.469
LSD$_{p\leq0.05}$	<.001	ns	ns	Ns	0.002	0.37	3.3	ns	ns	ns
P-value CS x N	<.001	0.549	0.034	0.01	<.001	0.061	<.001	0.66	0.13	0.919
LSD$_{p\leq0.05}$	0.86	ns	1.813	1.46	0.005	0.82	7.8	ns	ns	ns

Within a column, means followed by the same alphabets are not significantly different, CS x N is cropping system and N rate interactions, ns is not significant

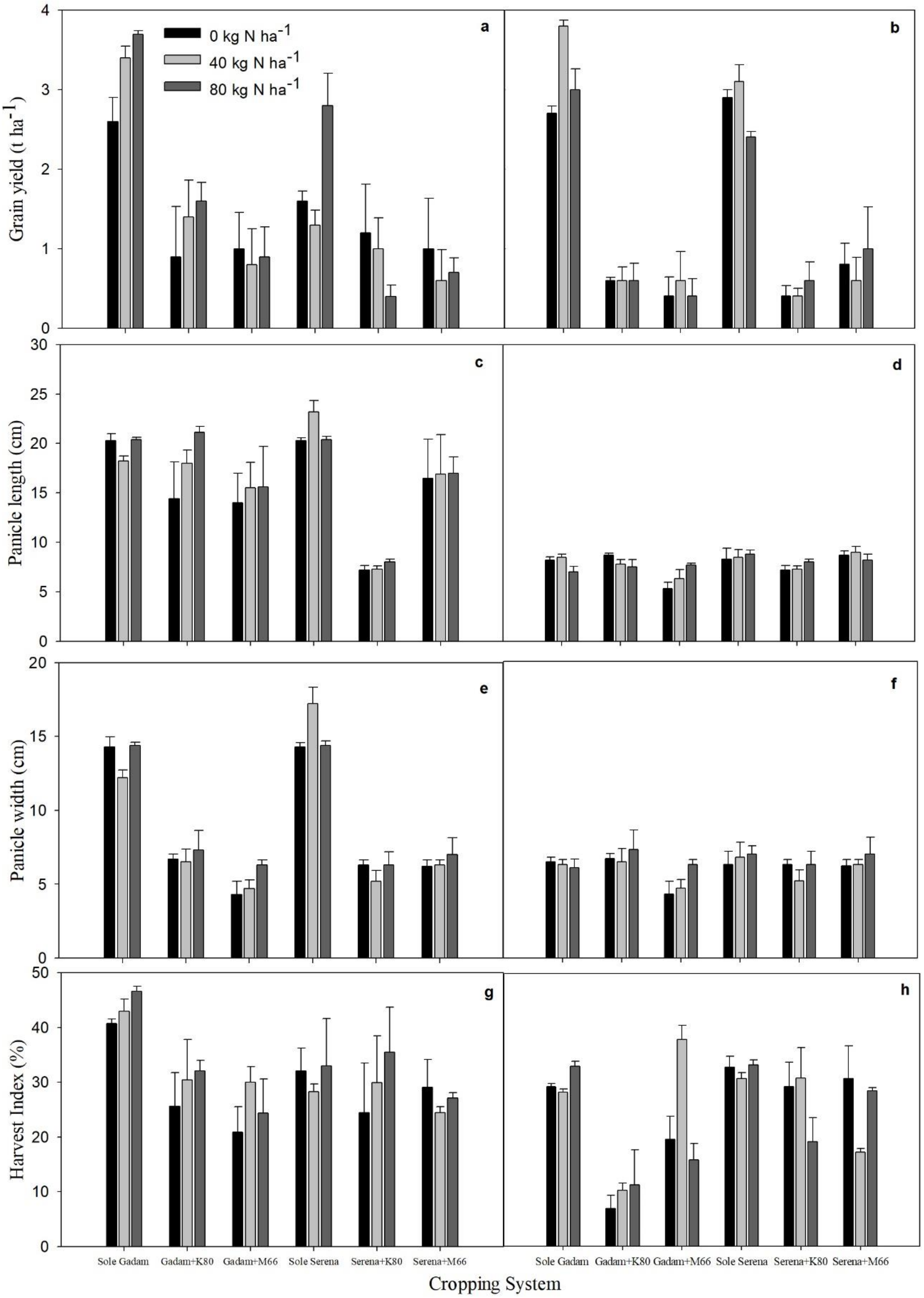

Figure 3.5. Sorghum grain yield, panicle width and length, and harvest index of two sorghum varieties (Gadam and Serena) grown under sole and intercrop system with two varieties of cowpea (K80 and M66) and in interaction with three N rates (0, 40 and 80 kg N ha^{-1}) at Igoji (a, c, e, g) and Katumani (b, d, f, h) KALRO research stations during 2018/2019 short rain season

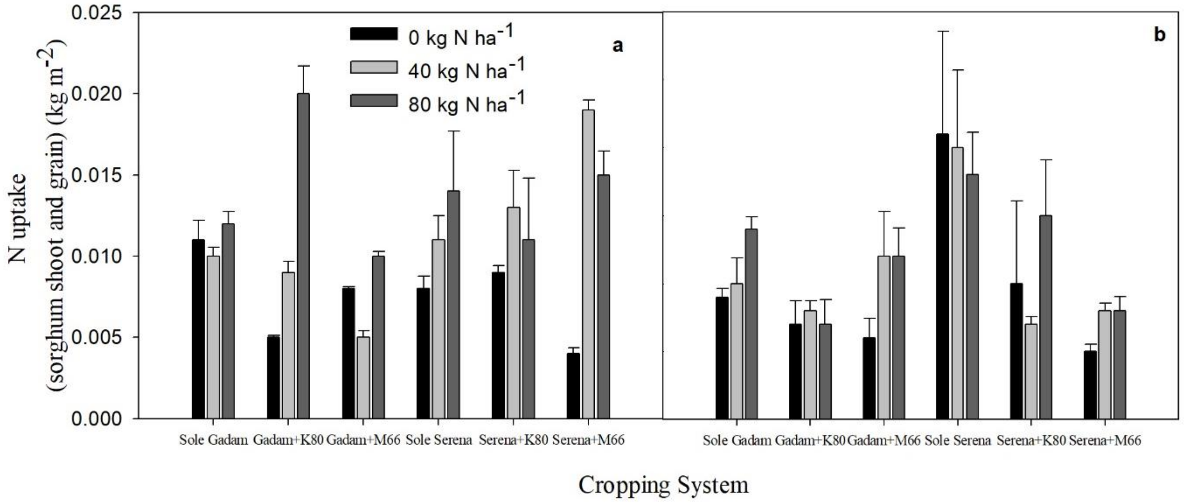

Figure 3.6. N uptake of two sorghum varieties (Gadam and Serena) grown under sole and intercrop system with two varieties of cowpea (K80 and M66) and in interaction with three N rates (0, 40 and 80 kg N ha^{-1}) at Igoji (a) and Katumani (b) KALRO research stations during 2018/2019 short rain season

The number of fertile tillers m^{-2} significantly differed between Gadam and Serena in Igoji whereby Gadam yielded more fertile tillers m^{-2} by 4.7 tillers compared with Serena in sole cropping system however, no difference was observed in an intercrop system. Nonetheless, the variation in the number of fertile tillers m^{-2} between Gadam and Serena in both sole and intercrop system was insignificant in Katumani (Table 3.4). The effect of cropping system on the fertile tillers m^{-2} was significant in Igoji (P = 0.044) and Katumani (0.016). In Igoji, irrespective of the cowpea variety, intercropping reduced the number of fertile tillers m^{-2} for Gadam by 6.2 (Table 3.4). However, intercropping Serena with cowpea had no effect on the number of fertile tillers m^{-2}. In Katumani, intercropping Gadam and Serena with either K80 or M66 significantly reduced number of fertile tillers m^{-2} by 8.2 tillers for Gadam and 9.1 tillers for Serena (Table 3.4).

Addition of N significantly increased the number of fertile tillers plant m^{-2} in Igoji (P = 0.021) but not in Katumani (Table 3.4). In Igoji, addition of 80 kg N ha^{-1} increased the mean number of fertile tillers plant m^{-2} by 1.1 tillers compared with control plots and by 0.9 tillers with application of 40 kg N ha^{-1}. Nonetheless, there were no significant effect of the cropping system x N rate on the mean number of fertile tillers plant m^{-2} in both experimental sites (Table 3.4).

The panicle weight of Gadam and Serena did not vary significantly however cropping system effect on panicle weight was significant in Igoji ($P = 0.039$) and Katumani ($P = 0.044$). In Igoji, intercropping Gadam with M66 significantly reduced the mean panicle weight by 8.3 g but there was insignificant effect of intercropping Gadam with K80 on the panicle weight. Likewise, irrespective of the cowpea variety, panicle weight of Serena was significantly reduced by 6.9 g (Table 3.4). In Katumani, panicle weight of Gadam was significantly reduced by 7.3 g by intercropping with K80 however, there was no effect of intercropping Gadam with M66 on the panicle weight. Further, intercropping significantly reduced the panicle weight of Serena by 7 g, irrespective of the cowpea variety (Table 3.4). Nonetheless, there were no significant effects of N and cropping system x N rate on sorghum panicle weight in both sites (Table 3.4).

The number of spikelets panicle^{-1} of Gadam and Serena significantly varied in Igoji and Katumani ($P <.001$). Serena variety produced 9.8 and 13.5 spikelets more than Gadam variety in Igoji and Katumani respectively however there was no variation in the number of spikelets between sorghum grown as sole crop and in an intercrop with cowpea within the same variety (Table 3.4). Nonetheless N rates, cropping system × N rate had no effect on the number of spikelets panicle^{-1} in both experimental sites. Therefore, in the present study, variety effect superseded the main factors (cropping system and N rate) (Table 3.4).

As illustrated in Table 3.4, the weight of 1000 seeds significantly differed between Gadam and Serena in both sites. A thousand seed- weight of Gadam was higher than for Serena by 3.7 g in Igoji and 3.5 g in Katumani. Cropping system effect on 1000 seeds weight was significant in Igoji ($P = 0.002$) and Katumani ($P <.001$) (Table 3.4). In Igoji, intercropping

Gadam with either K80 or M66 did not significantly influence the 1000-seed weight however, intercropping Serena with M66 significantly increased 1000-seed weight by 3.6 g over sole Serena. In Katumani, intercropping Gadam with K80 significantly reduced the 1000 seed weight by 4.5 g; however, intercropping Gadam with M66 did not significantly affect the 1000-seed weight. Further, intercropping Serena with K80 significantly reduced the 1000 seeds weight by 3.8 g but there was insignificant effect of intercropping Serena with M66 on the panicle weight. Nonetheless, addition of N and cropping system x N effect on 1000 seeds weight was insignificant in both sites (Table 3.4).

Table 3.4. Number of fertile tillers m^{-2}, panicle weight, Number of spikelets $panicle^{-1}$ and weight of 1000 seeds of two sorghum varieties (Gadam and Serena) grown in sole and intercrop system with two varieties of cowpea (K80 and M66) and at three N rates (0, 40 and 80 kg N ha^{-1}) at Igoji and Katumani KALRO research stations during 2018/2019 short rain season

	Igoji				Katumani			
Treatments	Number of fertile tillers m^{-2}	Panicle weight (g)	Number spikelets per panicle	weight of 1000 seeds	Number of fertile tillers m^{-2}	Panicle weight (g)	Number spikelets per panicle	weight of 1000 seeds (g)
Cropping System (CS)								
Sole Gadam	6.9a	35.9a	22.7b	31.1a	16.3a	31.5ab	24.3b	33.6a
Gadam + K80	0.7b	29.2ab	21.2b	30.7a	8.1bc	24.2c	22.7b	29.1b
Gadam + M66	0.5b	27.6b	24.7b	30.9a	5.9bc	27.6bc	23.7b	32.9a
Sole Serena	2.2b	36.1a	34.3a	27.4b	13.0ab	34.6a	37.3a	30.1b
Serena + K80	2.6b	29.2b	33.7a	26.1b	2.6c	27.6bc	32.0a	26.3c
Serena + M66	1.7b	27.6b	34.4a	31.0a	3.9c	26.1bc	35.8a	30.7b
P-value	0.044	0.039	<.001	0.002	0.016	0.044	<.001	<.001
$LSD_{p\leq0.05}$	4.1	6.6	5.2	2.3	7.7	6.4	5.6	1.7
N rates								
0 kg N ha^{-1}	1.9c	31.4a	28.4a	30.06a	7.4a	26.7a	28.9a	30.33a
40 kg N ha^{-1}	2.1b	31.3a	27.6a	29.50a	8.1a	28.7a	28.3a	30.72a
80 kg N ha^{-1}	3.0a	30.2a	29. 6a	29.06a	9.4a	30.5a	30.6a	30.28a
P-value	0.021	0.352	0.389	0.341	0.258	0.256	0.352	0.803
$LSD_{p\leq0.05}$	0.8	ns	Ns	Ns	ns	ns	ns	ns
P-value CS x N	0.107	0.352	0.399	0.236	0.438	0.282	0.352	0.761
$LSD_{p\leq0.05}$	ns	ns	Ns	Ns	ns	ns	ns	ns

Within a column, means followed by the same alphabets are not significantly different, CS x N is cropping system and N rate interactions, ns is not significant

3.4.4. Effect of cropping system on cowpea phenology

Cowpea varieties differed in phenology whereby K80 matured 12 days earlier than M66 in sole and intercropping system; however, there was no difference in the number of days to 50% flowering for both varieties. Intercropping had no effect on the duration from sowing to 50% flowering and from flowering to 90% physiological maturity for both cowpea varieties (Figure 3.7).

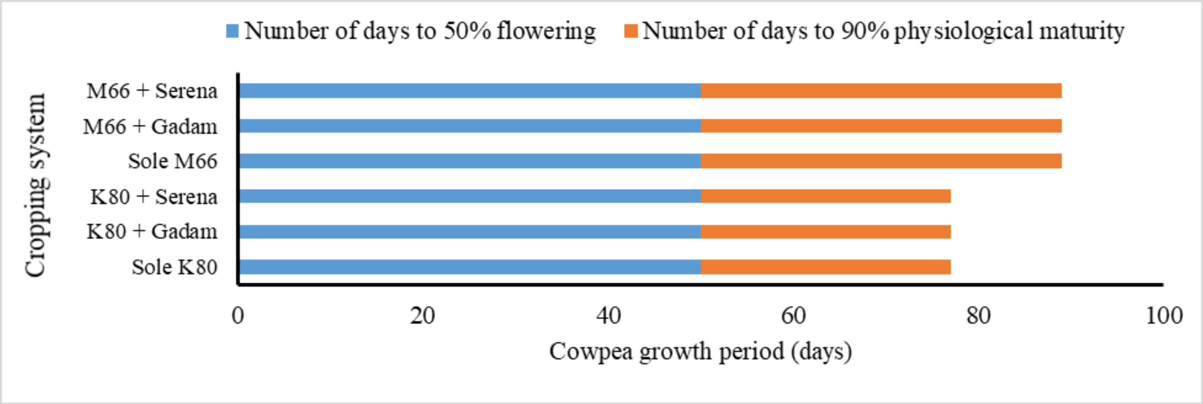

Figure 3.7. Phenology of two cowpea varieties (M66 and K80) grown under sole and an intercrop system with two varieties of sorghum (Gadam and Serena) at Igoji and Katumani KALRO research stations during 2018/2019 short rain season

3.4.5. Effect of cropping system and nitrogen rate on cowpea growth parameters

The plant height did not differ significantly between K80 and M66 across the sampling periods in both experimental sites (Table 3.5). However, cropping system effect on plant height was significant in Katumani at 6 weeks after planting (WAP) ($P = 0.004$) but no effect was detected in Igoji. At 6WAP in Katumani, intercropping increased the plant height of K80 by 5.7 cm irrespective of the sorghum variety (Table 3.5). Similarly, plant height of M66 was significantly increased by 5.5 cm over sole crops by intercropping with Serena however, no significant effect of intercropping M66 with Gadam was observed. Nonetheless, cropping system effect on plant height at 4 and 8 WAP was insignificant in both experimental sites (Table 3.5).

