# EFFECTS OF SOIL MOISTURE REGIMES, PLANTING DENSITY AND INTERCROPPING ON GROWTH AND YIELD OF SELECTED SOYBEAN CULTIVARS IN KENYA

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**A Thesis Submitted to Graduate School in Partial Fulfilment of the Requirements for Doctor of Philosophy Degree in Agronomy of Egerton University**

**EGERTON UNIVERITY**

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# DECLARATION AND RECOMMENDATION

## Declaration

This thesis is my original work and has not been presented in any university and institution of higher learning for any award.

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## Recommendation

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## COPYRIGHT

## DEDICATION

This humble effort, the fruit of my thoughts and studies, is dedicated to my son Praise and daughter Louisa for being deprived of father's love and care during my study period.

## ACKNOWLEDGEMENTS

Glory be to the Almighty God for the gift of life and for seeing me through the turbulent study period. I thank Egerton University for giving me an opportunity to study at a world class university that advocates for advancement of humanity. The support offered by the University towards my academic study is herein acknowledged. I sincerely recognize and profoundly appreciate the support and inputs of my academic advisors, Professor Josephine P. Ouma and Professor Erick K. Cheruiyot, for their untiring efforts in shaping my research concept and for their timely technical guidance and advice throughout my study period. My study at Egerton University was made possible with the financial support from Government of Malawi through the Agricultural Productivity Programme for Southern Africa (APPSA) under the Department of Agricultural Research Services, to which I am heavily indebted. I thank the Centre Directors and staff of Tea Research Institute in Kericho and Kenya Agricultural and Livestock Research Organisation in Njoro, the Principal of Siaya Agricultural Training Centre and the Officer In-Charge of Busia (Kenya) prison for allowing me to use their research fields and equipment. I whole-heartedly thank Professor Nancy Mungai for allowing me to use her greenhouse without which my research work could never have been the same. Martha, my dear wife and best friend. Thank you for the moral and spiritual encouragement during my study period. Thank you for patiently and diligently taking care of our son Praise and our daughter Louisa in my absence. To all my family members, my Mum, Dad, brothers and sisters, I say thank you a million times for your prayers and words of encouragement. 'Nyasaye Ogwedhu'.

## ABSTRACT

Soybean [*Glycine max* (L) Merrill] yields in Kenya range from 445-1200 kg ha$^{-1}$ against potential yields of 3500 kg ha$^{-1}$. The low yields are attributed to soil moisture stress and use of poor agronomic practices. The objectives of the study were to determine effect of soil moisture regimes on $CO_2$ assimilation, growth and yield of selected soybean cultivars; to determine effect of planting density on yield and yield components of soybean and to determine effect of soybean and maize intercropping on stomata conductance, shoot characteristics and yield of soybean. A greenhouse moisture stress study was laid out in a randomized complete block design (RCBD) in a 6 by 4 factorial treatment arrangement and was replicated three times. Soil moisture regimes (80, 60, 40 and 20% of field capacity) and cultivars (Gazelle, Nyala, EAI 3600, DPSB 8, Hill and DPSB 19) were first and second factors, respectively. Field moisture stress study used RCBD in a split plot arrangement with three replicates. Moisture regimes (100, 75, 50 and 25% of soybean crop water requirement) and cultivars (as in experiment 1) were main plot and sub plot factors, respectively. The third experiment evaluated effects of planting density on yield and yield components of soybean using a 5 by 2 factorial arrangement in RCBD. Planting densities (10, 12, 20, 40 and 80 plants per m$^2$) and cultivars (EAI 3600 and DPSB 19) were first and second factors respectively. The fourth experiment determined effect of soybean and maize intercropping on stomata conductance, shoot characteristics and yield of soybean. The experiment was conducted using RCBD with 3 replicates. Soil moisture stress significantly ($p < 0.001$) reduced soybean shoot and root growth of all tested cultivars. Leaf relative water content, stomata conductance, photosynthetic rate and sub-stomatal $CO_2$ levels significantly ($p < 0.001$) declined with increasing soil moisture stress. Cultivar DPSB 19 had higher stomata conductance but reduced transpiration rate at lower soil moisture levels. Highest number of nodules per plant were attained at 10 plants m$^{-2}$ which was 34.76% more than number of nodules obtained at 80 plants m$^{-2}$. Soil moisture depletion at 80 plants m$^{-2}$ was 15.22% higher than at the lowest plant population of 10 plants m$^{-2}$. Intercropping maize and soybean significantly ($p < 0.01$) reduced soybean leaf area, IPAR, stomatal conductance and photosynthetic rate. Intercropping reduced soybean yield by 80.72% though 1M:1S row pattern gave relatively higher soybean yields than other intercropping patterns. Soybean cultivar DPSB 19 is recommended for production under soil moisture stress conditions while planting soybean at 20 plants m$^{-2}$ is recommended for optimum soybean yields. Planting maize and soybean in 1M:1S row pattern should be used when intercropping the two crops.

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## ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| **ABA** | = Abscisic Acid |
| **ANOVA** | = Analysis of Variance |
| **BNF** | = Biological Nitrogen Fixation |
| **CCI** | = Chlorophyll Content Index |
| **CGR** | = Crop Growth Rate |
| **CR** | = Competitive Ratio |
| **CV** | = Coefficient of Variation |
| **CWR** | = Crop Water Requirement |
| **FAO** | = Food and Agricultural Organization of the United Nations |
| **FC** | = Field Capacity |
| **IPAR** | = Intercepted Photosynthetically Active Radiation |
| **KALRO** | = Kenya Agricultural and Livestock Research Organization |
| **LA** | = Leaf Area |
| **LAI** | = Leaf Area Index |
| **LER** | = Land Equivalent Ratio |
| **LRWC** | = Leaf Relative Water Content |
| **LSD** | = Least Significant Difference |
| **PAR** | = Photosynthetically Active Radiation |
| **PWC** | = Permanent Wilting Point |
| **RCBD** | = Randomized Complete Block Design |
| **RCGR** | =Relative Crop Growth Rate |
| **RUE** | = Radiation Use Efficiency |
| **SLM** | = Specific Leaf Mass |
| **TDR** | = Time Domain Reflectometer |

# CHAPTER ONE
# INTRODUCTION

## 1.1 Background information

Soybean (*Glycine max* L. Merrill) is a native of East Asia and is one of the important legume crops. Area under soybean production worldwide is estimated at 123.55 million hectares with total production of 352.6 million metric tonnes (FAO, 2017). Soybean is the most traded amongst the major tropical legumes constituting 83.8% annual revenue from all legume crops combined, which is estimated at US$ 31.0 billion (Abate *et al*., 2012). In Africa, Nigeria and South Africa are the major exporters of soybean while Tanzania, Somalia and Kenya are net importers of the crop (USDA, 2018). Soybean was first introduced in Kenya by the British colonial administration in 1909 with an ultimate purpose of establishing a large-scale industrial crop that would help account for the rationale of establishing the colony, pay up for costs of building the Kenya–Uganda railway and as a raw material for British industries (Jackson, 2016). During post-colonial governments, soybean received minor attention despite the crop playing a significant role in food relief efforts through importation of the crop from the Republic of South Africa and Uganda (Abeli, 2016). Neglect of the crop continued with subsequent Kenyan governments after independence, poor policy in soybean production and promotion, utilization messages which focus on maize as food crop, with coffee, tea and pyrethrum as cash crops to the detriment of soybean (Jackson, 2016).