Further, addition of N significantly affected plant height at 6 WAP (P = 0.05) and 8 WAP (P = 0.008) in Katumani but fertilizer N effect on plant height in Igoji was insignificant. At 6 WAP, addition of 80 kg N ha^{-1} significantly increased plant height of cowpea by 2 cm compared with control plots however there was no difference detected between cowpea height attained with addition of 40 kg N ha^{-1} and counterparts in control plots (Table 3.5). On the other hand, at 8 WAP, addition of 40 kg N ha^{-1} significantly increased cowpea height by 4.6 cm compared with addition of 80 kg N ha^{-1} but no difference was detected between cowpea height attained with addition of 40 kg N ha^{-1} and counterparts in control plots. Additionally, the effect of N addition on plant height at 4 WAP and the interactions between cropping system and N rates across the sampling period was insignificant in both sites (Table 3.5).

Table 3.5. Cowpea plant height at 4, 6 and 8 weeks after planting (WAP) of two cowpea varieties (K80 and M66) grown in sole and intercrop system with two varieties of Sorghum (Gadam and Serena) and at three rates of N (0, 40, 80 kg N ha^{-1}) at Igoji and Katumani KALRO research stations during 2018/2019 short rain season

	Igoji			Katumani		
Treatments	4	6	8	4	6	8
Cropping system (CS)						
Sole K80	26.7a	30.8a	45.9a	22.3a	32.9c	35.3a
K80+Gadam	25.9a	30.0a	58.3a	24.8a	38.6ab	33.1a
K80+Serena	23.0a	28.1a	52.8a	24.6a	38.7ab	31.7a
Sole M66	26.4a	31.8a	48.8a	22.7a	36.6bc	37.3a
M66+Gadam	22.6a	27.0a	43.8a	23.1a	35.2bc	29.6a
M66+Serena	27.2a	32.5a	45.1a	25.6a	42.1a	34.3a
P -value	0.919	0.89	0.279	0.235	0.004	0.854
LSD$_{p\leq0.05}$	ns	Ns	Ns	ns	3.9	ns
N rates						
0 kg N ha^{-1}	25.7a	30.1a	48.8a	23.4a	36.1b	33.9ab
40 kg N ha^{-1}	25.6a	30.7a	50.4a	23.8a	37.8ab	35.7a
80 kg N ha^{-1}	24.6a	29.2a	48.2a	24.3a	38.1a	31.1b
P-value	0.729	0.654	0.416	0.827	0.05	0.008
LSD$_{p\leq0.05}$	ns	Ns	Ns	ns	1.7	2.8
P-value CS x N	0.724	0.514	0.16	0.827	0.977	0.28
LSD$_{p\leq0.05}$	ns	Ns	Ns	ns	ns	ns

The means within a column followed by the same alphabets are statistically similar, CS x N – cropping system and N rate interactions, ns is not significant

The number of effective root nodules plant^{-1} between K80 and M66 significantly differed at 6 WAP in Katumani (P <.001) where K80 recorded more root nodules than M66 by 9.1 (Table 3.6). However, intercropping had no significant effect on the number of effective root nodules plant^{-1} at 4 and 8 WAP in Katumani. Nonetheless, the effect of cropping system, N rates and cropping system x N rates effect on the number of effective root nodules plant^{-1} was insignificant across the sampling period in Igoji (Table 3.6).

Table 3.6. Number of effective root nodules at 4, 6, 8 WAP of two cowpea varieties (K80 and M66) grown in sole and in an intercrop system with two varieties of sorghum (Gadam and Serena) and at three rates of N (0, 40, 80 kg N ha^{-1}) at Igoji and Katumani KALRO research stations during 2018/2019 short rain season

	Igoji			Katumani		
Treatments	4	6	8	4	6	8
Cropping system (CS)						
Sole K80	8.8a	3.8a	3.8a	10.3a	24.7a	19.0a
K80 + Gadam	8.0a	6.8a	2.7a	10.6a	25.8a	21.3a
K80 + Serena	6.8a	3.4a	2.4a	11.3a	26.6a	23.7a
Sole M66	10.7a	7.7a	3.9a	10.0a	15.6b	17.9a
M66 + Gadam	15.6a	4.4a	4.4a	9.4a	16.7b	15.0a
M66 + Serena	11.4a	3.8a	3.2a	9.0a	14.8b	18.1a
P-value	0.838	0.497	0.751	0.48	<.001	0.34
$LSD_{p\leq0.05}$	ns	ns	ns	ns	3.6	ns
N rates						
0 kg N ha^{-1}	9.7a	5.6a	3.6a	9.4a	21.6a	20.6a
40 kg N ha^{-1}	10.9a	4.5a	3.4a	10.6a	21.6a	18.2a
80 kg N ha^{-1}	10.1a	4.9a	3.2a	10.3a	18.8a	18.7a
P-value	0.783	0.632	0.793	0.368	0.083	0.186
$LSD_{p\leq0.05}$	ns	ns	ns	ns	ns	ns
P-value CS x N	0.734	0.761	0.921	0.572	0.24	0.11
$LSD_{p\leq0.05}$	ns	ns	ns	ns	ns	ns

The means within a column followed by the same alphabets are not significantly different, CS x N is cropping system and N rate interaction, ns is not significant

The LAI between K80 and M66 significantly differed in Igoji but the variation between the cowpea varieties in Katumani was insignificant whereby, the LAI of M66 was 1.5 higher than K80 in Igoji (Table 3.7). The effect of cropping system on the LAI was significant in Katumani (P <.001) however, in Igoji, the LAI of K80 and M66 attained in sole cropping system and in an intercrop with sorghum were statistically at par which implied that variety effect superseded cropping system (Table 3.7). In Katumani, intercropping M66 with Gadam significantly reduced the LAI by five units but there was no significant difference in the LAI of K80 in sole and in an intercrop with sorghum (Table 3.7). Nonetheless, the addition of N and the interaction between cropping system and N rate had no significant effect on the LAI of K80 and M66 in both experimental sites (Table 3.7).

At branching, cowpea dry biomass was significantly affected by cropping system ($P < .001$), N rates ($P < .001$) and interactions between cropping system and N rates ($P < .001$) in both sites (Table 3.7). In Igoji, intercropping K80 with either Gadam or Serena significantly reduced dry biomass at branching by 0.001 kg m^{-2} while M66 dry biomass was significantly reduced by 0.005 and 0.003 kg m^{-2} by intercropping with Gadam and Serena respectively (Table 3.7). In Katumani, intercropping K80 with Gadam significantly reduced dry biomass by 0.001 kg m^{-2} and by 0.003 kg m^{-2} when intercropped with Serena (Table 3.7).

Dry biomass of cowpea at branching increased with addition of N whereby in Igoji, addition of 80 kg N ha^{-1} increased cowpea dry biomass by 0.001 kg m^{-2} compared with control plots and 40 kg N ha^{-1} however no difference was detected between cowpea dry biomass attained with addition of 40 kg N ha^{-1} and control plots (Table 3.7). Similarly, in Katumani, addition of 40 kg N ha^{-1} increased cowpea dry biomass by 0.001 kg m^{-2} compared with control plots and addition of 80 kg N ha^{-1} but no difference was detected between cowpea biomass attained with addition of 80 kg N ha^{-1} and control plots (Table 3.7).

Cropping system x N rate effect was significant on cowpea dry biomass at branching whereby, addition of significantly increased dry biomass across treatments in both sites expect sole M66 in Igoji where the effect of N was not significant (Figure 3.8).

At physiological maturity, there was significant effect of cropping system (P <.001), N rate (P <.001) and cropping system x N rates (P <.001) in both sites (Table 3.7). In Igoji, intercropping K80 with Gadam and Serena significantly reduced dry biomass by 0.003 and 0.002 kg m^{-2} respectively while dry biomass of M66 was significantly reduced by 0.002 and 0.001 kg m^{-2} by intercropping with Gadam and Serena respectively (Table 3.7). In Katumani, intercropping K80 and M66 with Gadam significantly reduced the dry biomass of both varieties by 0.002 kg m^{-2} and by 0.001 kg m^{-2} when intercropped with Serena (Table 3.7). Addition of N negatively impacted cowpea dry biomass since the cowpea dry biomass attained with addition of either 40 or 80 kg N ha^{-1} were lower than cowpea dry biomass attained in control plots where no fertiliser was added in both sites hence addition of N reduced dry biomass (Table 3.7).

Cropping system x N rate effect on biomass at physiological maturity was significant in both sites (P <.001) (Table 3.7). Addition of N did not significantly affect the dry biomass of the K80 under sole and intercrop system in both experimental sites. On the other hand, sole M66 responded to N addition in both sites with the peak biomass attained with addition of 40 kg N ha^{-1} marginal effects of N on M66 biomass in an intercrop with Gadam and Serena were observed (Figure 3.8).

The crop growth rate (CGR) of cowpea from branching to physiological maturity between K80 and M66 significantly differed in both sites whereby, the growth rate of K80 was higher than M66 by 0.216 g m^{-2} day^{-1} in Igoji and 0.078 g m^{-2} day^{-1} in Katumani (Table 3.7). Further, cropping system effect on the cowpea growth rate was significant in Igoji (P <.001) and Katumani (P <.001) (Table 3.7). In Igoji, intercropping K80 with Gadam and Serena significantly reduced the CGR of K80 by 0.17 and 0.14 g m^{-2} day^{-1} respectively however irrespective of the sorghum variety, intercropping insignificantly affected the crop growth rate of M66 (Table 3.7).

In Katumani, intercropping K80 with Gadam significantly reduced the growth rate by 0.133 g m^{-2} day^{-1} however, intercropping K80 with Serena had no significant effect on CGR of K80. Further, intercropping M66 with Gadam and Serena significantly reduced the growth rate by 0.056 and 0.03 g m^{-2} respectively (Table 3.7). Nonetheless, the highest growth rate was recorded in unfertilized plots in both sites implying addition of N insignificantly affected growth rate of M66.

Cropping system x N rate effect on CGR of cowpea was significant in both sites ($P <.001$) (Table 3.7). As illustrated in Figure 3.8, the CGR of K80 was not affected with addition of N both in sole and intercrop systems in both sites where CGR of unfertilized crops in both cropping systems exceeded CGR of counterparts in an intercrop with sorghum (Figure 3.8). On the contrary, M66 responded to N in Igoji whereby the CGR of M66 in sole and intercrop with sorghum increased proportionally with addition of N with peak CGR attained with addition of 80 kg N ha^{-1} however in Katumani, while CGR of M66 grown as sole crop and M66 intercropped Gadam increased with addition of N, CGR of M66 intercropped with Serena was not affected by addition of N as crops in control plots had higher CGR compared with counterparts fertilized with N (Figure 3.8).

Table 3.7. Leaf area index, dry mass (DM) at flowering and harvest, crop growth rate (CGR) of two cowpea varieties (K80 and M66) grown in sole and intercrop system with two varieties of sorghum (Gadam and Serena) and at three N rates (0, 40, 80 kg N ha^{-1}) at Igoji and Katumani KALRO research stations during 2018/2019 short rain season

	Igoji				Katumani			
Treatments	Leaf area index	DM branching (kgm^{-2})	DM maturity (kgm^{-2})	CGR (g m^{-2} day^{-1})	Leaf area index	DM branching (kgm^{-2})	DM maturity (kgm^{-2})	CGR (g m^{-2} day^{-1})
Cropping system (CS)								
Sole K80	2.8b	0.007b	0.012a	0.280a	6.4a	0.008a	0.011a	0.200a
K80 + Gadam	2.3b	0.006c	0.009cd	0.110c	6.9a	0.007b	0.009d	0.067d
K80 + Serena	2.0b	0.006c	0.010bc	0.140b	6.6a	0.005c	0.010bc	0181a
Sole M66	4.3ab	0.010a	0.010bc	0.064de	6.3a	0.006c	0.010b	0.122b
M66 + Gadam	3.8ab	0.005d	0.008d	0.086cd	1.3b	0.005c	0.008e	0.066d
M66 + Serena	6.3a	0.007b	0.009d	0.056e	1.4ab	0.007b	0.009cd	0.092c
P-value	0.011	<.001	<.001	<.001	<.001	<.001	<.001	<.001
LSD$_{p\leq0.05}$	3.2	0.001	0.001	0.028	1.5	0.001	0.001	0.021
N rates								
0 kg N ha^{-1}	3.73a	0.006b	0.011a	0.18a	5.2a	0.006b	0.0111a	0.720a
40 kg N ha^{-1}	3.28a	0.006b	0.009b	0.10b	5.0a	0.007a	0.0092b	0.769c
80 kg N ha^{-1}	3.71a	0.007a	0.009b	0.89b	4.3a	0.006b	0.0085c	0.115b
P-value	0.724	<.001	<.001	<.001	0.17	<.001	<.001	<.001
LSD$_{p\leq0.05}$	ns	0.0003	0.0005	0.022	ns	0.0003	0.0004	0.017
Pvalue CS x N	0.724	<.001	<.001	<.001	0.170	<.001	<.001	<.001
LSD$_{p\leq0.05}$	ns	0.001	0.001	0.05	ns	0.001	0.0011	0.039

Within a column, means followed by the same letter are not significantly different, CS X N is cropping system and N rate interactions, ns is not significant