Soybean in Kenya is mostly grown by smallholder farmers and total land area under soybean production is estimated at 2,759 hectares (FAO, 2011) with yields ranging from 445 to 1,200 kg per hectare (Collombert, 2013). Annual demand for soybean in Kenya exceeds 100,000 metric tonnes (D’Alessandro *et al*., 2015), the highest in Eastern African region. However annual soybean production in the country is still low at 4,335 metric tonnes per annum leaving a deficit of close to 95% (FAO, 2013) which is cushioned through imports (Figure 1.1). Soybean production across Kenya varies considerably depending on biotic and abiotic factors, market availability, farm gate prices and production costs (Tinsley, 2009). Soybean is used as food and feed for it has high protein content (40 %) which is suitable for both human and livestock (Singh and Shivakumar, 2010). It contains 30% carbohydrates, large amounts of dietary fiber, vitamins, and minerals. Soybean consists of 20% oil which contributes to edible oil production (Hartman *et al*., 2011). It is estimated that 90% of soybean produced and imported into Kenya is used in formulation of livestock feeds (Chianu *et al*., 2008). In addition, soybean improves soil fertility through biological nitrogen fixation. In recent years, soybean has received attention as raw material for bio-diesel production (Thoenes, 20017).

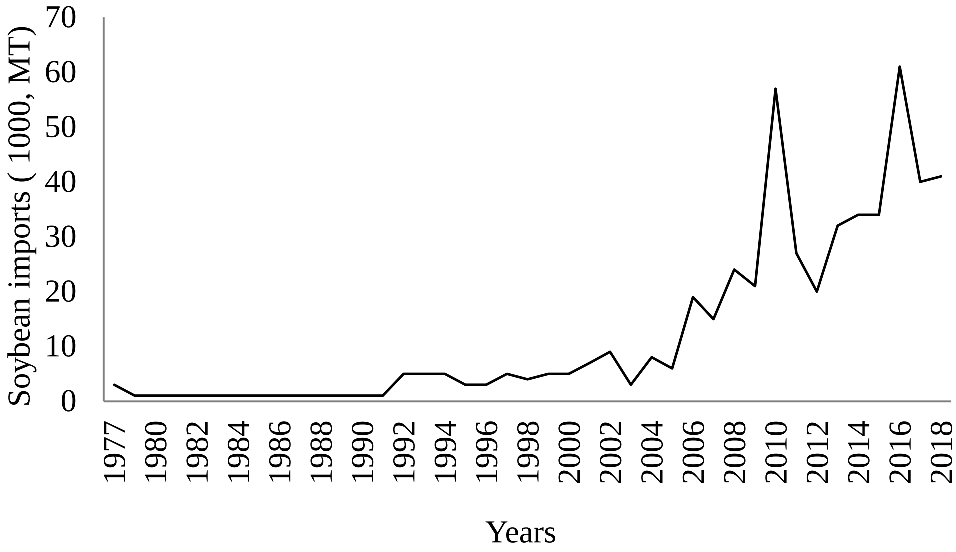


Figure 1.1 Annual soybean imports for Kenya, MT = metric tonnes. Source USDA, 2018).

Soil moisture stress is one of the key abiotic factors that limit attainment of optimum soybean yields by reducing soybean plant growth and maturation causing fewer pods to form with fewer and/or small seeds (Wei *et al*., 2018). In recent times, global climatic change has brought in new weather patterns that have caused shifts in temperature and rainfall and these altered weather patterns have increased soybean crop vulnerability to moisture stress and disease infections (Rosenzweig *et al*., 2001). Water stress at seedling and flowering stages may decrease soybean yield by 28% and 45% respectively due to decreased photosynthetic rate, stomatal conductance and transpiration rate (Ohashi *et al*., 2006). Inappropriate use of soybean production practices such as incorrect seeding rates contribute to low soybean yields in the country. In addition, while most of Kenyan research and production recommendations for the crop are done for monocultures, much of soybean production in the country is grown under intercropping with maize and newly planted sugarcane (Tinsley, 2009). Apart from soil moisture stress, soybean production is also limited by declining soil fertility, poor seed quality and insect pests and diseases attach (Njeru *et al.*, 2013).

## 1.2 Statement of the problem

Soybean yields obtained by smallholder farmers in Kenya range from 445-1200 kg $ha^{-1}$ which is low compared to potential yields of 3,500 kg $ha^{-1}$. With an annual soybean production of 4,335 metric tonnes, the country fails to meet its annual soybean demand of 100,000 metric tonnes leaving a deficit of 95% which is cushioned through imports. The imports of soybean and its products costs the Kenyan Government over US$ 25.54 million annually which is a significant drain on foreign exchange reserves with a negative effect on the macroeconomic stability of the country. While different soybean cultivars have been made available to the farming community across Kenya by the national soybean breeding programme at Kenya Livestock and Agricultural Research Organization (KALRO) to boost production of the crop, soybean yields continue to be poor across the country and factors contributing to these low yields are not clearly understood. Information is also lacking on the response of released soybean cultivars to moisture stress despite moisture stress being one of the critical factors affecting physiological and biochemical processes of the crop. In addition, recommendations are not available in the country on appropriate agronomic practices which can be used as adaptive mechanisms to limit moisture stress in soybean production. Under limited soil moisture stress, use of poorly adapted soybean genotypes coupled with poor agronomic practices lead to soybean yield losses of 28-45% contributing to food and income insecurity at household levels. The study on the response of soybean cultivars to soil moisture stress, identification and use of soil moisture stress resilient soybean cultivars coupled with use of appropriate planting density and spatial row arrangements was therefore necessary to increase soybean production in Kenya.

## 1.3 Objectives

### 1.3.1 Main objective

To contribute to increased soybean yields through use of appropriate soybean cultivars, planting density and intercropping for enhanced food and income security at household level.

### 1.3.2 Specific objectives

i. To determine the effect of soil moisture regimes on carbon dioxide assimilation, growth, yield and yield components of selected soybean cultivars under greenhouse and field conditions.

ii. To determine the effect of planting density on yield and yield components of selected soybean cultivars.

iii. To determine the effect of soybean and maize intercropping on stomata conductance, shoot characteristics and yield of selected soybean cultivars.

## 1.4 Hypotheses

i. Varying soil moisture regimes has no effect on carbon dioxide assimilation, growth, yield and yield components of selected soybean cultivars.
ii. Planting density has no effect on yield components and yield of selected soybean cultivars.
iii. Intercropping soybean and maize has no effect on stomata conductance, shoot characteristics and yield of selected soybean cultivars.

## 1.5 Justification of the study

Changes in climatic conditions all over the world due to influence of global warming is creating unusual weather phenomena often in form of water deficits which expose crop plants to moisture stress conditions (Alizadeh *et al*., 2014). It is therefore necessary to understand the interaction between crop cultivars and the prevailing soil moisture conditions. Understanding the response of soybean to limited soil moisture stress, identification and use of moisture stress tolerant cultivars in addition to using appropriate agronomic practices would help reduce impact of moisture stress and hasten soybean yield improvement (Bulut and Gürkan, 2017). This is more important considering that more than one third of global food production is through cultivation under moisture stress conditions (Gassert, 2013). With increase in world population, the agricultural sector faces the challenge of increasing food production by 70-100% by the year 2050 (FAO, 2009). This challenge is however compounded by competition for land and water from other sectors of the economy pushing agricultural activities to marginal lands where water limitations affect crop production (Bruinsma, 2009).