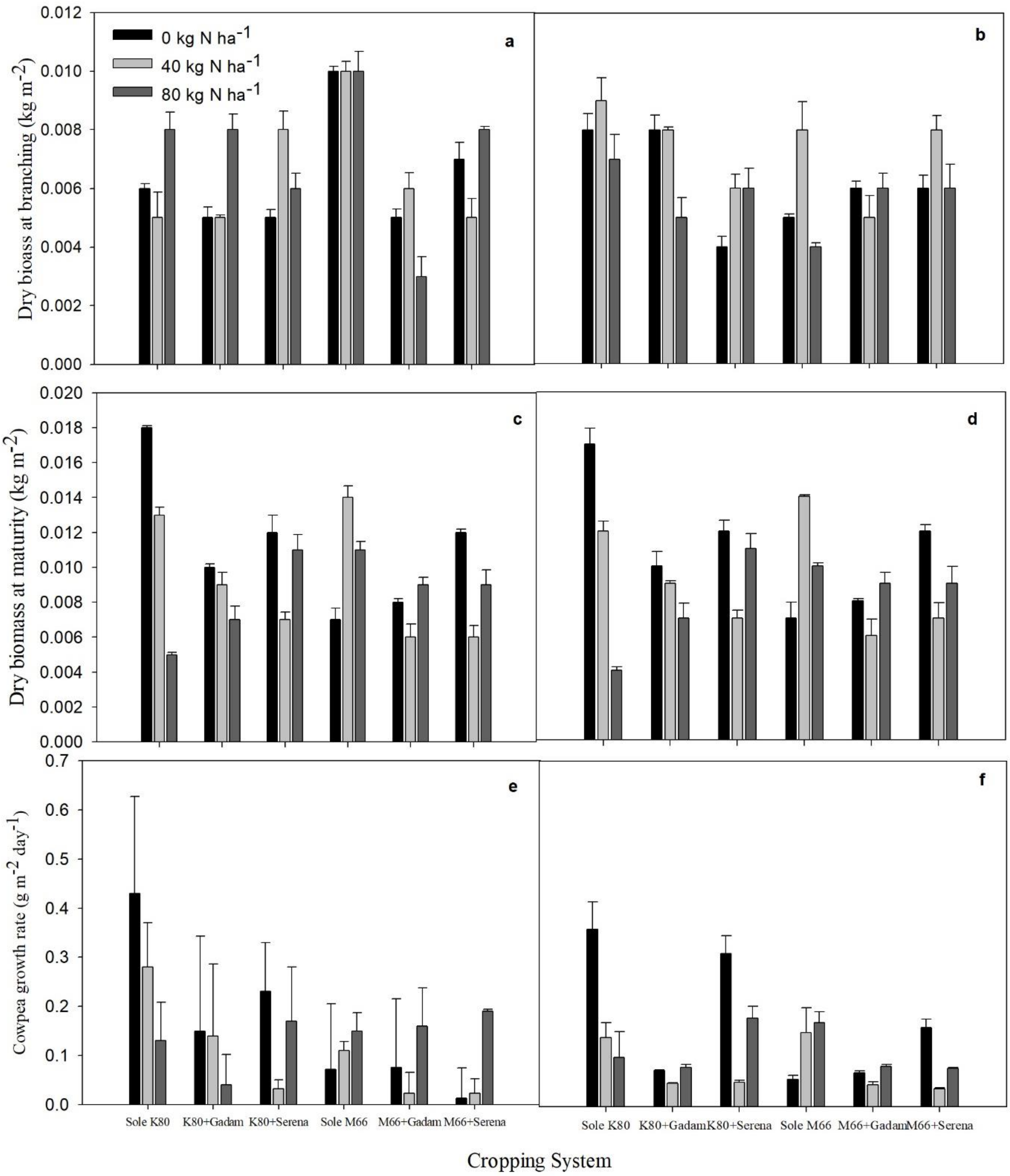

Figure 3.8. Dry biomass (DM) at branching and physiological maturity of two cowpea varieties (K80 and M66) grown under sole and intercrop system with two varieties of Sorghum (Gadam and Serena) and in interaction with three N rates (0, 40, 80 kg N ha^{-1}) at the Igoji (a, c, e) and Katumani (b, d, f) KALRO research stations during 2018/2019 short rain season

3.4.6. Effect of cropping system and nitrogen rate on cowpea yield and yield parameters

Grain yield did not differ significantly between K80 and M66, however, cropping system influenced cowpea grain yield in Igoji (P = 0.034) and Katumani (P = 0.021). In Igoji, intercropping K80 with Serena significantly reduced grain yield by 0.51 t ha^{-1} (54%) compared with sole crops but grain yield of K80 was insignificantly affected by intercropping with Gadam (Table 3.8). Intercropping M66 with either Gadam or Serena effect on grain yield was insignificant. In Katumani, intercropping K80 with Serena significantly reduced grain yield by 0.55 t ha^{-1} (50%) compared with grain yield of sole crops but intercropping M66 with either Gadam or Serena insignificantly affected on grain yield (Table 3.8). Nonetheless, addition of N and cropping system × N rate did not influence cowpea grain yield in both sites (Table 3.8).

The number of pods $plant^{-1}$ of K80 and M66 did not differ significantly in both experimental sites (Table 3.8). On the other hand, cropping system effect on the number of pods $plant^{-1}$ was significant in Igoji (P = 0.018) but no significant effect of cropping system on the number of pods $plant^{-1}$ was observed in Katumani (Table 3.8). In Igoji, intercropping M66 with Serena significantly reduced the number of pods $plant^{-1}$ by three but there was no significant effect of intercropping M66 with Gadam on number of pods $plant^{-1}$. Further, intercropping K80 with either Gadam or Serena had insignificant effect on the number of pods $plant^{-1}$. Nonetheless, application of fertilizer N and cropping system × N rates had insignificant influence on the number of pods $plant^{-1}$ in both experimental sites (Table 3.8).

The number of seeds pod^{-1} of K80 and M66 did not vary remarkably in both sites. On the other hand, cropping system effect on the number of seeds pod^{-1} was significant in Katumani (P = 0.01) but the seeds pod^{-1} was insignificantly affected by cropping system in Igoji (Table

3.8). In Katumani, intercropping K80 with Gadam significantly reduced the number of seeds pod^{-1} by one seed but intercropping K80 with Serena had no significant effect on the number of seeds pod^{-1}. Additionally, intercropping M66 with either Gadam or Serena had no significant effect on the number of seeds pod^{-1}. Nonetheless, addition of N and cropping system × N rates had insignificant influence on the number of seeds pod^{-1} (Table 3.8).

The 100 seed weight of K80 and M66 did not differ significantly in both sites. However, cropping system effect on the 100 seeds weight was significant in Katumani ($P = 0.05$) but insignificant in Igoji (Table 3.8). In Katumani, intercropping K80 with Serena significantly reduced the 100 seed weight by 0.55 g however no significant effect of intercropping on the 100 seeds weight of M66 was observed. Nonetheless, addition of N and the interaction between cropping system and N rates had no significant effect on 100 seeds weight in both experimental sites (Table 3.8).

Table 3.8. Cowpea grain yield, number of pods plant^{-1}, number of seeds pod^{-1} and 100 seed weight of two cowpea varieties (K80 and M66) grown in sole and intercrop system with two varieties of sorghum (Gadam and Serena) and at three N rates (0, 40, 80 kg N ha^{-1}) at Igoji and Katumani KALRO research stations during 2018/2019 short rain season

	Igoji				Katumani			
Treatment	Grain yield (t ha^{-1})	Number of pods per plant	Number of seeds per pod	100 seed weight (g)	Grain yield (t ha^{-1})	Number of pods per plant	Number of seeds per pod	100 seed weight (g)
Cropping system (CS)								
K80	0.95a	8.0a	12.0a	17.7a	1.09a	12.0a	15.0ab	16.56a
K80+Gadam	0.94a	6.0ab	14.0a	17.6a	0.72ab	12.0a	14.0b	16.11a
K80+Serena	0.44b	5.0b	9.0a	17.2a	0.54b	9.0a	15.0abc	16.44a
M66	0.90b	6.0ab	9.0a	17.8a	0.81ab	11.0a	16.0a	16.67a
M66+Gadam	0.44b	4.0bc	10.0a	18.3a	0.60ab	9.0a	17.0a	17.22a
M66+Serena	0.69ab	3.0c	10.0a	18.3a	0.60ab	10.0a	17.0a	17.22a
P-value	0.034	0.018	0.296	0.591	0.021	0.56	0.01	0.232
LSD$_{p\leq0.05}$	0.39	2.7	Ns	Ns	0.49	ns	1.4	ns
N rates								
0 kg N ha^{-1}	0.70a	6.0a	13.0a	17.8a	0.73a	10.0a	15a	16.78a
40 kg N ha^{-1}	0.68a	5.0a	9.0b	17.8a	0.71a	12.0a	16a	16.67a
80 kg N ha^{-1}	0.80a	6.0a	13.0a	17.8a	0.74a	10.0a	16a	16.78a
P-value	0.358	0.869	0.038	0.94	0.94	0.186	0.55	0.974
LSD$_{p\leq0.05}$	ns	ns	2.7	Ns	ns	ns	ns	ns
P-value CS x N	0.25	0.35	0.33	0.974	0.846	0.687	0.056	0.974
LSD$_{p\leq0.05}$	ns	ns	Ns	Ns	ns	ns	ns	ns

Within a column, means followed by the same alphabets are not significantly different, CS X N is cropping system and N rates interaction, ns is not significant

3.4.7. Land equivalent ratio

The statistical analysis of data revealed that in Katumani, the highest LER of 1.56 was attained by Gadam+M66 (partial LER of sorghum, 0.44 and cowpea 1.12) and the lowest LER, 0.88 attained with Serena + K80 combination (partial LER of sorghum, 0.39 and cowpea, 0.49). In Igoji, the highest LER was 1.37 attained with Gadam + K80 combination (partial LER of sorghum, 0.5 and cowpea 0.82) and the lowest LER was 1.04 attained with Serena+K80 (partial LER of sorghum, 0.60 and cowpea, 0.44) (Table 3.9). A LER of 1.56

and 1.37 in Katumani and Igoji respectively indicates monoculture would need 56.3% and 36.5% more area planted to produce the same combined yields of sorghum/cowpea in an intercrop. Nonetheless, the total LER of the intercropping combinations did not differ significantly in Igoji although all the LER for the different intercropping combinations were greater than unity (>1) (Table 3.9). In Igoji, the maximum total LER of 1.23 was attained with addition of 40 kg N ha^{-1} while in Katumani, the highest LER of 1.44 was attained by application of 80 kg N ha^{-1} (Table 3.9). These results implied that total the total LER was increased by 14% in Igoji and 36% in Katumani compared with control plots where no fertilizer was applied.

Table 3.9. Partial and total LER of two varieties of sorghum (Gadam and Serena) grown in an intercrop system with two cowpea varieties (K80 and M66) at Igoji and Katumani KALRO research stations during 2018/2019 short rain season

	Igoji			Katumani		
Treatments	Partial LER-Sorghum	Partial LER-Cowpea	Total LER	Partial LER-Sorghum	Partial LER-Cowpea	Total LER
Cropping systems (CS)						
Gadam+K80	0.548a	0.817a	1.365a	0.513a	0.618ab	1.131ab
Gadam+M66	0.566a	0.505a	1.071a	0.444ab	1.119a	1.563a
Serena+K80	0.597a	0.440a	1.038a	0.392b	0.491b	0.883b
Serena+M66	0.532a	0.688a	1.221a	0.494a	0.673ab	1.167ab
P-value	0.722	0.147	0.347	0.04	0.0125	0.014
LSD$_{p\leq0.05}$	ns	ns	Ns	0.069	0.13	0.598
N rates						
0 kg ha^{-1}	0.391b	0.697a	1.088a	0.197b	0.821a	1.018a
40 kg ha^{-1}	0.664a	0.563a	1.227a	0.582a	0.514a	1.096a
80 kg ha^{-1}	0.627a	0.579a	1.206a	0.603a	0.841a	1.444a
P-value	0.011	0.302	0.603	<.001	0.492	0.339
LSD$_{p\leq0.05}$	0.1805	ns	Ns	0.02	ns	ns
P-value CS x N	0.965	0.352	0.670	0.338	0.819	0.847
LSD$_{p\leq0.05}$	ns	ns	Ns	ns	ns	ns

Within a column, means followed by the same alphabets are not significantly different, CS x N is interaction between cropping system and N rate, ns is not significant, N= 72

3.4.8. Relationships between sorghum grain yield and yield components

The study revealed positive and significant correlation between sorghum grain yield and leaf area index (LAI), number of fertile tillers, panicle weight, harvest index (HI) and growth rate in sole cropping system in both experimental sites (Table 3.10). Conversely, thousand (1000) seed weight and number of spikelets were weakly and insignificantly correlated with sorghum grain yield in both cropping systems. In an intercropping system, the number of fertile tillers was strongly and positively correlated with grain yield however, LAI, panicle weight, HI, number of spikelets and growth rate were weakly and insignificantly correlated with grain yield. Hence, an increase in the LAI, number of fertile tillers, panicle weight, HI and growth rate would certainly increase in sorghum grain yield hence suitable criteria for yield improvements.

Table 3.10. Correlation coefficients between sorghum yield parameters and grain yield grown under sole and intercrop system at Igoji and Katumani KALRO research station during the 2018/2019 short rain season

		Igoji		Katumani	
Cropping System	Traits*	r	P-value	r	P-value
Sole	Leaf area index	0.98	0.001	0.88	0.048
	Number of fertile tillers m^{-2}	0.84	0.035	0.89	0.016
	Panicle weight	0.83	0.039	0.89	0.019
	Harvest index	0.89	0.016	0.95	0.004
	1000 seed weight	0.51	0.299	0.32	0.531
	Number of spikelets	0.41	0.421	0.51	0.307
	Crop growth rate	0.95	0.004	0.83	0.042
Intercrop	Leaf area index	0.56	0.061	0.20	0.526
	Number of fertile tillers m^{-2}	0.69	0.011	0.03	0.939
	Panicle weight	0.037	0.910	0.25	0.443
	Harvest index	0.047	0.884	0.25	0.435
	1000 seed weight	0.12	0.707	0.31	0.335
	Number of spikelets	0.34	0.272	0.52	0.085
	Crop growth rate	0.072	0.823	0.01	0.978

r is correlation coefficients; *: values used for the traits are averages of the 3 blocks in sole and intercrop and at 0, 40 and 80 kg N ha^{-1}

3.5. Discussion

3.5.1. Effect of intercropping and nitrogen rate on sorghum phenology and growth

The time to 50% flowering and 90% physiological maturity was insignificantly affected by cropping system, N rates and cropping system × N rate. This could have been caused by limited competition for growth resources in sole and intercropping systems. Related to these findings, Rashid et al. (2004) reported planting patterns and sorghum-legume intercropping as regards to maturity of sorghum was non-significant.

Further, the insignificant effect of cropping system, N rate and cropping system × N rate on sorghum plant height across the sampling period could be attributed to competition for resources not being very tense which could have caused unrestrained resource supply to the plant to affect plant height. Further, inefficient light interception to increase photosynthetic rate as well as poor absorption of applied N could be excluded. These results are consistent with findings of Nawal (1997) who found no significant effect of intercropping on sorghum plant height who attributed to limited competition for resources in a sorghum/pigeon pea and cowpea intercropping system in Sudan. Further, Birteeb et al. (2011) found that intercropping insignificantly affected maize plant height in a maize/legume intercropping. In a similar environment (UM2 agro ecological zone), Egesa et al., (2016) reported a general insignificant variation in the maximum mean height attained by sorghum plants across the treatments throughout the sampling period who attributed it to elevated interspecies competition for growth resources or reluctant phenological advancement of the crop in a sorghum-cowpea intercropping systems. Further, Sadeghi and Bahrani (2002) reported insignificant effect of N on maize plant height however, Shamme and Raghavaiah (2016) reported significant effect of N on sorghum plant height. The difference between the findings of this study and that of Shamme and Raghavaiah (2016) could be attributed to different soil conditions and varieties used in the study. While the present study findings agree with results of previous studies conducted in similar environments, further investigation on sorghum-legume intercropping and addition of various N effect is recommended in wider environments.

The leaf area index of Gadam grown as sole exceeded LAI of counterparts in an intercrop with cowpea by 0.53 units (over 50% compared with LAI of sorghum in an intercrop system). The competition for growth resources in an intercrop system could have negatively affected leaf growth hence contributed to the reduction in the LAI since LAI is a function of leaf area and number of laves plant^{-1}. Additionally, cropping system x N rate influenced LAI where addition of N increased LAI under intercrop system but this increase was insignificant to out-compete the LAI attained in sole cropping system. This suggests that there was significant suppression of crop growth under intercrop system where addition of N could not increase growth in an intercrop system higher than growth in sole crops. However, the present findings disagree with the findings of Yang et al. (2018) who indicated that intercropping increased LAI of maize in a maize/pea intercropping study in dryland environment. The variation in the results of the present study and that of Yang et al.

(2018) could be attributed to the differences in plant density, varieties used as test crop and differences in ecological conditions.