Optimization of soybean production would help reduce food, nutrition and income insecurity at household level in Kenya. Soybean farming is one of the most cost-effective ways resource-constrained smallholder farmers can use to maintain soil fertility of their lands as soybean helps to improve soil fertility through biological nitrogen fixation. Soybean fixes between 44 to 103 kg N $ha^{-1}$ (Sanginga *et al*., 2003; Kananji *et al*., 2013). The potential of soybean to significantly contribute to food and nutrition security and to generate substantial income for farmers is however constrained by low yields. Soybean yields amongst smallholder farmers in Kenya range between 445 – 1200 kg per hectare (Collombert, 2013) resulting in importation of over 95,000 metric tonnes of the crop to meet annual soybean demand (FAO, 2013). Optimization of soybean production and consumption would also help alleviate malnutrition in children and nutritional deficiencies in the elderly and people living with HIV and Aids. The Kenyan Nutrition Policy 2012-2022 reiterates the need to halve malnutrition levels in the country which soybean production and consumption can help to meet. In addition, increased soybean production would help narrow huge importations of soybean by the Kenyan Government and thus contribute to macroeconomic stability of the country (Giller *et al*., 2011). Apart from contributing to foreign exchange earnings through direct exports of the crop, soybean would also help provide raw materials to agro-based industries and in the process contribute to job creation in the country. Because of its economic, nutritional and functional importance, soybean warrants its cultivation in Kenya where over 30% of children are malnourished, unemployment is over 40% and use of inorganic fertilizer is low (Jackson, 2016). It was with this understanding that a study was conducted to determine the effect of varying soil moisture regimes on carbon dioxide assimilation, growth and yield components of selected soybean varieties and also to determine the effects of planting density and intercropping on yield and yield components of selected soybean cultivars in Kenya.

### 1.6 Scope and limitation of the study

The study determined the response of selected soybean cultivars to different soil moisture regimes under greenhouse and field conditions. Soil moisture stress regimes ranged from the near optimal field capacity and soybean crop water requirement to most limiting field capacity of 20% and 25% for greenhouse and field experiments respectively. Soil moisture stress tolerant soybean cultivars identified from soil moisture regime studies were then subjected to plant population and intercropping studies as mitigation mechanisms against soil moisture limitation. It was designed to conduct field soil moisture stress study solely under irrigation during dry months of December to March. However, 2018 season had early onset of rains which came at grain filling stage of late maturing varieties. The effect of early rains was however limited to yield data.

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# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 General description of soybean

Soybean was first domesticated in East Asia around 1700-1100 BC and belongs to the family Leguminosae and genus Glycine (Hymowitz and Newell, 1981). Soybean is self-pollinated, erect and bushy herbaceous annual plant (CFIA, 1996). Primary leaves are unifoliate, opposite and ovate, while secondary leaves are trifoliolate and alternate. Flowers are usually purple or yellow and pods contain 2-3 seeds. The plant is covered with very soft tiny brown hairs and root system consists of tap root from which lateral root system emerges (CFIA, 1996). Soybean growth is designated by vegetative and reproductive growth stages. The number of nodes on the main stem indicates the vegetative stage of that particular plant while flowering indicates the beginning of reproductive stages (Hay and Porter, 2006). Three types of growth habits are found amongst soybean genotypes; determinate, indeterminate and semi-determinate. Determinate growth is characterized by cessation of vegetative activity of the apical meristem after flowering. Indeterminate cultivars continue vegetative activity throughout the flowering period while semi-determinate types have indeterminate stems that terminate vegetative growth abruptly at flowering period (Hay and Porter, 2006). Soybean uses three-carbon ($C_3$) carbon fixation pathway whose characteristics include closure of stomata during hot dry days resulting in reduced photosynthesis (Wang *et al*., 2012).

## 2.2 Nature of resource competition in soybean

Resource competition is defined as a phenomenon that occurs when two or more organisms seek the same measure they require of any particular factor and when immediate supply of a particular factor is below the combined demand of organisms (Casper, 1997). Interplant competition occurs as a result of limited supply of radiant energy, nutrients, water, carbon dioxide and space (Park *et al.*, 2003). The competitive ability of a plant to form a canopy to exploit the environment efficiently for growth factors has been found to differ among varieties. In soybean, competitive stress exerted by spatial arrangement and phenotype of surrounding plants occurs differently amongst varieties grown in variety mixtures. Responses to such competition include differential effects on yield, plant height, number of branches, number of pods, seed weight and seed filling periods (Rizzardi *et al*., 2016). Knowledge of plant structural characteristics and yield relationships is therefore a prerequisite for increased soybean yields. Intraplant competition, on the other hand, is competition for limited growth resources between organs within the plant (Park *et al.*, 2003). Competition between vegetative and reproductive organs of the plant is recognized as an important element that affects soybean yields (Sadras and Denison, 2009). Important traits related to belowground competitive ability amongst soybean cultivars include root density, root surface area and rooting depth (Casper, 1997). Utilization of growth resources will therefore differ amongst soybean cultivars grown under stresses arising from limited soil moisture and increased plant population which may arise from increased planting density or from mixture of different plant species as is the case with intercropping.

**2.3 Water use and effects of soil moisture stress on soybean**

Water is important for all physiological and biochemical processes in plants and it comprises approximately 90% of plant body mass (Souza *et al*., 2013). Water is responsible for thermal regulation of the plant, plant cooling and supporting of the plant (Salisbury and Ross, 1992). Water also functions as a solvent through which gases, mineral nutrients and other solutes enter plant cells. Seasonal crop water requirement (CWR) for soybean varies between 450-700 mm with a daily water use of 4-6 mm depending on crop growth stage, climatic conditions and crop management practices (Singh *et al*., 2014). Water stress may reduce soybean plant growth resulting in yield losses of between 28-45 % depending on the stage of crop growth at which moisture stress occurs (Manavalan *et al.,* 2009; Thao and Tran, 2012). Water stress results in limited uptake of nitrogen, potassium, phosphorous and calcium disrupting biochemical processes in soybean plants (Lukowska and Józefaciuk, 2013). Water deficit conditions may also disrupt nitrogen metabolism and reduce nitrate reductase activity (Lipiec *et al.*, 2013; Landi *et al.*, 2017). In addition, water stress may also result in the reduction in photosynthesis which arises from the decrease in leaf expansion, impaired photosynthetic machinery, premature leaf senescence and the associated reduction in food production (Heidaiy and Moaveni, 2009). In environments where there is water restriction, soybean plants tend to close stomata to conserve water, reducing transpiration losses which may limit carbon dioxide intake into the leaf for photosynthesis (Bohnert and Jensen, 1996; Sales *et al*., 2013). Biological nitrogen fixation is dependent on available soil moisture and reduced soil moisture affects carbon concentration in soybean nodules which reduces rates of nitrogen fixation (Ku *et al*., 2013). Water stress affects soybean root architecture, root size, nodule number, nitrogenase activity and number of rhizobia in soils (Serraj, 2003).

## 2.4 Physiological and morphological responses of soybean under moisture stress

Water stress tolerance in soybean is achieved through various morphological, physiological and biochemical adaptations which include escape, avoidance, cell water conservation, cell membrane stability and production of plant growth regulators (Beck *et al*., 2007). Under water stress, soybean tend to increase root depth in the soil profile where water content is higher (Benjamin and Nielsen, 2006). Soybean root to shoot ratio increases under water deficit conditions and cessation of shoot growth is attributed to higher sensitivity to water stress of shoots than roots (Kavar *et al*., 2007). Water stress tolerant soybean genotypes have a larger leaf area compared to water stress susceptible soybean genotypes and this is associated with reduction in stomatal conductance and photosynthesis rate in tolerant genotypes (Stolf-Moreira *et al*., 2010). Under water limiting conditions, amounts of auxins, gibberellins and cytokinins decrease while those of abscisic acid and ethylene increase (Ku *et al*., 2013). Auxins induce new root development by breaking apical root dormancy induced by cytokinins and prolific root system is vital for water stress tolerance. In soybeans, abscisic acid as a growth inhibitor is produced under water limiting conditions which alters the relative growth of soybean plant parts such as increase in root to shoot dry weight ratio, inhibition of leaf area development and production of prolific and deeper roots (Turner *et al*., 2001). In soybeans, water stress increases expression of P5CS gene resulting in increased biosynthesis of proline, an amino acid which is required for maintenance of cell turgidity and stabilization of membrane thereby reducing electrolyte leakages (Hayat *et al*., 2012). Under ideal soil moisture conditions, reactive oxygen species (ROS) such as hydrogen peroxide and hydroxyl radicals are continuously synthesized and eliminated in chloroplasts and mitochondria as by-products of photosynthesis, photorespiration and respiration by soybean plants (Farooq *et al*., 2009). Under water stress, ROS are overproduced leading to soybean plant death (Taiz and Zeiger, 2006).

## 2.5 Planting density and crop production

Manipulation of plant density affects plant structural characteristics and helps improve insect pests and disease avoidance, lodging resistance, adaptation to mechanical harvesting and seed yield (Schutte and Nleya, 2018). A higher plant population may increase competition among crop plants for nutrients, light and space while lower population density may lead to inefficient use of natural resources and inputs (Mahesh *et al*., 2017). Total dry weight of leaves, leaf area index (LAI), crop growth rate (CGR) and relative crop growth rates (RCGR) are all dependent on plant density (Han *et al*., 2006). In soybeans, nutritional quality such as protein, oil and mineral content may depend on field production environment (Bellaloui *et al*., 2015).

Optimum plant density of soybean is dependent on cultivar, geographical location, season and agronomic practices (De Bruin and Pedersen, 2008). Different soybean cultivars have different growth patterns and that some areas have capacity to support higher planting densities than others. Differential response of soybean cultivars to planting densities warranted this study to look at the response of selected soybean varieties to different plant populations.

**2.6 Intercropping and agricultural production: principles and systems**

Multiple cropping systems account for 41-86% of African agriculture and food supply where crops like maize (*Zea mays*), sorghum (*Sorghum bicolor*), rice (*Oryza sativa*), millet (*Eleusine coracana*) and various legume crops are grown under different forms of mixed cropping systems (Thornton and Herrero, 2015). Although previous agricultural recommendations for most crops focused on sole cropping at the expense of intercropping systems, there is currently recognition of the value of intercropping because of its potential to contribute to high and stable crop yields with minimal use of inputs like inorganic fertilizers and pesticides. For organic sector, intercropping offers an effective means of producing healthy, safe and high quality food in the context of environmentally sound production. Intercropping offers stable crop yields and food security to farmers with small land holdings which is becoming a common phenomenon in most African countries like Kenya due to increases in human population.

Intercropping is governed by principles and concepts which mimic nature as a model for ecological stability (Sullivan, 2003). The first principle, that cooperation is more apparent than competition, asserts that in an ecosystem there is a symbiotic association amongst organisms and that there is more cooperation in nature than competition. The second principle is that stability of intercropping tends to increase with increasing diversity. This principle suggests that the more complex and diverse communities become, and the fewer fluctuations in numbers of given species, the more stable communities tend to be. In intercropping, each crop must have adequate space to maximize cooperation and minimize competition between them. To accomplish this, four concepts that are considered in intercropping are spatial arrangement, plant density, maturity dates of crops being grown and plant architecture (Sullivan, 2003).

Commonly used intercropping systems worldwide include row intercropping (where one or more crops are planted in regular rows and other crops may be grown simultaneously in row or randomly with the first crop), mixed intercropping (where two or more crops are sown simultaneously with no distinct row arrangement), strip intercropping (where two or more crops are planted simultaneously in different strips wide enough to permit independent cultivation but narrow enough for the crops to interact ergonomically) and relay intercropping (where two or more crops are planted simultaneously during part of the life cycle of each. A second crop is planted after the first crop has reached its reproductive stage but before it is ready for harvest (Sullivan, 2003).

This study used spatial arrangement, planting density and differences in maturity of soybean and maize crops as some of ecological concepts to help improve soybean yields by smallholder farmers in the country. Soybean and maize were grown in different row arrangements in order to determine best spatial arrangement that would help optimize soybean yield.

## 2.7 Effects of soil moisture, planting density and intercropping on biological nitrogen fixation

Biological nitrogen fixation changes with moisture levels and agronomic practices including planting density and intercropping systems (Mehmet, 2008). Excessive soil moisture and waterlogging prevent development of root hairs and reduce diffusion of oxygen in soybean roots (Al-Suhaibani *et al*., 2013). While water stress conditions reduce number of rhizobia in soil which lead to inhibition of nodulation and fixation of nitrogen by soybeans, prolonged water deficit conditions cause soybean nodule decay (Kaschuk *et al*., 2009). Extreme temperatures which are synonymous with water deficit conditions reduce biological nitrogen fixation through reduced activity of nitrogenase enzyme which is critical for effective biological nitrogen fixation by soybeans (Zahran, 1999). Planting soybean at low rates increases interspecific competition while planting at very high population density leads to intraspecific competition both of which reduced the effectiveness of biological nitrogen fixation in soybeans (Madanzi *et al*., 2012). Depending on crop mixtures, intercropping can result in competition for water and nutrients which reduces efficiency of biological nitrogen fixation amongst soybean genotypes. Depletion of nitrogen from root zone of legume crops like soybean by non-leguminous components in intercropping may however promote increased biological fixation of a leguminous crop (He, 2009).

## 2.8 Assessment of intercropping productivity

Land equivalent ratio (LER) is one of the common indexes used in the evaluation of intercropping productivity (Seran and Brintha, 2010). Land equivalent ratio values of more than one indicate intercrop efficiency and give an indication of magnitude of sole cropping required to produce the same yield on a unit of intercrop land (Yahuza, 2011). The partial land equivalent ratio (PLER) measures the relative competitive abilities of the individual components of an intercrop system. The species with higher partial LER is considered to be more competitive for growth limiting factors than the species with lower partial LER (Thobatsi, 2009).

**2.9 Benefits and limitations of intercropping**

Intercropping allows more efficient utilization of the available resources such as light (radiation use efficiency), water and nutrients as a result of differences in competitive ability for growth resources between the component crops (Keating and Carberry, 1993). Full canopy cover from component crops in intercropping helps reduce the impact of rain drops leading to reduction in soil loss (Seran and Brintha, 2010). Deep roots of component crops break soil hardpans and use moisture and nutrients from deeper down in the soil while shallow roots bind the soil at the surface and thereby help to reduce soil erosion (Undie *et al.*, 2012). Intercropping with legumes such soybean helps to improve soil fertility through biological nitrogen fixation (BNF). In addition, after the intercrop is harvested, decaying roots and fallen leaves provide nitrogen and other nutrients for the next crop (Stern, 1993). Intercropping provides high insurance against crop failure in areas subjected to extreme weather conditions such as drought and floods (Ijoyah and Fanen, 2012) making it much less risky than monocropping considering that if one crop of a mixture fails, the component crops may still be harvested providing a greater food and financial stability to farmers (Dwivedi *et al.*, 2015). In addition, farmers may be better able to cope with seasonal price variability of commodities which often can destabilize their income (Kinama and Pierre, 2018). Intercropping can provide better lodging resistance for some crops highly susceptible to lodging. Lodging may lead to disease infections and mechanical damage whereas loss of plant height reduces efficiency of light interception. Intercropping encourages crop diversification thereby reducing labour costs (Gurigbal, 2010).