On the other hand, addition of N significantly increased LAI by 0.08 units (28%) compared with LAI attained in control plots. The positive influence of N on plant growth and development could have influenced this results where growth of vegetative parts especially leaves was enhanced due to N hence this contributed to increased LAI which is a function of leaf area and average number of leaves plant^{-1}. Related to these findings, Sibhatu and Belete (2015) reported that addition of N increased LAI by 35% compared with control plots where no fertilizer was applied. Additionally, Shamme and Raghavaiah (2016) reported that LAI increased with N supply in sorghum. Further, Haghighi et al. (2010) reported an increase in LAI of maize with addition of N and Yang et al. (2018) reported LAI of maize was increased by 11 to 19% with application of N fertilizer compared with control plots where no fertilizer was applied.

Therefore, since LAI is positively and significantly correlated with grain yield, these results suggest that sorghum under sole cropping system and in N fertilized plots will produce more yield than counterparts in an intercrop with cowpea and with no fertilizers applied. Hence the results imply that sole cropping system and addition of N was effective in increasing vegetative growth of sorghum since LAI is a function of leaf area and number of leaves plant^{-1} which partially agree with the study hypothesis. Related to these findings, Sankarapandian et al. (2013) reported a positive correlation between sorghum grain yield and LAI.

Likewise, intercropping significantly reduced dry biomass by at least 20% irrespective of the cowpea variety while the CGR of Serena intercropped with M66 was reduced by 54% while CGR of Gadam was not affected by intercropping. This might have been due to stiff competition for growth resources (nutrients, moisture, light) in an intercrop system which affected growth of vegetative and reproductive parts (steam, leaves, panicle) resulting into low biomass production. In a related study, Legwaila et al. (2012) found that dry biomass of sole maize exceeded biomass of maize in an intercrop with cowpea in a maize/cowpea intercropping study. Furthermore, Harris et al. (1987) found that dry matter weight of sorghum in a sole cropping system exceeded dry matter of counterparts an intercrop system for sorghum-groundnut intercropping study.

These results therefore signify low sorghum grain yield in an intercrop system since there is a positive correlation between Grain yield and biomass and CGR. Hence the results suggest sole cropping system was efficient in biomass accumulation where competition for growth resource might have been minimal compared to intercrop system; however, further investigation across ecological zones is required

Addition of 80 kg N ha^{-1} increased dry biomass at 50% flowering by 43% and dry biomass at 90% physiological maturity by 20% while crop growth rate was increased by 30% but no difference was detected between 40 and 80 kg N ha^{-1}. This result could be attributed to increased photosynthetic rate and consequently higher accumulation of dry matter. These findings are consistent with results of Yang et al. (2018) who reported addition of N significantly increased crop growth rate in an integrated N in maize/pea intercropping in arid zone in china. Further, Sibhatu and Belete (2015) reported that dry biomass increased with N addition where application of 61.5 kg N ha^{-1} over yielded 11.4% of the treatments in control plots. Similarly, YAA (2017) revealed that application of N increased total biomass yield in sole and intercropped sorghum.

Generally, cropping system x N rate significantly affected biomass and crop growth rate under sole cropping system whereby, addition of N increased these parameters while marginal effects was observed in an intercrop system. This could be attributed to limited competition for essential growth resources in sole cropping system compared with intercrop. These findings are consistent with results of Abebe et al. (2016) and Mahmoud et al. (2013) who found that integrating N in soybean-maize intercropping system increased LAI, biomass and growth rate of maize. These findings also agree with results of Makoi et al. (2010) who found that sorghum grown as sole had higher photosynthetic rates which increased growth rate compared with counterparts in mixed culture for sorghum/cowpea intercropping study. The overall results suggest that sole cropping system and N addition was effective in enhancing sorghum growth.

3.5.2. Effect of intercropping and nitrogen rate on sorghum yield and yield components

Intercropping significantly reduced sorghum grain yield by 53% for Gadam and 42% for Serena in Igoji and by 54% for both varieties in Katumani irrespective of the cowpea. The most likely reason for this variation could be stiff competition for resources like soil nutrients, sunlight and water in the intercropped sorghum which affected growth and production of sufficient photosynthates for grain filling in an intercrop system. Cropping system × N rate significantly increased grain yield where sole sorghum grain yield increased proportional to N rate. This could be associated to efficient use of N in sole with limited competition hence increasing sorghum grin yield. Related to the present findings, an earlier study on sorghum-cowpea intercropping in the ASALs found that sole sorghum significantly exceeded yields of intercropped sorghum by 38% (3011 kg ha^{-1} in sole and 1865.8 kg ha^{-1} in an intercrop with cowpea) (Karanja et al., 2014). This study attributed the yield reductions to competition for available resources and space. Further, a study on sorghum-legume intercropping in dry environment reported that sole sorghum exceeded 31.0% of the intercropped sorghum yield which was attributed to competition for light, nutrients and water in the intercrop system (Sibhatu and Belete, 2015). Further, Abraha et al. (2015) in a maize-forage legume intercropping study reported that grain yield of sole maize was higher than counterparts in an intercrop system. Earlier study on sorghum-cowpea intercropping in the arid and semi-arid lands (ASALs) reported that sole sorghum significantly exceeded yields of intercropped sorghum irrespective of planting pattern

(Oseni, 2010). This study attributed high yield in sole compared to intercrop absence of competition. Further, Getachew et al. (2013) reported that intercropping suppressed maize grain yield in maize/legume intercropping study. This suggests that sole cropping system was effective in increasing the individual grain yields of sorghum since growth resources can be utilized without competition from companion crop compared with an intercrop system. However, evaluation of sorghum-legume intercropping across agro-ecological zone deserves further investigation.

Further, sorghum grain yield in the present study was significantly increased by 27% with addition of 40 kg N ha^{-1} and by 21% with application of 80 kg N ha^{-1} compared with control plots where no fertiliser was applied. This could be justified by the important role of N in increasing growth and development of plant reproductive parts and photosynthetic capacity that resulted into higher yields. The results agree with both the study hypothesis and previous studies. An earlier study reported the maximum sorghum grain yield was produced in N fertilized plots while the lowest grain yield was produced in control plots without fertilizer N addition (Shamme and Raghavaiah, 2016). Further, the results of this study are consistent with a previous study which reported that peak grain yield was attained with addition of N in winter wheat (Blankenau et al., 2002).

Hence, addition of N was advantageous in enhancing grain yields but no effect was detected with addition of 40 and 80 kg N ha^{-1}. These results suggest that addition of N increases sorghum yield to a level where an increase in N will not have any impact on yield. Therefore, in the present study, 40 kg N ha^{-1} can be recommended to farmers as an optimum economical rate for sorghum production in the areas of this study and similar agro-ecological zones but studies across other agro-ecological zones is required.

Gadam and Serena panicle length was reduced by 23.6% and 64.8% and panicle width by 62.5% and 57.6% respectively due to intercropping. This could be due to absence or less competition for growth resources in sole cropping system compared with intercropping. However, application of 80kg N/ha increased panicle length by 9.9%. These results could be attributed to positive effect of N in increasing growth development of sorghum productive parts. Related to these results, Oseni (2010), reported sorghum-cowpea intercropping caused significant declines in sorghum ear length beyond critical intercrop density.

In the present study, harvest index of sole sorghum exceeded intercropped sorghum by at least 30% for Gadam and 14% for Serena and cropping system × N rate was effect on HI was significant where by addition of N increased HI under sole cropping system. This could have been due to limited competition for growth resources in sole cropping than in intercrop; however, environmental factors and the effectiveness of the crop to convert dry matter to economic yield could not be excluded. These results corroborate with findings of Saleem et al. (2011) reported higher harvest in sole maize compared with intercropped maize in maize/legume intercropping systems. In the present study, N rate had no significant effect on sorghum HI. Related to these findings, Shamme and Raghavaiah

(2016) reported that HI of sorghum did not increase with N rate. Since harvest index is defined by how efficient a crop coverts dry matter to grain yield (Shamme and Raghavaiah, 2016) and has been positively correlated with grain yield under sole cropping system, these results suggest that sorghum in sole cropping system will produce high yield compared with counterparts in an intercrop with cowpea.

Sorghum panicle weight is an essential yield attributes that is positively and strongly correlated with sorghum grain yield. An overall analysis from the present study revealed that intercropping reduced panicle weight by an average of 23%. This was likely due to lack of competition for growth resources and better partitioning of dry matter to grain yield in sole than in an intercrop system. Earlier study in a similar environment (dry land) in Kenya by Karanja et al. (2014) reported higher sorghum panicle weight in sole sorghum compared with intercrop in sorghum-cowpea intercropping study in medium potential agro ecological zone in Kenya. Similarly, Shamme and Raghavaiah (2016) reported significant influence of variety on panicle number/weight but N had no significant effect. Panicle weight of sorghum was positively and significantly correlated with sorghum grain yield in sole cropping system but did not correlate with grain yield under intercrop system. The present findings agree with results of Singh and Govilla (1989) who reported positive correlations between grain yield and panicle weight in pearl millet. This results suggest that grain yield of sorghum grown as sole is likely to produce more yield compared with sorghum in an intercrop with cowpea.

Tillering is an important agronomic trait that can compensate for poor plant stand to produce higher grain yield under favourable conditions (Kim et al., 2010). In the present study, tillering varied between the two experimental sites and variety where tillering was generally higher in Katumani compared with Igoji and Gadam yielded more fertile tillers compared with Serena by 4.7 fertile tillers m^{-2}. This could be attributed to difference in the ecological conditions between the two sites and the genetic difference between Gadam and Serena since tillering is regulated by the genetic factors, environment and the management practices and the interaction of the three factors (Brent, 2018). Further, in both experimental sites, intercropping sorghum with cowpea significantly reduced the number of fertile tillers m^{-2}. These findings could be justified by high population density in an intercrop system resulting into decreased tillering because of high completion for growth resources (water and nutrients) compared with sole cropping system (Brent, 2018). Related to these findings, Nawal (1997) reported that intercropping reduced the number of tillers in sorghum/cowpea/pigeon pea intercropping study in Sudan. Further, Dantata (2014) reported significantly high yield number of tillers in sugarcane was obtained in sole cropping in a sugar cane-cowpea intercropping. Similarly, the presence of nitrogen could have contributed to cytokinin synthesis which consequently increased the growth and development of the number of fertile tillers (Shamme and Raghavaiah, 2016). Nitrogen application increased the number of fertile tillers by 1.1 tillers compared with control plots. These findings confirm the results of Shamme and Raghavaiah (2016) who reported sorghum tillers increased with enhanced N rates. Furthermore, Abebe (2016) reported higher tillers with increasing N application in wheat where application of 92 kg N ha^{-1} had 28.6 % more tillers than control. Additionally, a study on bread wheat by Genene (2003), also found that the number of sorghum tillers increased with N addition.

The study results further showed the number of fertile tillers m^{-2} was positively and significantly correlated with grain yield in sole and intercropping system. This could be due to the fact that fertile tillers produce grains under favourable conditions which contribute to the overall harvest (Kim et al., 2010). Similar findings were reported by Sankarapandian et al. (2013) in sorghum, Singh and Govilla (1989)) in pearl millet who reported positive correlations between sorghum grain yield and tillers. Therefore, since the number of fertile tillers for sorghum in sole cropping system exceeded tillers of sorghum in an intercrop system, the results suggest that sorghum in sole cropping system and fertilised with N which have high tillering will likely produce high grain yield compared with counterparts in intercrop system and control plots. It should be tillering could also be influenced by genetic and environmental (Kim et al., 2010), hence evaluation of more than two varieties across different environments in future studies is required.

Serena variety yielded more spikelets by 9.8 and 13.5 in Igoji and Katumani respectively than Gadam variety however cropping system, N rates and interactions effects on spikelets were insignificant**.** The variation in the number of spikelets between the two varieties could be associated with genetic differences where Serena variety could have efficiently utilized growth resources better than Gadam. Moreover, reduced competition for growth resources in sole compared with intercrop could have contributed to higher number of spikelets per head in sole compared with intercrop. These findings corroborates with results of Rashid et al. (2004) who reported sole sorghum produced maximum number of grains panicle^{-1} compared with sorghum grown in the association with mung bean. Similarly, Biosci et al. (2014) reported a reduction in number of grains per cob of maize when associated with intercrops.

One thousand seed weight is an essential yield trait which is influenced least by environmental factors (Shamme and Raghavaiah, 2016). In the present study, intercropping did not significantly affect thousand seed weight however variety effect was large which is consistent with findings of Nawal (1997) who reported intercropping sorghum with cowpea and pigeon pea had no effect on hundred seed weight. Further, the effect of N on thousand seed weight was insignificant. These findings are consistent with results of Abebe (2016) who found the rate of N fertilizer application and location insignificantly affected thousand seed weight of wheat. Similarly, Melesse (2007) reported no significant influence of addition of N on bread wheat 1000 kernel.

Nitrogen uptake varied between the varieties and increased with increasing N rate however Intercropping effect on N uptake was inconsistent. Our results disagree with findings of Kanakeri (1991), who reported that intercropping significantly increased N uptake by sorghum. These findings agree with results of, Shamme and Raghavaiah (2016) who reported that N uptake varied among sorghum genotypes and an increase in N uptake in grain and straw increased was proportional to N application. Similarly, YAA (2017) reported that average nitrogen uptake increased significantly by increasing nitrogen levels and was significantly higher in sole cropping system.

Cropping system and N rate interaction effect on the grain yield, harvest index, panicle length, panicle width and N uptake was significant whereby, addition of N significantly increased these traits in sole cropping system however the interaction effect on these traits was inconsistent. These could be attributed to the limited or absence of intra-species competition for growth resources in sole cropping system hence applied N was sufficiently utilized. The present study findings are consistent with results of (Blankenau et al., 2002; Getachew et al., 2013; Sibhatu and Belete, 2015) who reported significant effect of cropping system interactions on these parameters.

3.5.3. Effect of intercropping and nitrogen rate on cowpea phenology and growth

Intercropping had no significant effect on the number of days to 50% flowering and 90% physiological maturity however variation was observed between the two varieties where K80 matured 12 days earlier than M66. This variation could be attributed to genetic factors between the two varieties (Ndiso et al., 2015). Intercropping significantly increased plant height of K80 by 15% and M66 by 13% compared with sole crops at 6 weeks after planting (WAP). The results could be attributed to efficient utilisation of growth resources in and intercrop system. These findings are consistent with results of Karanja et al. (2014) who reported intercropping cowpea with sorghum increased cowpea plant height.

Cropping system and N rates insignificantly influenced the number of effective root nodules plant^{-1} which implied that the competition for resources and shading effect of sorghum in an intercrop system was not very tense as to significantly reduce the number of effective root nodules since shading effect significantly inhibits the branching of cowpea and hinders N fixation (Hall and Patel, 1987). The study findings agree with results of Kombiok et al. (2005) who reported that cropping systems had no effects on nodule number and nodule weight who attributed to limited competition for resources. However, these results disagree with findings of Sibhatu and Belete (2015) who reported sole cowpea yielded higher number of nodules than their intercropped counterparts due to the effect of shading by sorghum affecting fixation of N in the soil. The variety effect was large at 6 weeks after plant (50% flowering/flower initiation stage) where K80 produced 9 effective root nodules more than M66. Similar findings were reported by Zoumana et al. (2012) who reported variation in the number of root nodules with variety.

The non-significant effect of N on the root nodules could be attributed to limited competition for carbon between cowpea and N for nitrification process and resources (nutrients, water, light, space) due to large differences in the maturity period between cowpea and sorghum. The study findings however disagree with results of Herridge (1982) found that addition of N at higher rate caused low cowpea nodulation and N fixation. This attributed to inhibition of thread, slow growth and rapid senescence of nodules when N is added in either nitrate or ammonium form. The difference in the results could be attributed to difference in agro-ecological conditions and variation in the varieties used.