Depending on crop mixtures, competition for light, water and nutrients may occur between mixed crops which may result in yield losses (Mucheru-Muna *et al*., 2010). Growth environment encountered by a component crop in intercropping may be different from that of the sole crop which may result in competition and have a significant negative impact on the growth and yield of the crop. In addition, intercropping is thought to be difficult with practical management, especially where there is a high degree of mechanization or when the component crops have different requirements for fertilizers, herbicides, and pesticides. Additional cost for separation of mixed grains, poor produce quality arising from mixtures, lack of marketing of mixed grains, problems at harvest due to lodging, and grain loss at harvest can also be serious drawbacks of intercropping (Seran and Brintha, 2010).

Limitations of intercropping in this study were minimized through use of soybean and maize as a legume and cereal crops respectively. Soybean cultivar DPSB 19 which was used in intercropping study matured much earlier than maize cultivar (513). This helped minimize demand for nutrients during critical stages of crop development of the two crops.

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# CHAPTER THREE

# EFFECT OF SOIL MOISTURE REGIMES ON CARBON DIOXIDE ASSIMILATION, GROWTH AND YIELD OF SELECTED SOYBEAN CULTIVARS UNDER GREENHOUSE CONDITIONS


## Abstract

Soil moisture stress reduces crop yields by limiting carbon dioxide assimilation and mineral nutrient acquisition. A greenhouse experiment was conducted over two seasons to determine the effect of soil moisture regimes on $CO_2$ assimilation, growth and yield of selected soybean (*Glycine max* (L) Merrill) cultivars. The experiment was conducted using randomized complete block design (RCBD) in a 4 by 6 factorial treatment arrangement and was replicated three times. Soil moisture regimes (80, 60, 40 and 20% of field capacity) and cultivars (Gazelle, Nyala, EAI 3600, DPSB 8, Hill and DPSB 19) were first and second factors, respectively. Collected data were subjected to analysis of variance (ANOVA) using Linear Mixed Model in GENSTAT. Moisture stress significantly ($p < 0.001$) reduced soybean plant height, stem thickness, number of leaves and branches, leaf area, root diameter, root length, root surface area, root volume, root biomass, shoot to root ratio and nodulation of all tested cultivars. Cultivar DPSB 19 had largest leaf area while cultivar EAI 3600 had highest root volume, root biomass and number of nodules per plant compared to other cultivars. Leaf relative water content, stomata conductance, photosynthesis rate and sub-stomatal $CO_2$ concentrations significantly ($p < 0.001$) declined with increasing soil moisture stress. Total leaf chlorophyll content increased ($p < 0.001$) with increased soil moisture stress. Moisture stress significantly ($p < 0.001$) reduced number of pods per plant, number of seeds per pod and yield of all tested soybean cultivars. Pod abortions significantly ($p < 0.01$) increased with increased soil moisture limitation. Cultivars DPSB 19 and DPSB 8 had relatively higher leaf relative water content and stomata conductance at reduced soil moisture regime of 20% moisture at field capacity indicating moisture stress tolerance potential of the cultivars. This, in addition to early maturity attribute, cultivar DPSB 19 is recommended for production under soil moisture stress conditions and that 40% moisture at field capacity be a cut-off point beyond which supplementary irrigation be implemented to optimize soybean yields.

### 3.1 Introduction

Soil moisture stress has become a recurring event as occasioned by changes in climatic conditions due to global warming (Abedinpour, 2012). Soil moisture stress is a critical abiotic constraint limiting plant growth resulting in yield losses of between 8-43 % depending on the stage of crop growth at which moisture stress occurs (Elliot *et al*., 2014).

Water stress limits uptake of nitrogen, potassium, phosphorous and calcium disrupting biochemical processes in crop plants (Lisar *et al*., 2012). Water deficit conditions may also affect nitrogen metabolism and reduce nitrate reductase activity (Farooq *et al*., 2009). In addition, water stress reduces photosynthesis which may arise from the decrease in leaf expansion, impaired photosynthetic machinery, premature leaf senescence and the associated reduction in synthesis of photoassimilates for plant growth. In environments where there is water restriction, crop plants tend to close stomata to conserve water which reduces carbon dioxide intake into the leaf for photosynthesis (Flexas *et al*., 2009). Biological nitrogen fixation is dependent on available soil moisture and reduced soil moisture affects carbon concentration in nodules of legume crops which reduces rates of nitrogen fixation (Ku *et al*., 2013). Water stress affects plant root architecture, root size, nodule number, nitrogenase activity and number of rhizobia in soils (Kunert *et al*., 2016).

Understanding the response of soybean to limited soil moisture stress and identification and use of moisture stress tolerant varieties is therefore an option to reduce negative impacts of moisture stress and hasten soybean yield improvement (Farooq *et al*., 2009). This is more important considering that two thirds of global food production is through cultivation under moisture stress conditions (Madhu and Hatfield, 2015). Equally challenging to agriculture sector is the need to increase current food production levels by between 70 to 100% by year 2050 in order to meet food requirements of the ever increasing human population (Alexandratos and Bruinsma, 2012). Optimization of soybean production and yields would therefore help narrow human food requirements and consequently help alleviate malnutrition in children and nutritional deficiencies in the elderly and people living with HIV and Aids. It is with this understanding that a study was undertaken to determine the effect of varying soil moisture regimes on carbon dioxide assimilation, growth, yield components and yield of selected soybean cultivars in Kenya.

### 3.1.1 Effect of soil moisture stress on shoot and root growth attributes

Hossain *et al.* (2014) indicated that progressive restriction of soil moisture significantly reduced shoot length as well as root fresh and dry masses for soybean cultivars grown under sequential soil drying and rewetting. Drought susceptible cultivars responded most sharply to water restriction and that shoot length, fresh and dry shoot masses were respectively 44.30%, 17.37% and 30.68% of corresponding masses of well-watered plants. Root length reduction of 65.26% for varieties grown under restricted moisture compared to well-watered plants was reported. A study by Atti *et al.* (2004) on the response of indeterminate soybean cultivars to chronic water deficit during reproductive development under greenhouse conditions indicated decreases in soybean plant height, total plant canopy, number of fully developed leaves and number of primary braches due to water stress. Well-watered plants showed a sigmoid increase in plant height throughout the growth cycle while plant height of water stressed plants reduced by 84%. Leaf induction rate was reduced by 53% and 88% under moderate and severe stresses respectively. In addition, number of branches per plant reduced by 33% and 28% under moderate and severe stress, respectively, compared to well-watered plants. Leaf rolling, leaf wilting and paraheliotropism were observed in soybean plants under moisture stress which resulted in vertical profile of plant canopy. Atti *et al.* (2004) went on to suggest that the decrease in plant vegetative growth rate under moisture stress was an indicator that water deficit at reproductive development might have induced an early switch from vegetative to reproductive growth. Moisture stress depressed nodule weight per plant and nitrogenase activity in soybean plants grown under limited soil moisture (Streeter, 2003). In addition, concentration of nitrogen was about 80% higher in drought stressed nodules relative to well-watered plants.

Reduction in soybean plant height, number of branches per plant, number of leaves per plant, shoot fresh and dry weights due to water stress were also reported by Amira and Qados (2014). Highest reduction in plant growth parameters were observed under severe water stress of 40% field capacity. Decreases in plant growth were attributed to decreases in cell elongation emanating from the inhibitory effect of water shortage on growth-promoting hormones.