The study revealed that leaf area index (LAI) of M66 was significantly reduced by five units when intercropped with sorghum but LAI of K80 was not affected by intercropping. The likely reason for the reduction of LAI in an intercrop system could be related to stiff competition for growth resources such as nutrient, light, moisture which are essential for vegetative growth hence contributed to low average number of leaves plant^{-1} smaller leaf area and consequently low LAI. Related to these findings, Adem (2006) reported intercropping significantly reduced cowpea LAI in a sorghum-cowpea intercropping who attributed the reduction to competition for growth resources. On the contrary, Kombiok et al. (2005) reported that cropping system did not significantly change the LAI of cowpea who attributed to absence of competition. However, addition of N did not significantly affect the LAI of cowpea. This could be attributed to the fact that cowpea fixes its own N hence was able to meet its own N requirement without depending on external N supply. The present study results however disagree with findings of Abebe et al. (2016) so soybean/maize intercropping system where LAI of soybean increased with addition of N.

Intercropping significantly reduced the dry biomass of both cowpea varieties by 0.001 kg m^{-2} to 0.003 kg m^{-2} at branching and physiological maturity. Further, the growth rate of cowpea from branching to physiological maturity was significantly higher in sole crop system by at least 50% for K80 and 25% for M66 compared with counterparts in intercrop with sorghum. Additionally, cropping system and N rate effect on dry biomass and CGR was significant whereby addition of N increased dry biomass and CGR in both sites. This was attributed to limited competition for growth resources in sole cropping system hence more dry matter was accumulated in the stem, branches and leaves in sole cropping system. Similar, Getachew et al. (2013) reported that intercropping forage legume with maize significantly reduced the dry biomass of forage legumes. Further, Karanja et al. (2014) reported that dry biomass of sole cowpea exceeded dry biomass of cowpea in an intercrop with sorghum. Nitrogen application of 80 kg N ha^{-1} increased cowpea dry biomass 14.3% compared with the control plots. The finding corroborates with results of Sibhatu and Belete (2015) who reported that highest dry biomass of cowpea was recorded in N fertilized plots and lowest when no fertilizer was applied. Similarly, Shamme and Raghavaiah (2016) reported increase sorghum biomass with addition of N fertiliser.

Generally, cowpea growth parameters (Plant height, LAI, number of root nodules, crop growth rate) performed better under sole cropping system and with addition of N. This therefore suggests that cowpea is better grown in sole cropping system with minimum addition of N since external N supply did not influence key growth parameters such as plant height, LAI and number of nodules. However, further detailed investigation is required to provide more evidence.

3.5.4. Effect of intercropping and nitrogen rate on cowpea yield and yield components

Sorghum-cowpea intercropping reduced grain yield of K80 by more than 50% while grain yield of M66 was not affected by intercropping. This could be attributed to shading effect of sorghum on cowpea and competition for space, light, moisture and nutrients. Similar results were reported by Oseni (2010), reported yield of cowpea was suppressed by sorghum where cowpea grown as sole had higher grain yield compared to cowpea in an intercrop with sorghum. Further, the results are consistent with findings of Egbe and Idoko (2012) who reported significant reduction in the grain yield of cowpea in an intercrop system due to effect of shading by sorghum which could have reduced the photosynthetic rate of cowpea hence reducing their yields. Additionally, Solomon and Kibrom (2014) reported that sole cropped produced higher soybean yields in sole than intercrop for maize-soybean intercropping. Layek et al. (2014b) reported that intercropping soybean with pearl millet, sorghum and maize significantly reduced pods plant^{-1}, seeds pod^{-1} and grain yield of soybean. The study attributed the reduction in yield to stiff competition by the companion crops. Similar results were also reported by Mead and Willey (1980) who found that the yield of cowpea was depressed by sorghum.

Intercropping significantly reduced the number of pods of M66 by over 50% however, intercropping had no effect on the number of pod plant^{-1} of K80. This could be attributed to stiff competition for resources affecting the number of pods^{-1} and sorghum shading effect. The findings confirm results of Sibhatu and Belete (2015) who reported non-significant effect of cropping system and nitrogen effect on number of pods plant^{-1} of cowpea for sorghum-cowpea intercropping. Similarly, Liben, et al. (2002) reported an insignificant influence of intercropping on number of seed pod^{-1} in the maize-faba bean intercropping.

The cropping system, N rates and cropping system x N rates effects on the number of seeds pod^{-1} were insignificant. The findings of this present study are in agreement with findings of Liben et al. (2002), reported insignificant effect of cropping system on faba bean seed pod^{-1} in maize-faba bean intercropping study. Moreover, the findings also corroborates with results of Legwaila et al. (2012), who reported insignificant difference in the number of seeds per pod between the sole cowpea and intercropping for maize cowpea intercropping.

The 100 cowpea seed weight was remarkably reduced by 0.55 g due to intercropping effect. This could be due competition for nutrients in an intercrop system which reduced the translocation of photosynthates during grain filling hence reducing grain weight. The present study findings are in conformity with results of Legwaila et al. (2012), who reported there were significant differences in the weight of cowpea seeds between treatments due to cropping system in maize/cowpea intercropping system.

These results therefore suggest that intercropping did not only reduce the grain yield of sorghum but also significantly reduced cowpea grain yield and yield traits. Therefore, sole cropping is an appropriate cropping system for cowpea production. On the other hand, cowpea yield was insensitive to external N supply in the present study which could be attributed to its ability to fix sufficient N symbiotically however further study under different N rates and more than one season and environment is required to validate these results.

3.5.5. Effects of cropping system × N rate interaction on growth and yield of the sorghum and cowpea

Cropping system × N rate significantly affected sorghum CGR and grain yield while cowpea growth and yield traits were not affected by the main effects interactions. Under sole cropping system, addition of N increased these traits while the increase was marginal under intercrop system. This could be linked to non-proportional sharing of soil N sources resulting from competition between sorghum and cowpea and limited fixation of N by the cowpea in an intercrop system resulting to low grain yield in an intercrop system as opposed to sole cropping system (Jensen et al., 2020). Similarly, the present results findings corroborated with findings of YAA (2017) who reported that application of N increased total biomass yield in sole and intercropped sorghum.

Overall, the results show that although intercropping reduced sorghum yield, present results show that there is potential to exploit cropping system × N interactions to increase yields, more so in during periods of adequate moisture. Future studies should consider evaluating sorghum yield performance across agro-ecologies and N rates under sorghum-cowpea intercropping since significant variations in the cropping system × nitrogen interactions were observed in the two experimental sites.

3.5.6. Land equivalent ratio

The LER is an important tool to evaluate the performance of an intercropping systems. In the present study, all the different intercropping combination was all greater than unity (LER>1), with the highest LER being1.563 and 1.365 in Katumani and Igoji respectively despite reduction of the individual grain yield of sorghum and cowpea in an intercrop system. This could be due effective utilization light, moisture and nutrients in the intercrop system than in the sole crop system. These findings imply that sole cropping of either sorghum or cowpea would require 0.365 in Igoji and 0.563 in Katumani more units of land to get the same yield obtained from the intercropping system. Similarly, Oseni (2010) reported the total LER was highest where sorghum and cowpea achieved 70 and 38 % of their sole yields respectively. Furthermore, present study findings are consistent with results of Deljoo et al. (2004) who reported high land equivalent ratio greater unity in a sorghum cowpea intercropping.

Further, the total land use efficiency was significantly increased with the addition of nitrogen by 14% and 36% with application of 40 and 80 kg N ha^{-1} respectively compared with control plot. These results conform with findings of Sibhatu and Belete (2015) who reported the highest LER (1.46) achieved with addition of N.

Therefore, these results suggest that intercropping sorghum with either K80 or M66 with application of 40 kg N ha^{-1} is an effective intercropping combination to maximize crop productivity per unit area of land and ensure economic efficiency. However, intercropping sorghum with other legume other than cowpea in more than one season and different environments is recommended to further validate these findings.

3.6. Conclusion

Intercropping significantly reduced CGR and grain yield of sorghum and cowpea by about 50% while addition of N increased CGR of sorghum by about 30% and sorghum grain yield by 27% however, N insignificantly affected cowpea grain yield. Thus, the overall findings suggest that sole cropping system and addition of N fertilizer was effective in increasing sorghum crop growth rate and yield hence is recommended for commercial production of sorghum. Intercropping increased overall land productivity (LER>1) hence the practice is useful to ensure food security at household level, however, screening and breeding of cowpea varieties compatible with sorghum in intercrop systems is desirable to reduce sorghum grain yield losses observed in the current study. Additionally, although intercropping reduced CGR and sorghum grain yield by about 50%, present results show that there is potential to exploit cropping system × N interactions to increase yield to improve food security, more so seasons with adequate rainfall. Further, the lack of significant differences in grain yield between the application of 40 and 80 kg N ha^{-1} suggests that sorghum yield could be maximized at lower N rates. Gadam out-yielded Serena in the present system hence highly recommended to farmers in the study areas for commercial production under sole cropping system with addition of 40 kg N ha^{-1}.

CHAPTER 4: INTERCROPPING AND NITROGEN FERTILIZATION ALTERED THE PATTERNS OF LEAF SENESCENCE IN THE CANOPY OF SORGHUM

4.1. Abstract

Leaf senescence regulates grain yield but the modulation of leaf senescence in sorghum under legume-based intercrop systems and nitrogen (N) fertilization is not known. The time-course of sorghum leaf senescence and its association with grain yield was investigated in an intercrop system with two sorghum and cowpea varieties each. Factorial combinations of sorghum-cowpea intercrops, and three fertilizer N rates were laid out in RCBD with a split-plot arrangement and replicated three times. Sorghum leaf senescence was assessed from flowering to maturity at both whole-plant level and flag-leaf level. At the whole-plant level, leaf senescence was scored visually by counting the number leaves presenting more than 50% green leaf area while the greenness of the flag leaf was tracked using SPAD 502 chlorophyll meter. A logistic function in SigmaPlot was fitted to estimate four traits of leaf senescence, including minimum and maximum SPAD units (SPADmin, SPADmax), time to loss of 50% SPADmax (EC50) and the rate of senescence. Intercropping reduced peak leaf greenness of the flag leaf (SPADmax) by 8 SPAD units but prolonged green leaf area at the whole-plant level by 0.2 leaves plant^{-1} day^{-1}. Fertilizer N delayed leaf senescence at both whole-plant by 0.4 leaves plant^{-1} day^{-1} and flag-leaf scale by 9 SPAD units with addition of 80 kg N ha^{-1} and 5 SPAD units with addition of 80 kg N ha^{-1} compared with control plots. Gadam was five SPAD units greener than Serena. While EC50 did not correlate with grain yield, sorghum yield was positively and strongly correlated with SPADmax, SPADmin and rate of leaf senescence. This suggests that the peak leaf greenness in the period bracketing flowering determined grain yield but the delay in leaf senescence might have been non-functional. However, effects of competition in sorghum-legume intercropping and source-sink relationships on the patterns of sorghum leaf senescence deserve further investigation.

Keywords: Leaf greenness, EC50, rate of senescence, SPAD, yield

4.2. Introduction

Intercropping and best management practices of fertilizer nitrogen can increase crop yield in dryland environments (Karanja et al., 2014; Sibhatu and Belete, 2015). However, previous studies on intercropping and nitrogen use only focused on crop growth and yield but with limited information on leaf senescence. In cereal crops, leaf senescence patterns profoundly impact grain yield and quality by regulating source-sink relationships for nutrient demand (Feller et al., 2008; Gong et al., 2019). Five traits are used to describe the leaf senescence patterns, and they include the maximum and minimum leaf greenness, the start of senescence, time to loss of 50% of peak leaf greenness, and the rate of senescence (Christopher et al., 2014; Kitonyo et al., 2018). Prolonged leaf greenness has been correlated with higher grain yield in sorghum (*Sorghum bicolor* (L.) Moench) (Kassahun et al., 2010; Christopher et al., 2014), wheat (*Triticum aestivum*) (Kitonyo et al., 2017) and maize (*Zea mays*) (Kitonyo et al., 2018). In addition, delayed but rapid rate of leaf senescence was reported to increase wheat grain mass (Xie et al., 2016). Manipulation of these traits of senescence could potentially increase grain yield of sorghum in drylands, where both rainfall amount and frequency decline as crops mature (Huho, 2017).

Cereal-legume intercropping is a sustainable agricultural practice of simultaneously growing at least two crops on the same land (Sibhatu and Belete, 2015). The principle goal of intercropping is to increase crop productivity from a unit area where available growth resources are efficiently utilized (Ram and Meena, 2014). Intercropping often has advantages over sole cropping of improved crop diversification (Oseni, 2010) and fertility of the soil due to the legume's ability to fix atmospheric N symbiotically (Layek et al., 2018). Other advantages of intercropping include: soil and moisture conservation especially in the dry environments, provision of stable yield and weed management (Layek et al., 2018). Further, intercropping and other practices such as mulching have been reported to regulate senescence through increased net photosynthetic duration and prolonged leaf greenness in proso-millet (Ali et al., 2018; Gong et al., 2019).

In spite of the wide adoption of intercropping in tropical environments, the practice has some limitations. For instance, an earlier study established that sorghum and cowpea grain yield grown in sole crop system exceeded yields of counterparts in an intercrop system (Karanja et al., 2014). Additionally, a study on sorghum-cowpea intercropping reported that sole sorghum exceeded 31% of the intercropped sorghum yield (Sibhatu and Belete, 2015). This is because of interspecific competition for resources like soil nutrients, sunlight and water in the intercropped sorghum (Karanja et al., 2014). Further, cereals like sorghum are nutrient-exhaustive crops and the legume may not meet all the N requirement of the cereal without external fertilizer N supply (Das et al., 2014). However, while the effect of intercropping on sorghum growth and yield has been reported in previous studies, its influence on senescence traits in cereals like sorghum has not been widely understood.

While nitrogen (N) is essential in boosting crop growth and development, it is one of the most limiting nutrients globally (Yang and Udvardi, 2018). In addition to its limitation, only 30 - 40% of fertilizer N is converted into harvested product in cereals (Shamme and Raghavaiah, 2016). Further, poor management practices have failed to maintain a congruence between plant nutrient demand and supply which often compromises nutrient use efficiency and reduce grain yield (Dobermann, 2007). Nitrogen economy of the crop has been shown to regulate the patterns of senescence in many crops, sorghum included (Li et al., 2018). Source-sink relations, which impacts N remobilization from senescing leaves to the reproductive structures also impacts leaf senescence (Luoni et al., 2019). In cereal crops, yield is maximized when at least 90% of N in the vegetative tissues is mobilized to the grain (Kassahun et al., 2010). Under moisture stress conditions, prolongation of leaf greenness has been demonstrated to improve grain yield, stem mass and lodging resistance (Christopher et al., 2014). In maize, the maximum leaf greenness before flowering has been correlated with grain yield and yield traits (Kitonyo et al., 2018).

Sorghum flag leaf is the last to emerge from the whorl at the boot stage and tends to be smaller than the other leaves (Gerik et al., 2003). The flag leaf plays a very key function in providing photosynthates for grain filling, particularly in moisture stress conditions (García et al., 2010). Therefore, decline in photosynthetic rate of flag leaf or removal of flag leaf leads to significant yield decrease (Ji et al., 2012). Leaf senescence gradually starts with the mature leaves losing their green leaf area and finally the whole plant including the flag leaf (Gregersen et al., 2013; Chen et al., 2015). Leaf senescence is reported to be triggered by genetic factors (Thomas and Howarth, 2000; Yang and Udvardi, 2018). Additionally, moisture and nutrient stresses, pathogen infection as well as temperature variations are reported to control leaf senescence in monocarpic crops (Kitonyo et al., 2018).