A study in Brazil by Sartori *et al.* (2016) indicated that irrigation resulted in an increase in root length, root diameter, root surface area and root volume of irrigated soybean compared to non- irrigation plants under deep tillage. Madhu and Hatfield (2015) reported that soybean plants grown under optimal soil moisture conditions produced greater number of root nodules per plant which was 42% and 155.5% more than number of nodules obtained at low and high soil moisture conditions, respectively. Root dry matter accumulation by determinate and indeterminate soybean cultivars was not affected by moisture stress (Machado *et al.*, 2017).

Responses of root growth to moderate soil water deficit in wheat (*Triticum aestivum*) seedlings under greenhouse conditions was studied by Saidi *et al.* (2010). Results indicated that moisture deficit did not have significant effect on root length but a significant reduction in root surface area was recorded in wheat plants grown at soil field capacity. Moisture stress studies in tea [*Camellia sinensis* (L) O. Kuntze] by Cheruiyot *et al.* (2010) indicated that shoot to root ratio was not significantly influenced by varying soil water content. Significant increases in root to shoot ratio at lower soil water potential were reported by Dos Santos *et al*. (2018) in studies with rice (*Oryza sativa*).

### 3.1.2 Effect of soil moisture stress on leaf area, leaf expansion rate and specific leaf mass

Leaf area is an expression of cumulative cell expansion and division during leaf growth and is an important parameter in determination of light interception and productivity of plants (Koester *et al*., 2014). Specific leaf mass (SLM), which is an adaptive strategy to cope with moisture stress by plants, is defined as the amount of photosynthetic tissue per unit leaf area (Gutschick and Wiegel, 1988). An increase in specific leaf mass under water stress indicates that plants may have continued to accumulate dry matter in the leaves even under water stress conditions.

Total leaf area reduction in soybean cultivars subjected to drought stress conditions were reported by Chowdhury *et al.* (2016). In this study, leaf area amongst soybean cultivars under drought stress was reduced by 74% and 54% at vegetative and pod development stages, respectively compared to leaf area accumulated by non-stressed plants. In the same study, moisture stress significantly reduced specific leaf mass of soybean cultivars. A similar trend was reported by Amira and Qados (2014) where plants grown at field capacity had significantly higher leaf area compared to stressed plants grown at 49% field capacity. Water stress decreased soybean plant total leaf area by 52.7% and 74.5% under severe and medium moisture stress respectively compared to plants grown under optimal soil moisture level in a study by Atti *et al.* (2004). The same study also indicated that water deficit decreased the ratio of photosynthetic leaf area by 7% and 10% at medium and severe stress levels respectively as opposed to well-watered plants, an effect which was linked to accelerated leaf senescence under lower moisture regimes. Madhu and Hatfield (2015) indicated that soil moisture and soybean cultivars did not have significant effect on leaf area of soybean genotypes grown under elevated carbon dioxide and soil moisture. Nonetheless, increase in specific leaf area was observed with increase in soil moisture status.

Moisture stress studies on tea by Cheruiyot *et al.* (2010) indicated that tea leaf area and leaf to total biomass ratio were significantly influenced by soil water content with leaf growth declining with declining water deficit. In maize (*Zea mays* L.), Rahman *et al*. (2004) reported a reduction in maize leaf area due to moisture stress while Saidi *et al.* (2010) reported reduced leaf area in wheat plants in response to moderate soil water deficit.

### 3.1.3 Effect of soil moisture stress on leaf relative water content

Leaf relative water content (LRWC) measures the dehydration status of a plant relative to its maximum water holding capacity at full turgidity (Tenentzap *et al*., 2015). Pejić *et al*. (2012) indicated that water stress significantly reduced leaf relative water content in soybean grown in response to varying intensities of irrigation. Amira and Qados (2014) reported 80% leaf relative water content in soybean plants grown at 100% field capacity compared to 77.6% for plants grown at 40% field capacity. Reduced percent leaf relative water content was also reported by Hossain *et al.* (2015) in soybean plants subjected to soil drying and application of abscisic acid. The reduction tendency of percent leaf relative water content of drought susceptible soybean cultivars was significantly faster (65.7%) from initiation of soil drying compared to drought tolerant cultivars. A reduction of 7.3% in leaf relative water content in drought stressed soybean plants was reported by Mannan *et al.* (2016). Streeter (2003) reported that soybean plants grown under moisture stress registered lowest leaf relative water content of 80% compared to leaf relative water content of 90.4% for well-watered soybean plants. Results of a study with pot grown tomatoes (*Solanum lycopersicum* L.) by Sibomana *et al.* (2013) indicated a 24.7% reduction in leaf relative water content in severely stressed tomato plants compared to plants supplied with adequate water.

### 3.1.4 Effect of soil moisture stress on leaf chlorophyll content

Atti *et al.* (2004) reported a decline of 11% in chlorophyll content in soybean plants grown under severe stress compared to well-watered plants. According to results by Amira and Qados (2014), the concentration of chlorophylls 'a' and 'b' and carotenoids were decreased significantly by increasing soil moisture deficit with a reduction in photosynthetic pigments more pronounced at 40% field capacity. The decrease in chlorophyll content under moisture stress were in part attributed to oxidative damage of chloroplast lipids and proteins. Mannan *et al.* (2016) reported a significant decrease in chlorophylls 'a' and 'b' and total photosynthetic pigments in leaves of soybean plants grown under drought stress conditions. Reductions in photosynthetic pigments under drought stress were attributed to decreases in leaf water status in soybean. In maize, Rahman *et al.* (2004) and Muhumed *et al*. (2014) have reported an increase in total chlorophyll and carotene contents of maize cultivars with an increase in water tress. In all varieties studied, there was an inverse relationship between chlorophylls 'a' and 'b' contents. Studies with chickpea by Mafakheri *et al*. (2009) reported reduced chlorophyll 'a' and 'b' content in response to drought stress

### 3.1.5 Effect of soil moisture stress on leaf gas exchange

Photosynthesis determines the rate of plant growth while stomata conductance indicates the degree of carbon dioxide and water vapour exchange between ambient and inner leaf (Chowdhury, 2016). In a study to determine the effect of drought stress on gas exchange in soybean varieties, Chowdhury *et al.* (2016) indicated that soybean plants grown under water stress exhibited lower photosynthesis rate than plants grown at optimal soil moisture conditions. Photosynthesis rate ranged from 26.87 to 29.81 and 17.14 to 22.06 µmol $CO_2$ $m^{-2}$ $s^{-1}$ under non- stressed and stressed conditions, respectively. The decrease in photosynthesis rate under moisture stress were partly attributed to reduced stomata conductance, lowered transportation of photosynthate to leaves, reduced leaf area and a reduction in chlorophyll concentration in leaves. Chowdhury *et al.* (2016) also reported reduced stomata conductance ranging from 78.52% to 93.20% amongst soybean cultivars grown under moisture stress compared to plants grown under optimal soil moisture levels. Lower stomata conductance under limiting soil moisture conditions were attributed to lower leaf water potential and leaf relative water content.

Hosain *et al.* (2014) reported that moisture stress reduces photosynthesis and stomatal conductance in soybean with a higher net photosynthesis rate amongst drought tolerant soybean genotypes compared to drought susceptible genotypes. Results of the study further indicated that stomata conductance of drought tolerant cultivars diverged significantly faster as moisture stress period progressed compared to stomatal conductance of drought susceptible cultivars. Atti *et al.* (2004) reported reduction in transpiration rate, stomata conductance and photosynthesis in indeterminate soybean cultivars grown to chronic water deficit during reproductive development under greenhouse conditions. The impact of moisture stress was greater at the most severe stress levels. In addition, the study results revealed a positive correlation for photosynthesis, stomata conductance and transpiration at all moisture regimes.

Hossain *et al.* (2015) studied the response in gas exchange and water status between drought tolerant and susceptible soybean cultivars with exogenous abscisic acid (ABA) application, results of which indicated that stomata conductance of leaves was markedly affected by application of exogenous abscisic acid. A rapid reduction in stomata conductance was however observed in drought tolerant cultivars compared to drought susceptible ones. An increase in stomata conductance and carbon dioxide assimilation was observed in soybean plants grown at soil field capacity compared to lower soil moisture levels (Machado *et al*., 2017).

Sibomana *et al.* (2013) reported that well-watered tomato plants had higher stomata conductance of 228 mmol $m^{-2}$ $s^{-1}$ compared to plants grown at 40% pot water capacity. A 46% reduction in transpiration rate was also observed in most stressed (40% pot water capacity) tomato plants while highest rate of transpiration was observed in plants that received 100% pot water capacity.

### 3.1.6 Effect of soil moisture stress on yield components, yield and grain quality

A strong negative effect of up to 92.7% of moisture stress on number of pods per plant in soybean were reported by Atti *et al.* (2004). Study results also indicated a 35.4% reduction in both pod dry weight and grain yield in soybean cultivars under moisture stress. Severe water stress led to floral abortions translating into fewer pods per plant and related reduction in grain yield. Amira and Qados (2014) reported a reduction in number of pods and seed yield per plant and 100 seed weight in soybean plants grown under moisture stress. The most negative effect of water stress on yield components and yield of soybean was recorded at 40% field capacity and at this moisture level, number of pods per plant, number of seeds per plant, 100 seed weight and grain yield were decreased by 48.4%, 51.5%, 16.3% and 32.6% respectively. Highest soybean grain yield of 13.5g per plant was registered at 100% field capacity compared to 6.6g per plant at 40% field capacity. Chemical analysis of soybean seeds in the same study showed that total carbohydrates, amino acids and percent protein contents of soybean grain were significantly reduced in soybean plants grown at 40% field capacity as compared to soybean plants grown at 100% field capacity. A study on influence of genotypes on protein and oil concentration of soybean seeds by Dos Santos *et al.* (2010) indicated that protein content in soybean seeds was dependent on type of soybean cultivar used. Protein content amongst soybean cultivars ranged from 35.09% to 41.33%.

Madhu and Hatfield (2015) reported that soybean plants grown under normal (7.5 mm) soil moisture condition produced maximum number of pods per plant which was greater by 45.5% and 28.9% compared to soybean plants planted under low (5.0 mm) and high (10.0 mm) soil moisture conditions respectively.

In tomatoes, Sibomana *et al.* (2013) reported that moisture deficit reduced number of tomato fruits per plant and total fruit yield. The highest tomato fruit yield of 69.6 tonnes per hectare was registered in plants subjected to 100% pot water capacity. Number of tomato fruits per plant was reduced by 25% to 34% under limited soil moisture compared to plants supplied with 100% pot water requirement.

It is evident from the review that previous soil moisture stress studies with soybean generated varied but contradictory responses of the crop to soil moisture limitation. Results varied with geographical location of study areas meaning that local environmental conditions play a major role in plant response to moisture stress. This emphasizes the need for continuous soil moisture stress studies so as to align crop production recommendations to prevailing local environmental conditions. Previous studies were generally on effects of short duration moisture stress (less than 20 days) implemented at either vegetative or reproductive growth stages of soybean plants. Soil moisture regimes in the current study were imposed from 30 days after seed germination up to physiological maturity of the crop which meant subjecting plants to soil moisture stress conditions almost the entire growth period. This could provide much better responses than short duration soil moisture stresses as is the case with previous studies. In addition, most previous soybean moisture stress studies were carried with determinate soybean cultivars. Considering that water stress imposed on indeterminate varieties affects both vegetative and reproductive development as vegetative growth continues after flowering, it was prudent for this study to ascertain how soybean cultivars with determinate and indeterminate growth habits would respond to soil moisture stress limitation. While response of soybean shoot growth to moisture stress has been the focus of most previous studies, below ground system has received limited attention. This study looked at soybean root growth and nodulation responses to moisture stress whose results would help contribute to understanding of the manner in which soil moisture stress impacts on soybean root system.

## 3.2 Materials and methods

### 3.2.1 Site description

The experiment was conducted in pots in a greenhouse at Egerton University, Njoro campus. Egerton University ($0^o$ 22'S; $35^o$ 56'E) is at 2267 meters above sea level (m.a.s.l) with annual mean air temperature of 15.9ºC (FAO-UNESCO, 1994; Jaetzold *et al*., 2010). Soil growth medium was a mixture of clay loam soil and river sand in a 2:1 ratio. Soil analyses were performed at the soil science laboratory at Egerton University to determine initial quantities of total nitrogen (N), extractable potassium (K) and available phosphorous (P) prior to mixing with river sand. Composite soil samples were collected from 0- 15 cm and 15- 30 cm (Brady and Well, 2002).

Growth medium was put in planting pots measuring 18 cm in height and 22 cm in diameter giving a pot volume of 6,842 $cm^3$. Planting pots were placed on a bench 100 cm above greenhouse floor. Natural lighting was used for plant growth and daily minimum and maximum temperatures were taken using a minimum and maximum bulb thermometer.

### 3.2.2 Determination of water at field capacity

A planting pot used in the experiment was filled with soil and then saturated for several hours with water until all micro pores were filled with water. The top of the pot was covered with plastic sheet to avoid evaporation. After overnight, the moisture content at 100% field capacity (FC) was determined using time domain reflectometer (IMKO-HD2) by inserting time domain reflectometer probes vertically in the pot soil. The amount of water held by the soil at subsequent field capacities were then determined with reference to soil moisture level at 100% FC; and then used to come up with the following: 80%, 60%, 40% and 20% of FC. After sowing, moisture levels in all treatments were maintained close to 100% field capacity for 30 days after which respective soil moisture treatment regimes were initiated up to physiological maturity of the crop. After initiation of moisture regime treatments, soil moisture regimes at respective field capacities were monitored using TDR and changes in soil moisture were corrected by supplying additional water.

### 3.2.3 Experimental design and treatments

The experiment was conducted using the randomized complete block design (RCBD) with a 4 x 6 factorial treatment arrangement with 3 replicates. Treatments consisted of two factors: factor 1 being moisture regimes and factor 2 being soybean cultivars. Soil moisture regimes were at 80%, 60%, 40% and 20% of soil moisture content at field capacity. Soybean cultivars used in the experiment were Gazelle, Nyala, EAI 3600, DPSB 8, Hill and DPSB 19. Soybean seeds were obtained from Kenya Agricultural and Livestock Research Organization in Njoro. Cultivars used in the study were selected based maturity period, yielding potential and tolerance to insect pests and diseases. Growth habits and phenology of soybean cultivars are as follows.

Table 3.1 Growth habits and phenology of soybean cultivars used in the experiment

| | Cultivar name | Characteristics |
|---|---|---|
| 1 | Gazelle | indeterminate, medium maturity |
| 2 | Nyala | determinate, early maturity |
| 3 | EAI 3600 | determinate, early maturing |
| 4 | DPSB 8 (TG x 1895-33F) | indeterminate, promiscuous, late maturity |
| 5 | Hill | determinate, medium maturity |
| 6 | DPSB 19 (TG x1740-2F) | indeterminate, promiscuous, medium maturity |

### 3.2.4 Planting and crop management

Soybean seeds were inoculated with BIOFIX *(Bradyrhizobium japonicum)* inoculant strain USD 110 from Mea Limited–Kenya at the rate of 10 g $kg^{-1}$ of seed prior to sowing. Three soybean seeds were sown in each pot and thinned to one plant per pot 14 days after emergence. Each treatment had 4 plants per replicate. Triple Super Phosphate (TSP) and Muriate of Potash (MOP) were applied as basal dressing fertilizers at the rates of 0.68 g per pot (30 kg P $ha^{-1}$) and 0.27 g per pot (30 kg K $ha^{-1}$) respectively. Hand weeding was done in pots as weeds appeared.