Sorghum is an essential source of food and feed for populations in the dry environments (Deb et al., 2004). Of recent, sorghum has gained a high demand in the market as a raw material for making malt by breweries hence making it an important cash crop for communities in the dry lands (Kilambya and Winters, 2013). Therefore, increasing sorghum productivity will not only address food insecurity but also increase household income through the sale of sorghum (Mwadalu and Mwangi, 2013; Kilambya and Winters, 2013). However, inappropriate cropping systems, nutrient mining and limited use of agricultural inputs are the main drivers of low sorghum yield (Sibhatu and Belete, 2015). Therefore, strategies such as sorghum-legume intercropping with carefully managed N-fertilizer application could improve sorghum grain yield. Also, understanding physiological processes such as senescence and their association with grain yield would help in the sorghum yield improvement process.

Thus, the objective of the study was to investigate the time-course of post-flowering leaf senescence of sorghum under intercrop and sole cropping systems and different fertilizer N rates, as well as understand how senescence modulates grain yield. This study hypothesized that intercropping sorghum with cowpea and higher fertilizer N rates could delay leaf senescence and increase grain yield of sorghum.

4.3. Materials and methods

4.3.1. Site

The study was conducted at KALRO in Katumani and Igoji research stations during the 2018/2019 short rain season where an experiment was established in each site. Katumani is 575 meters above sea level (masl) and located 01º 35'S, 37º 14'E while Igoji is 1770 masl and located 0°11'13" S, 37°40'10" E and 1770 masl (Njiru et al., 2010). Further details of the site are presented in Chapter three of this thesis.

4.3.2. Treatments and experiment design

Treatments consisted of two cropping systems (intercrops and sole), four crop varieties (two sorghum varieties and two cowpea varieties) and three fertilizer N rates (0, 40 and 80 kg N ha^{-1}). Cowpea was sown between two rows of sorghum in intercropping system. Gadam and Serena sorghum varieties and M66 and K80 cowpea varieties, were used as test crops for this study. Fertilizer N was supplied from urea (46% N) applied at the planting rows and tillering stage at a ratio of 1:3. A 60 P kg ha^{-1} inform of triple super phosphate (TSP) uniformly applied to all treatment plots. Further details on experimental treatments and design are presented in Chapter three of this thesis.

4.3.3. Experiment management

Sorghum seeds were sown using spacing of 0.75 m and 0.20 m between rows and plants respectively while cowpea seeds were planted at a row spacing of 0.6 m and 0.3 m between plants within a row in sole cropping system. Under intercrop, sorghum was sown at a row spacing of 0.9 m and 0.2 m between plants and cowpea was sown in between two rows of sorghum at 0.3 m between plants. Both crops were planted at a seed rate of 10 kg ha^{-1} and thinning was done two weeks after emergence to achieve plant population density of 6.7 plants m^{-2} and 5.6 plants m^{-2} for sorghum and cowpea respectively in sole cropping system and 5.6 plants m^{-2} and 3.7 plants m^{-2} for sorghum and cowpea respectively in an intercrop system. Further details on experimental management are presented in Chapter three of this thesis.

4.3.4. Data collection

4.3.4.1. Post flowering weather data

Daily minimum and maximum rainfall and temperature data before sorghum flowering to physiological maturity were collected from weather stations in both sites. The collected data was used to compute the average monthly rainfall and temperature.

Weather conditions from before flowering until physiological maturity are shown in Figure 4.1. Data was consistent with long term average for both sites shown in Chapter three of this thesis, where rainfall tapers and temperatures increase as the crop matures. The difference in the mean total rainfall post flowering between Igoji and Katumani (195 mm) indicates Katumani was much drier than Igoji however, the mean temperatures between the two sites were relatively similar. Details of the weather are presented in Chapter three of this thesis.

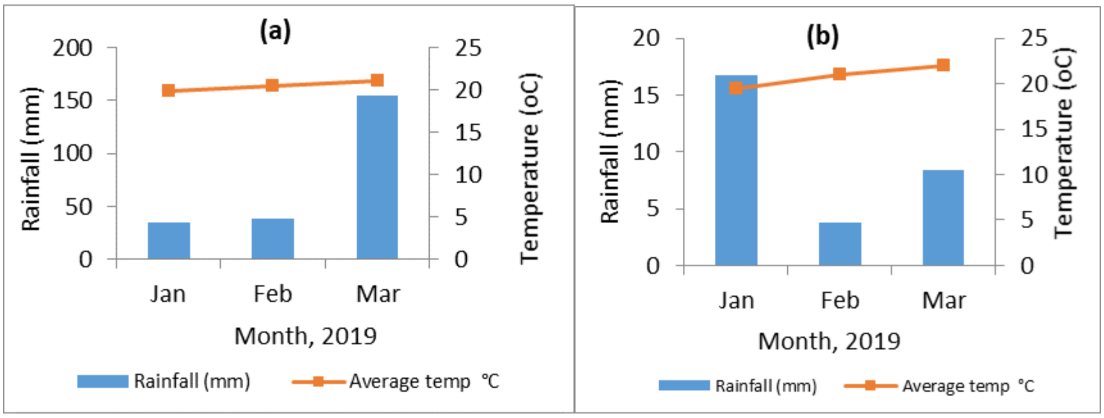

Figure 4.1. Monthly rainfall and temperature from flowering to physiological maturity of sorghum at Igoji (a) and Katumani (b) KALRO research stations during 2018/2019 short rain season

4.3.4.2. Leaf senescence at the whole-plant level

In each plot, five sorghum plants were tagged for repeated measurements of leaf senescence. Leaf senescence at the whole plant level was visually scored from 10 days after flowering through to physiological maturity by counting the total number of leaves presenting more than 50% green leaf area plant^{-1}. The number of green leaves was recorded at 10, 20, 30, 40 and 50 days after flowering for five plants and means were computed to represent each plot.

4.3.4.3. Senescence of the flag leaf

In each plot, five sorghum plants were tagged for repeated measurements of leaf senescence of the flag leaf using a SPAD 502 chlorophyll meter (Kitonyo et al., 2018). Chlorophyll content of sorghum flag leaf was measured 10 days after flowering to physiological maturity. For each tagged sorghum plant, three SPAD units were collected at different points of the flag leaf at the tip, middle and bottom, and the mean computed. The average SPAD unit for five plants was computed to represent each plot.

4.3.4.4. Analysis of leaf senescence

SPAD data was subjected to a logistic regression function in SigmaPlot version 10.0 (Systat Software, Inc., San Jose California USA, www.systatsoftware.com) to fit the time course of leaf senescence from 10 days of sorghum flowering through to maturity. Similar to Christopher et al. (2014) and Kitonyo et al. (2018), the function estimated four parameters of leaf senescence, including the peak leaf greenness (SPADmax), time to the loss of 50% of SPADmax (EC50), minimum leaf greenness at maturity (SPADmin), while the slope of the curve gave the rate of leaf senescence (RS as SPAD units day^{-1}) (Equation 4.1, Figure 4.2). The logistic function was fitted for each plot and traits of leaf senescence subjected to analysis of variance.

$$y = SPAD\min + \frac{SPAD\max - SPAD\min}{1 + (\frac{x}{EC50})RS} \tag{4.1}$$

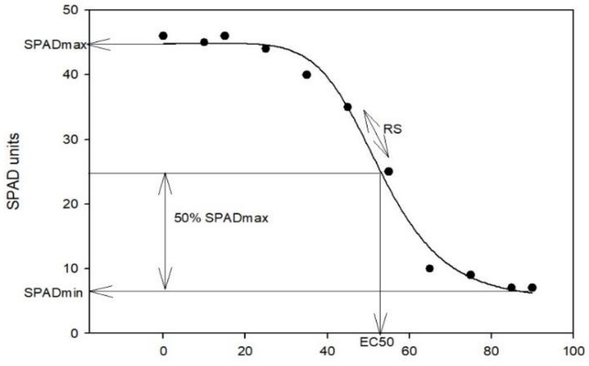

Figure 4.2. An illustration of the fitted logistic curve in SigmaPlot and the estimated traits of leaf senescence of two sorghum varieties (Gadam and Serena) grown in sole and an intercrop system with two varieties of cowpea (K80 and M66) at Igoji and Katumani KALRO research stations during 2018/2019 short rain season

4.3.5. Data analysis

Data were subjected to analysis of variance by GenStat 14th Edition at 5% probability level. All the measured variables' residuals were normally distributed hence transformations were not required. Treatment means were compared and separated using the least significant difference (LSD) test at probability level of 5% (Gomez and Gomez, 1984). Similar to (Kitonyo et al., 2018), relationships between the traits of leaf senescence and, grain yield and yield traits were examined by correlation analysis using SigmaPlot version 10.0.

4.4. Results

4.4.1. Senescence at the whole plant level

There were significant differences in the leaf number presenting more than 50% green leaf area during the entire sampling period (Table 4.1). Intercropping and fertilizer N application significantly delayed leaf senescence but interactions between cropping system and N rate were inconsistent (Figure 4.3). In both Katumani and Igoji, intercropping Gadam and Serena with either cowpea variety delayed leaf senescence by 0.1 and 0.2 leaves plant^{-1} day^{-1}, respectively, or 0.56 and 1.12 leaves m^{-2} day^{-1}, respectively, considering a plant density of 5.6 plants m^{-2} in an intercrop system (Table 4.1).

Significant effects of N application on leaf senescence at the whole plant level were observed in both sites ($P < 0.01$). Addition of N significantly prolonged leaf greenness by 0.4 leaves plant^{-1} day^{-1} or 2.24 leaves m^{-2} day^{-1} compared with control plots but with little effects detected between 40 and 80 kg N ha^{-1} in all sampling stages (Table 4.1). Cropping system × N rate interactions influence on the leaf senescence at the whole plant level were inconsistent throughout the sampling period in Igoji and Katumani (Figure 4.3). In Igoji, while cropping system × N rate significantly affected the number of leaves plant^{-1} that presented over 50% green leaf area at 10, 40 and 50 days after flowering, the interaction effect was only significant at 20 days after flowering in Katumani (Table 4.1).

Table 4.1. Number of green leaves at 10, 20, 30, 40 and 50 days after flowering (DAF) of two sorghum varieties (Gadam and Serena) grown under sole and intercrop system with two varieties of cowpea (K80 and M66) and three N rates at Igoji and Katumani KALRO research stations during 2018/2019 short rain season

Treatment	Igoji					Katumani				
	10	20	30	40	50	10	20	30	40	50
Cropping System (CS)										
Sole Gadam	5.8c	6.1b	6.0b	3.6b	2.3c	4.4bc	4.3b	3.4ab	3.0bc	2.1b
Gadam + K80	6.6ab	6.7ab	7.4a	4.4a	3.4a	4.9a	4.4b	3.2b	2.7cd	2.0b
Gadam + M66	6.4ab	6.7ab	7.7a	4.7a	3.7a	5.0a	4.9a	3.8a	3.6a	2.8a
Sole Serena	6.0bc	6.7ab	6.0b	4.3a	2.7bc	4.3c	3.7c	2.9c	2.3d	1.4c
Serena + K80	6.1bc	6.7ab	7.8a	4.6a	2.9b	4.9a	4.8a	3.8a	3.2ab	2.3b
Serena + M66	6.8a	7.2a	6.8ab	4.8a	3.6a	4.8ab	4.4b	3.7a	2.7cd	2.0b
P-value	0.001	0.02	0.007	0.01	0.009	0.043	0.019	0.05	0.05	0.031
LSD$_{p\leq0.05}$	0.5	0.9	1.1	0.5	0.4	0.40	0.3	0.3	0.4	0.3
N rate										
0 kg N ha^{-1}	3.8b	4.3b	5.5b	2.0b	0.9b	2.9b	2.6b	1.5b	1.0b	0.2b
40 kg N ha^{-1}	7.6a	8.0a	7.7a	5.6a	4.1a	5.7a	5.3a	4.4a	3.9a	3.1a
80 kg N ha^{-1}	7.4a	7.7a	7.6a	5.6a	4.3a	5.6a	5.4a	4.4a	3.8a	3.1a
P-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LSD$_{p\leq0.05}$	0.37	0.6	0.80	0.38	0.29	0.28	0.20	0.23	0.30	0.24
P-value CS x N	0.046	0.212	0.329	0.046	0.001	0.534	0.042	0.363	0.924	0.307
LSD$_{p\leq0.05}$	0.9	ns	ns	1.1	1.2	ns	1.0	ns	ns	ns

The means within a column followed by the same alphabets are not significantly different, CS x N is interaction between cropping system and N rate, ns is not significant

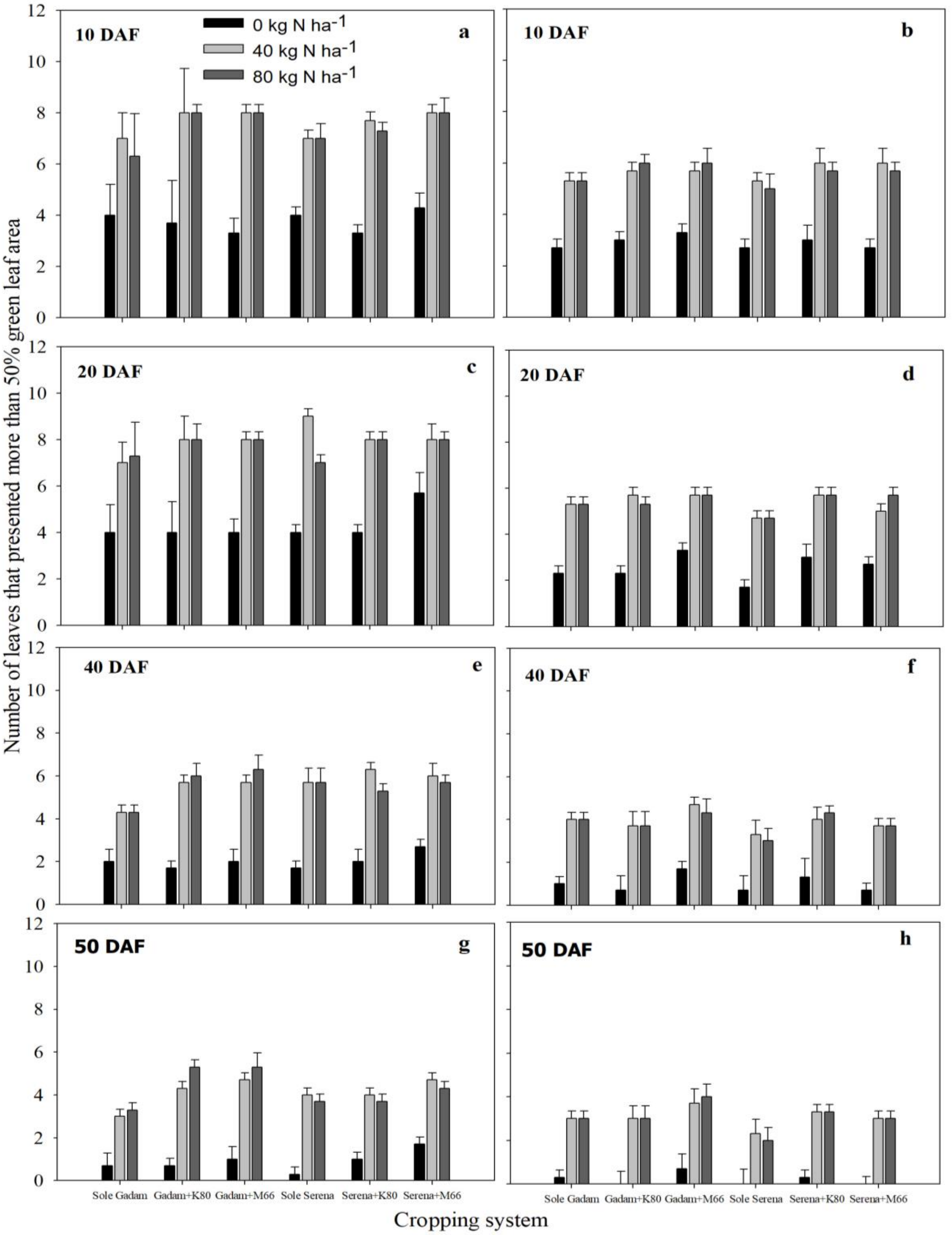

Figure 4.3. Number leaves that presented more than 50% green leaf area at 10, 20, 40 and 50 days after flowering (DAF) of two sorghum varieties (Gadam and Serena) grown in sole and intercrop system with two varieties of cowpea (K80 and M66) and interactions with 0, 40 and 80 kg N ha-1 at the KALRO research stations in Igoji (a, c, e, g) and Katumani (b, d, f, h) during 2018/2019 short rains season

4.4.2. Senescence of the flag leaf

Cropping systems ($P < 0.05$), N rates in Igoji ($P < .001$) and Katumani ($P = 0.004$) and cropping system × N rate only in Igoji ($P = 0.003$) significantly affected the peak greenness of the flag leaf (SPADmax) (Table 4.2). Gadam was seven SPAD units greener than Serena in Igoji but no significant differences were observed in Katumani. Irrespective of cowpea variety, intercropping significantly reduced SPADmax by 8 SPAD units, compared with sole crop system in Igoji but in Katumani, intercropping effects were marginal (Table 4.2). In Igoji, addition of 80 kg N ha^{-1} significantly increased SPADmax by five units compared with control plots. Similarly, in Katumani, addition of 40 kg N ha^{-1} significantly increased SPADmax by nine units compared with control but without significant differences between 40 and 80 kg N ha^{-1} (Table 4.2). The highest SPADmax was recorded under sole cropping system with addition of N while intercropping without N supply had the lowest SPADmax (Figure 4). Cropping system × N rate effects on SPADmax were significantly large whereby the highest SPADmax was recorded under sole crop system with the addition of N while intercropping without N supply had the lowest SPADmax (Figure 4.4).

The minimum SPAD unit of the flag leaf (SPADmin) did not vary between Gadam and Serena and was insignificantly affected by cropping system, N rate and cropping system × N rate (Table 4.2). No significant effect was observed between the two sorghum varieties on time to loss of 50% maximum SPADmax (EC50). In addition, EC50 was not affected by cropping systems but the addition of nitrogen delayed leaf senescence (Table 4.2). In Igoji, EC50 was delayed by 7.5 days with addition of 80 Kg N ha^{-1} while in Katumani, leaf senescence delayed by 11 days compared with unfertilized plots.

Significant effects of cropping system on the rate of senescence were observed in Katumani ($P = 0.006$) but not in Igoji ($P > 0.05$). However, under sole crop system, Gadam senesced faster than Serena, but only in Katumani. Cropping system × N rate interaction had no significant effect on rate of senescence in both sites (Table 4.2). Intercropping Gadam with either K80 or M66 significantly reduced the rate of senescence by four SPAD units day^{-1} but there were no differences in Serena. Application of 80 kg N ha^{-1} increased the rate of senescence by 2.6 SPAD units day^{-1} compared with control plots but no significant differences between 40 and 80 kg N ha^{-1} were observed (Table 4.2).

Table 4.2. Maximum leaf greenness (SPADmax), minimum leaf greenness (SPADmin), time to loss of 50% SPADmax (EC50) and the rate of leaf senescence (RS) means of two sorghum varieties (Gadam and Serena) grown under sole and intercrop system with two varieties of cowpea (K80 and M66) and N rate at Igoji and Katumani KALRO research stations during 2018/2019 short rain season

	Igoji				Katumani			
Treatments	SPADmax (SPAD units)	SPADmin (SPAD units)	EC50 (days)	RS (SPAD units day^{-1})	SPADmax (SPAD units)	SPADmin (SPAD Units)	EC50 (days)	RS (SPAD units day^{-1})
Cropping systems (CS)								
Sole Gadam	50a	10a	31a	6.4a	61ab	15a	24a	8.5a
Gadam + K80	41b	14a	29a	5.2a	64a	17a	23a	4.1b
Gadam + M66	42b	15a	27a	4.2a	56ab	15a	25a	4.6b
Sole Serena	43b	13a	31a	5.3a	57ab	16a	24a	5.9b
Serena + K80	42b	15a	30a	3.7a	52b	16a	23a	4.8b
Serena + M66	41b	13a	23a	4.0a	51b	16a	28a	5.0b
P-value	0.047	0.311	0.669	0.683	0.0148	0.992	0.347	0.006
LSD$_{p\le0.05}$	6	ns	ns	ns	11	Ns	ns	2.8
N rates								
0 kg N ha^{-1}	42b	13a	26b	3.1b	49b	14a	18b	4.8a
40 kg N ha^{-1}	41b	12a	26b	5.5a	62a	16a	27a	5.2a
80 kg N ha^{-1}	47a	15a	34a	5.7a	59a	18a	29a	6.1a
P-value	<.001	0.408	0.023	0.044	0.004	0.132	<.001	0.49
LSD$_{p\le0.05}$	3	ns	6	2.3	8	Ns	3	ns
P-value CS × N	0.003	0.606	0.332	0.127	0.427	0.094	0.252	0.142
LSD$_{p\le0.05}$	7.454	ns	ns	ns	ns	Ns	ns	ns

The means within a column followed by the same alphabets are not significantly different, CS x N is interactions between cropping system and N rate, ns is not significant

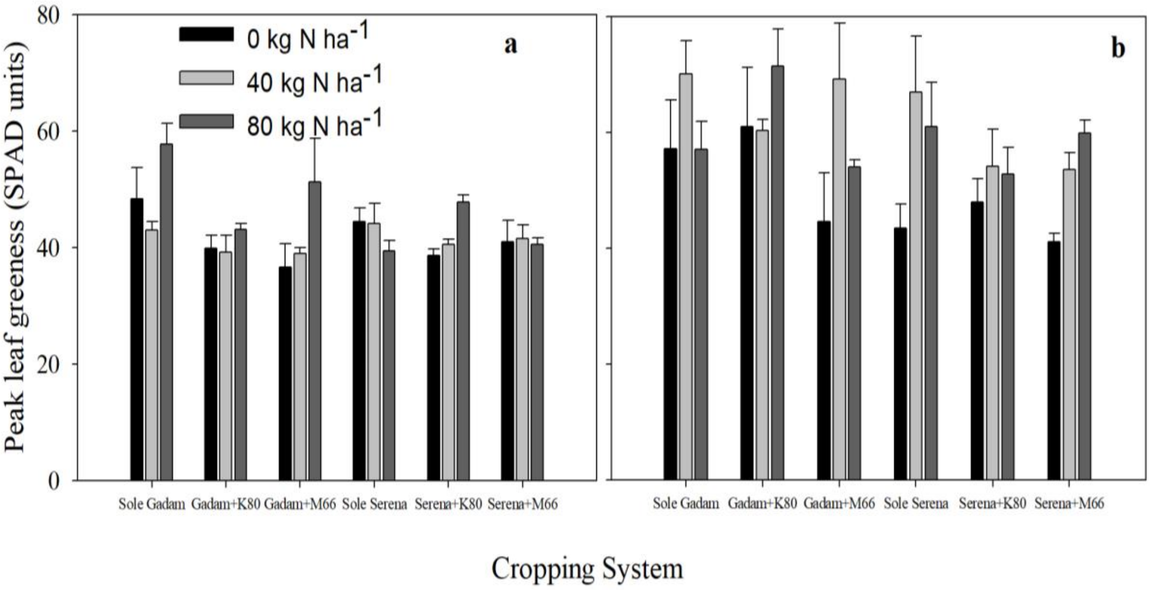

Figure 4.4. Peak leaf greenness (SPADmax) of two sorghum varieties (Gadam and Serena) grown under sole and intercrop system with two varieties of cowpea (K80 and M66) and interactions with 0, 40 and 80 kg N ha^{-1} at Igoji (a) and Katumani (b) KALRO research stations during 2018/2019 short rain season

4.4.3. Relationships between traits of leaf senescence and grain yield

Table 4.3 presents correlations between leaf senescence traits and sorghum grain yield and yield components under sole and intercrop systems. In both cropping systems, sorghum grain yield was significantly and strongly correlated with SPADmax and SPADmin in Igoji and Katumani. Similarly, panicle length and width, as well as grain size positively correlated with SPADmax in sole cropping system but not in the intercrop system. Additionally, under sole crop system only, sorghum grain yield positively correlated with the rate of senescence in Igoji but not in Katumani. Time to loss of 50% maximum SPAD (EC50) was weakly and inconsistently correlated with sorghum grain yield in both sole and intercropping systems.

Table 4. 3. Correlation coefficients between senescence traits and sorghum grain yield and yield parameters of two sorghum varieties (Gadam and Serena) grown in an intercrop system with two varieties of cowpea (K80 and M66) at 0, 40 and 80 kg N ha^{-1} at Igoji and Katumani KALRO research stations during the 2018/2019 short rain season

		Igoji				Katumani			
Cropping system	Traits*	SPADmax (SPAD units)	SPADmin (SPAD units)	EC50 (days)	RS (SPAD units day^{-1})	SPADmax (SPAD units)	SPADmin (SPAD units)	EC50 (days)	RS (SPAD units day^{-1})
Sole	Grain yield	0.82*	0.92*	-0.14ns	0.93*	0.77*	0.82*	0.05ns	0.75ns
	Panicle length	-0.53ns	0.94*	-0.19ns	0.79ns	-0.39ns	0.09ns	0.38ns	0.33ns
	Panicle width	-0.53ns	0.55ns	0.32ns	0.32ns	0.89ns	0.96*	0.42ns	-0.24ns
	Panicle weight	0.18ns	0.9ns	0.16ns	0.72ns	0.44ns	0.25ns	0.43ns	-0.18ns
	1000 seed weight	0.71*	0.5ns	0.18ns	0.81ns	0.95*	0.76*	0.51ns	-0.07ns
Intercrop	Grain yield	0.58*	0.75*	0.13ns	0.03ns	0.76*	0.89**	0.15ns	-0.07ns
	Panicle length	0.1ns	0.001ns	-0.05ns	0.34ns	0.44ns	0.46ns	0.09ns	0.38ns
	Panicle width	0.45ns	0.37ns	0.51ns	0.26ns	0.52ns	0.37ns	0.22ns	0.10ns
	Panicle weight	-0.57ns	-0.55ns	-0.37ns	-0.04ns	0.1ns	0.13ns	0.14ns	-0.003ns
	1000 seed weight	-0.31ns	-0.28ns	-0.5ns	0.11ns	0.14ns	0.005ns	0.2ns	0.27ns

SPAD$_{min}$: minimum leaf greenness; SPAD$_{max}$: maximum leaf greenness; EC50: time to loss of 50% SPADmax; RS: rate of senescence; ns is not significant; *p<0.05; **p<0.01; n=54

4.5. Discussion

4.5.1. Leaf senescence at the whole-plant level

Senescence is an important physiological process caused by an imbalance in the source-sink association, and the ability of source leaf to improve storage capacity (Gerardeaux et al., 2010). In the present study, intercropping significantly prolonged leaf greenness at whole plant level by 0.2 leaves plant^{-1} day^{-1} while cropping system x N rate effects significantly affected number of green leaves with more than 50% Greenleaf areas whereby addition of N proportionally increased the green leaf area. This could be linked to high levels of assimilates in leaves in an intercropping system and N-fertilized plots which contributed to slow degradation of chlorophyll compared with sorghum in sole cropping systems and unfertilized plots. The results support the study hypothesis that intercropping and N rates delay leaf senescence. Further, the findings of the present study reinforce previous studies. In a related study, the number of green leaves for sorghum in intercrop with cowpea exceeded counterparts in sole by at least 10% (Gong et al., 2019). Additionally, intercropping has been reported to extend photosynthetic duration to produce sufficient photosynthates that regulate leaf senescence (Gong et al., 2015).

Similarly, addition of N in the present study prolonged leaf greenness by 0.4 leaves plant^{-1} day^{-1} (2.6 leaves m^{-2} day^{-1}) compared with control plots. This might be due to the presence of N that contributed to increase in the development and size of chloroplasts, thus increasing photosynthetic capacity. These findings agree with an earlier study which reported that chloroplast size increased with increasing N (Li et al., 2013). The study results therefore imply that there was sufficient chlorophyll content due to N addition which significantly delayed senescence (He et al., 2002). Further, our results suggest that addition of N was more effective in delaying foliar senescence than intercropping since senescence of 0.4 leaves plant^{-1} day^{-1} were delayed with addition of N compared with 0.2 leaves plant^{-1} day^{-1} due to intercropping. However, no effects were detected between addition of 40 and 80 kg N ha^{-1} hence addition of N at a rate of 40 kg N ha^{-1} can be considered as an economically optimum rate to increase photosynthetic duration and sorghum grain yields. The delay in leaf senescence at whole plant level due to intercropping might have been non-functional since sorghum grain yield attained in intercrop sorghum was significantly lower than counterparts in sole cropping system. Hence, N influence in prolonging leaf greenness at whole plant level and its modulation of grain yield was significantly large and could have superseded intercropping effect. It is worth noting that pathogen infection could influence leaf senescence as reported in an earlier study by Kitonyo et al. (2018) hence in the present study, pest and diseases were timely controlled in all plots and their effect in influencing leaf greenness at whole plant level was minimized. However, environmental and genetic factors were beyond the scope of this study, which could have influenced leaf senescence hence, deserve more investigation.

4.5.2. Senescence of the flag leaf

Sorghum flag leaf plays an essential role in grain filling through maintenance of synthesis and transportation of photo-assimilates to the grain hence, investigation of the physiological state of the flag leaf is vital to correlate with grain yield (Biswal and Kohli, 2013). In the present study, the sorghum leaf senescence traits, which comprised SPADmax, SPADmin, EC50 and rate of senescence were modulated by cropping system, N rate and cropping system x N rate. Intercropping reduced SPADmax by 8 units while N application improved this trait. Further cropping system x N rate effect on SPADmax was significant where SPADmax increased with addition of N under sole and intercrop system. This could be attributed to reduced intra-species competition in sole compared with interspecies competition in an intercropping systems for growth resources (nutrients, water, light). Further, the presence of N could have highly contributed to the results which meant that there was adequate supply of photosynthates in the leaves, which resulted into high production of chlorophyll hence limiting loss of greenness.

Therefore, since SPAD measures the chlorophyll content in a plant leaf and is often associated with leaf greenness, the results implied that, there was slow degradation of chlorophyll in sorghum under sole cropping system compared with intercropping. Hence, the present study results suggest that sole cropping system and N rate interactions would delay the growth of sorghum reproductive organs, thus increasing the photosynthetic capacity of sorghum leaf due to improved supply of nutrients, both from eternal N supply and those from soil to sink organs. Furthermore, Borrell et al. (2014) and Jordan et al. (2012) reported that prolonged leaf greenness during grain filling was positively associated with yield when an equilibrium was established between supply of photosynthates and plant demand. These results therefore suggest that peak greenness (SPADmax) of the flag determined grain yield since yield recorded in sole crops exceeded yield of intercropped sorghum by more than 50% for both varieties; however, delaying leaf senescence at whole plant level might have been non-functional in modulating grain yield. This justifies the important role played by the flag leaf in determining grain yield hence sorghum smallholder farmers can be advised to ensure the flag leaf shouldn’t be compromised or damaged at any stage of the plant growth and development as this could negatively impact the final grain yield.

Maximum SPAD of the flag was significantly higher in Gadam sorghum variety than Serena by five units and Gadam out-yielded Serena in both sites which further justifies the strong correlation between peak leaf greenness of the flag and grain yield. This could have been due to the variation in the genes that control leaf senescence processes in the two sorghum varieties as reported in an earlier study that genotypic variation greatly influenced stay-green expression in wheat (Christopher et al., 2014). This study, however, did not examine the mechanisms and genetic controls underlying the identified leaf senescence traits (SPADmax, EC50, SPADmin and rate of senescence) which deserve to be investigated.

Addition of N increased EC50 and rates of senescence. These results were possibly due to the significant impact of N in the development of chloroplast, which increased the chlorophyll content in the plant leaves contributing to stay green. These results corroborate an earlier study which reported crops fertilized with N had significantly higher leaf greenness than crops in control plots (Kitonyo et al., 2018). However, intercropping significantly reduced the rate of senescence by four SPAD units day^{-1} while EC50 was insensitive to cropping system. These results suggest that maximum grain yields would be obtained in a sole cropping system and with addition of N compared with an intercrop system and unfertilized plots since SPADmax and rate of senescence are functions of yield in a sole cropping system (Jordan et al., 2012; Kitonyo et al., 2018).

Generally, cropping system x N rate effect was insignificant on SPADmin, EC50, rate of senescence however, significantly affected SPADmax whereby, addition of N significantly increased peak leaf greenness of sorghum flag leaf under sole cropping system whereas, marginal effects were observed in an intercrop system. Similar to the reasons stated above, limited or absence of competition of growth resources (nutrients, light, moistures) in sole cropping system could have contributed to the high peak greenness for sorghum grown under sole cropping system. This ensured sufficient production of photosynthates by sorghum under sole cropping system due to uninterrupted light interception and sufficient moisture which contributed to delayed leaf senescence of the flag since leaf senescence is driven by source-sink relation (Kitonyo et al., 2017).

4.5.3. Association between traits of leaf senescence and grain yield

Sorghum grain yield was proportional to SPADmax, SPADmin and rate of senescence. This positive correlation between key leaf senescence traits and grain yield could be linked to the essential role of sorghum flag leaf in grain filling due to its strategic position on the culm or immediately below the spike enabling it to intercept a lot of radiation. These findings confirm the results of a previous study where grain yield and yield components were functions of SPADmax (Gregersen et al., 2013). Similarly, other studies reported prolonged duration of photosynthesis during grain filling in the ASALs is associated with increased grain yield (Kassahun et al., 2010). Related to these findings, a statistically significant association between leaf greenness and grain yield in sorghum was reported (Masclaux-Daubresse et al., 2010).

However, an earlier study reported a strong negative correlation between EC50 and maize grain yields (Kitonyo et al., 2018), which is contrary to the present study since EC50 did not correlate with yield. This might be due to the variation type of crop, variety and soil fertility between the present study and that of Kitonyo et al. (2018). Therefore, SPADmax, SPADmin and RS are recommended as key selection criteria for yield improvement as they were positively correlated with grain yield. However, source-sink relationships in sorghum-cowpea intercropping across agro-ecological zones require further investigation.

4.5.4. Senescence and the modulation of grain yield

Sorghum grain yield and quality is profoundly modulated by delayed leaf senescence (peak leaf greenness) and faster rate of senescence. The former modulates grain yield by increasing the photosynthetic duration which results in high production of carbohydrates and sufficient supply of carbohydrates to the grain during grain filling stage and consequently resulting into high grain yield while the latter modulates grain yield by increasing the remobilisation of N from the senescencing leaf to the developing grain which consequently results into high grain yield (Masclaux-Daubresse et al., 2008; Kassahun et al., 2010; Kitonyo et al., 2018; Gong et al., 2019). Senescence is regulated by variety of complex factors including cropping systems, moisture stress, pest and diseases, genetic and environmental factors among others (Pommel et al., 2006; Kitonyo et al., 2018). Additionally, sink strength was reported to have modulated leaf senescence in sorghum (Borrell et al., 2001; Kitonyo et al., 2018), wheat (Biswas and Mandal, 1986; Xie et al., 2016; Kitonyo et al., 2018) and maize (Sadras et al., 2000; Kitonyo et al., 2018) under limited abiotic and biotic stresses. However, the present study was limited to investigating the effect of intercropping and N fertilizer on leaf senescence and neither focused on environmental and genetic factors nor comprehensively investigated other factors. The results also showed that the rate of senescence increased with addition of N but cropping system had no effect on this trait. Further, faster rate of senescence increased sorghum grain yield as evidenced by the strong and positive correlation between grain yield and rate of senescence. This could be attributed to the N remobilization from the senescing leaf to the grain especially during grain filling stage which suggests that the sink strength regulated the rate of senescence (Gregersen, 2011; Xie et al., 2016; Kitonyo et al., 2018). The positive correlation between rate of senescence and grain yield was further explained in previous studies which reported delayed leaf senescence in maize due to lack of grain (Antonietta et al., 2016; Kitonyo et al., 2018) and sunflower (Sadras et al., 2000; Kitonyo et al., 2018). Similar results were reported in wheat and maize where the rate of senescence increased with grain yield (Kitonyo et al., 2017), and rapid rate of grain filling was associated with a faster rate of senescence (Xie et al.,2016). Additionally, the present study showed N delayed leaf senescence at both whole plant and flag leaf level where SPADmax (peak leaf greenness) and number of green leaves significantly increased with addition of N compared with control plots but without significant differences between 40 and 80 kg N ha^{-1} while cropping system only significantly affected SPADmax. Peak leaf greenness modulated grain yield where by delayed leaf senescence was significantly and positively correlated with grain yield. This implied that N enhanced “stay green” phenotypic traits in sorghum and prolonged the leaf greenness causing a delayed N remobilization from the leaves (slow degradation of chlorophyll content) which helped prolonged photosynthetic capacity, and therefore enhanced photosynthates (carbohydrate) supply to the sink organs (developing grain) and consequently increasing the grain yield (Kassahun et al., 2010). Further, Gong et al. (2019) and Feller et al. (2008) indicated that leaf area duration and green leaf area proportionally affected the grain yield in millet by regulating the source-sink relationship. In the current study, intercropping delayed leaf greenness at whole plant level but was insignificantly correlated with grain yield which implied that delayed leaf senescence at whole plant level did not modulate sorghum grain yield.

4.6. Conclusions

Intercropping delayed leaf senescence at whole plant by 0.2 leaves plant^{-1} day^{-1} but reduced SPADmax of the flag by 8 SPAD units compared with sole crop system. Further, fertilizer N delayed leaf senescence at both whole-plant and flag-leaf scales. The EC50 did not correlate with grain yield, but sorghum yield was a function of SPADmax, SPADmin and rate of senescence. This suggests that the peak leaf greenness determined grain yield but the delay in leaf senescence might have been non-functional. Further, no significant effects were detected with increase in N from 40 kg N ha^{-1} to 80 kg N ha^{-1} on yield and leaf senescence. Hence, 40 kg N ha^{-1} can be recommended as economically optimum rate for sorghum production in the UM2 and UM4 agro-ecological zones. Also, traits correlated with grain yield could be considered as key criteria for grain yield improvement. However, the effects of interspecies and intra-species competition in sorghum-legume intercrop systems and source-sink relationships on the patterns of sorghum leaf senescence deserve further investigation across ecological zones.

CHAPTER 5: GENERAL DISCUSSION, CONCLUSION AND RECOMMENDATION

5.1. General discussion

Irrespective of the cowpea variety, the leaf area index (LAI) of sorghum was significantly reduced by 0.53 units (more than half) compared with LAI of sorghum in an intercrop system. This decrease in the LAI in an intercrop system could be linked to interspecies competition for nutrients, light and moisture which are key in influencing vegetative growth. Therefore, since LAI is a function of leaf area, number of leaves plant^{-1}, a reduction in growth of vegetative parts such as plant leaves will reduce LAI. However, addition of 80 kg N ha^{-1} increased the LAI of sorghum by 28% compared with control plots but no difference was detected between 40 and 80 kg N ha^{-1} which could be attributed to the essential role of N fertiliser in stimulating vegetative growth. Additionally, the cropping system x N rate significantly affected LAI where LAI of sole sorghum increased with addition of N. Likely reason could be the essential role of N in increasing vegetative growth and absence or limited competition for growth resources in sole cropping system hence ensuring unrestrained supply of nutrients for vegetative growth.

Crop growth rate of intercropped sorghum with cowpea was significantly reduced by 54% for Serena compared with sole crops but CGR of Gadam was not affected by intercropping. This might be attributed to increased competition between the two species in an intercrop system which consequently reduced growth of crop vegetative parts. While these findings are consistent with many earlier studies especially by Makoi et al. (2010) who reported CGR of sorghum was higher in sole cropping system than in a sorghum/cowpea intercropping system. In contrast, Yang et al. (2018) reported that intercropping increased CGR of maize in maize/pea intercropping in a semi-arid zone in china. Further, addition of 80 kg N ha^{-1} increased the crop growth rate of sorghum by 30% which may be attributed to the increased vegetative growth influenced by the presence of N fertilizer which is consistent with previous studies.

Grain yields of intercropped Gadam and Serena were significantly reduced by 53% for Gadam and 42% for Serena in Igoji and by 54% for both varieties in Katumani irrespective of the cowpea variety. The most likely reason for this variation could be interspecies competition for resources like soil nutrients, sunlight and water in the intercropped sorghum. The results of the present study do not support the study hypothesis that intercropping increases sorghum grain yields but are consistent with earlier studies. However, the current study also revealed that intercropping was productive than sole cropping in Igoji and Katumani (LER >1) hence intercropping can mitigate against crop failure and it is essential for producing sorghum to improve household food security.

Further, sorghum grain yield in the present study was significantly increased by 27% with addition of 80 kg N ha^{-1} compared with control plots but no difference was detected between addition of 40 and 80 kg N ha^{-1}. This might be attributed to the important role of N in increasing growth and development of plant reproductive parts and photosynthetic capacity that resulted into higher yields. The results are in conformity with both the study hypothesis and previous studies. The cropping system and N rate interaction significantly influenced sorghum grain yield where sole sorghum in N fertilised plots had higher yield than counterparts in intercrop and control plots. This could be explained by the absence of competition in sole cropping system and efficient utilisation of N.

The study also revealed that intercropping significantly reduced cowpea growth rate by 50% for K80 and 25% for M66 and grain yield of K80 by 50% while grain yield of M66 was not affected by intercropping. This could be linked to the effect of shading on cowpea by sorghum in an intercrop system hence limiting light interception by cowpea adversely affecting cowpea growth. In this study, cowpea did not respond to addition of N fertilisers which could be attributed to N self-sufficiency via symbiotic nitrogen fixations. These findings therefore suggest that sole cropping system was effective for cowpea production however further investigation on the effect various N rates on cowpea as well as compatibility cowpea in sorghum cropping system is required.

Investigation of intercropping effect on sorghum leaf senescence revealed that intercropping reduced flag leaf peak leaf greenness by 8 SPAD units but prolonged green leaf area at the whole-plant level by 0.2 leaves plant^{-1} day^{-1}. Fertilizer N delayed leaf senescence at both whole-plant level by 0.4 leaves plant^{-1} day^{-1} and flag-leaf scale by 9 SPAD units with addition of 40 kg N ha^{-1} compared with control plot. While EC50 did not correlate with grain yield, sorghum yield was a function of SPADmax and rate of leaf senescence. These findings could be attributed to increased moisture retention in an intercrop system limiting the rate of senescence at whole plant level.

Further, the presence of N could have enhanced chlorophyll content in the sorghum leaf hence reducing the rate of senescence. This is because senescence is a visible sign of chlorophyll degradation (He et al. 2002). The study further revealed higher rate of senescence was associated with high grain yield. This could be attributed to the high demand for N by the grain thus, accelerating leaf senescence (Sinclair et al., 1990). These findings are in agreement with findings of Xie et al., (2016) who found that increased rate of leaf senescence was proportional to wheat grain yield.

While intercropping delayed leaf senescence at whole plant level, the overall yield was low in an intercrop system which suggests that the influence of leaf greenness at whole plant was non-functional, however, peak leaf greenness of the flag has a strong influence on grain yield. The effects of competition in sorghum-legume intercropping and source-sink relationships on the patterns of sorghum leaf senescence deserve further investigation.

5.2. Conclusion

Intercropping significantly reduced CGR of sorghum by 54% for Serena but CGR of Gadam was not affected by intercropping while CGR of cowpea was reduced by 50% for K80 and 25% for M66 and grain yield of both crops by over 50%. Conversely, addition of N increased grain yield of sorghum by 27% compared with control plots but had no effect on cowpea yield. Therefore, sole cropping and addition of N were effective in increasing sorghum and cowpea growth and yield. However, although intercropping reduced sorghum yield, present results show that there is potential to exploit cropping system x N interactions to increase yield, especially in seasons with adequate rains. Lack of significant differences in grain yield between the application of 40 and 80 kg N ha^{-1} suggests that sorghum yield could be maximized at lower N rates. However, further studies are needed to establish the economically optimal N rate in sorghum production. Gadam variety was superior to Serena in terms of growth and yield performance. Further, there was a positive and strong correlations between sorghum grain yield and LAI, number of fertile tillers, panicle weight, HI and crop growth rate in sole cropping system. However, with exception of the number of fertile tillers, all other yield components were not correlated with sorghum grain yield under intercrop system. Therefore, these parameters could be considered as key criteria for yield enhancement under sole cropping.

The analysis of data on leaf senescence revealed that at whole plant level, intercropping delayed leaf senescence by 0.2 leaf plant^{-1} day^{-1} and addition of N prolonged leaf greenness by 0.4 leaf per day^{-1} hence the effect of N on delaying leaf senescence at whole plant level was twice the effect of intercropping. Analysis of the senescence of traits based on SPAD data collected from the flag leaf revealed, intercropping significantly reduced the maximum SPAD (SPADmax) by 8 units however addition of N increased SPADmax by 5 units. EC50 did not correlate with grain yield, but high sorghum yield was associated with SPADmax, SPADmin and faster rate of senescence. However, the peak leaf greenness of the flag determined grain yield but the delay in leaf senescence at whole plant level might have been non-functional. While overall findings suggest that senescence was mainly influenced by N fertilisers, further investigation on competition for growth resources in sorghum/cowpea intercrop system and source-sink on source-sink relationships and competition of ron the patterns of leaf senescence in sorghum-legume intercrop systems is required.

5.3. Recommendations

1. Sole cropping system is recommended for commercial production of sorghum while intercropping is recommended for sorghum production to meet house food security since land productivity was increased under intercrop system (LER>1).

2. Lower rate of N fertilisers (40 kg N ha^{-1}) is recommended for sorghum production since there was lack of significant differences in grain yield between the application of 40 and 80 kg N ha^{-1}.
3. Gadam sorghum variety is recommended for commercial production by smallholder farmers as a raw material for making malt and for food security in the study areas since it yielded better than Serena, has a short maturity period and it is the most preferred variety for making malt.
4. Further studies on growth and yield performance of Gadam sorghum variety under intercrop system with various legumes, spatial arrangements, crop densities and varying N rates across ecological zones desirable.
5. Further investigation on the effects of competition for growth resources in sorghum/cowpea intercrop system and source-sink relationships on the patterns of leaf senescence in sorghum-legume intercrop systems is desirable.
6. Screening and breeding of cowpea varieties compatible with sorghum in intercrop systems is desirable to reduce sorghum grain yield losses observed in the current study.

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