### 3.2.5 Data collection

Data were collected on the following parameters:

**Physiological parameters**

***Leaf photosynthesis rate and sub-stomatal carbon dioxide concentration***

Leaf photosynthesis rate and sub-stomatal carbon dioxide concentration were determined at 50% flowering and 50% podding stages of soybean growth on an abaxial side of a middle leaflet of a third trifoliate leaf from top of the plant. Photosynthesis rate and sub-stomatal carbon dioxide concentration were measured between 12.00 - 14.00 hours during sunny days using a TPS-2 portable photosynthesis system (V2.02-PP systems Inc., USA).

***Stomata conductance and stomata density***

Stomata conductance was determined at vegetative stage, 50% flowering and 50% podding stages of plant growth on an abaxial side of a middle leaflet of a third trifoliate leaf from top of the plant. It was measured between 12.00 - 14.00 hours on sunny days using a steady state leaf porometer (SC1, Decagon Devices, USA). The inverse of stomata conductance was calculated as an indicator of stomata resistance.

***Leaf chlorophyll content***

Chlorophyll 'a' chlorophyll 'b' and total chlorophyll contents were analyzed on a third trifoliate leaf at 50% flowering using a procedure described by Goodwin and Britton (1988). Collected leaves were wrapped in an aluminum foil and transported to the laboratory in an outdoor and indoor Marina cooler box. The analysis protocol involved preparation of extractant of acetone and hexane in 4: 5 ratio. A 0.5 g of leaf sample was then weighed, crushed with pestle and mortar and placed in centrifuge tube. Fifteen milliliters (mls.) of acetone: hexane solution were then added to the crashed leaf sample and centrifuged at 4000 revolutions per minute (r.p.m) for 10 minutes using a Centurion 6000 series centrifuge. The supernatant was then transferred with pipette into 25 ml volumetric flask. Residues were washed with 5 mls of acetone: hexane solution and centrifuged at 4000 r.p.m. for 10 minutes. The supernatant was again transferred into 25 ml volumetric flask with pipette and topped up to 25 mls with acetone: hexane mixture. Spectrophotometric determination of the samples was done using a Pharmacia Biotech Novaspec II spectrophotometer. Absorbance were determined at 663nm and 645nm for chlorophylls a and b respectively. Chlorophylls 'a' and 'b' were determined from the following equations:

Chlorophyll a: $\{(10.1E \times 663) - (10.1 \times E645) \times V\} / FW$ Equation 3.1

Chlorophyll b: $\{(16.4 \times E645) - (2.57 \times E663) \times V\} / FW$ Equation 3.2

Where:

E663 and E645 are the absorbance of chlorophyll a and b respectively;

V is the volume of the solution.

FW is the fresh weight of the sample.

***Leaf relative water content***

Leaf relative water content was measured on a third leaf from top of the plant at 50% flowering stage. Leaf samples were collected at midday and cut leaves were put in pre-weighed 150 milliliter tubes and sealed to avoid moisture loss. Closed tubes were put in an outdoor and indoor Marina cooler box and taken to laboratory where leaf fresh weights were measured. Equal amounts (150 milliliters) of distilled water was then added to tubes and samples placed in a refrigerator at 4°C for 24 hours for leaves to reach full turgor. After 24 hours, leaf samples were removed from plastic containers, blotted dry with paper towel and weighed to get turgid weights. Leaf samples were then oven dried at 65˚C for 24 hours after which dry weights were measured (Hossain *et al.*, 2014; Sade *et al*., 2015). Leaf relative water content was determined using the following formula:

LRWC (%) = [fresh leaf wt.- dry leaf wt. / leaf turgid wt.- dry leaf wt.] × 100% Equation 3.3

Where LRWC is leaf relative water content.

## Morphological parameters

### *Total leaf area, leaf expansion rate and specific leaf mass*

Leaf area was determined at vegetative, 50% flowering and 50% podding stages of plant growth on one tagged plant per treatment. Leaf area was measured using manual method developed by Norman and Campbell (1992). It involved determination of individual leaf length (*l*) and width *(w)* and multiplied the product by a coefficient *(k)* which is 0.67 for legumes. Leaf expansion rate was determined based on an increase of leaf area over time. A middle leaflet of a third trifoliate leaf from the top of soybean plant was tagged and its leaf area was determined by measuring its length and width and its leaf area computed as for total plant leaf area above. Leaf area measurements were done at almost the same time on each day over a period of 15 and 21 days for seasons 2017 and 2018 respectively. The difference in leaf areas between the preceding and the next day was taken as leaf expansion per day. Specific leaf mass (SLM) as an indicator of leaf thickness was computed from leaf dry mass and leaf area at 50% flowering stage using equation below.

Specific leaf mass = leaf dry mass/leaf area (g $cm^{-2}$) Equation 3.4

### *Shoot and root growth parameters*

Plant height, internode length, canopy diameter, number of branches per plant and number of leaves per plant were determined from a mean of three plants from each treatment per replicate. Plant height was measured using a measuring tape from the pot soil surface to the last node of soybean plant. Length of internode was measured using 30 cm ruler and was determined from a mean of three internodes measured from the bottom, middle and top positions of soybean plants. Soybean plant canopy diameter was measured using a measuring tape on the widest part of plant shoot. Stem diameter was determined from a mean of three readings from the bottom, middle and top positions of soybean plant's primary stem using a 0-150 millimeter digital caliper (09070705763-Mars). Number of branches and leaves per plant was determined by making individual counts of branches and leaves arising from primary stem of soybean plant. Days to 50% flowering were counted from the date of 50% seedling emergence.

Shoot/root ratio was determined at 50% flowering and one plant from each treatment was soaked in a 20 litres bucket of water for 5 minutes to loosen the soil. A plant with loosened soil was then put on 2 millimeter screens and cleaned until all soil and plant debris were removed. Separation of roots and shoot was done at crown level. All leaves were plucked leaving stems and branches. Plucked leaves were put in plastic bags while stems and branches were cut into 5 cm pieces and placed in separate plastic bags. Nodule counts and function were determined and active nodules were pink to red in colour when cut open while inactive nodules were green to brown in colour (Station, 2011). Root volume, root length, root diameter and root surface area were determined by scanning individual plant roots using Epson Expression 10000XL colour image scanner and analyzed using Winrhizo software (LA 2100-Regent Instruments Inc.). Separated shoot and root plant parts for determination on leaf, root and nodule biomasses were dried separately in an oven to constant weights at 60 °C for 24 hours (Hossain *et al.*, 2014). Mean weights of dried samples were taken as leaf, root and nodule biomass per plant.

***Number of days to flowering, podding and pod maturity***

Days to 50% flowering and 50% pod-set were counted from the date of emergence. Number of days from pod-set to 50% physiological maturity was determined when 50% of pods had attained brown colour (Kandel, 2015).

**Yield components and yield**

Number of pods per plant was determined from an average number of pods borne on three plants harvested per treatment. Pod length was measured using a 30 cm ruler on 10 pods randomly picked from harvested pods. Number of seeds per pod were determined by counting number of fully developed seeds from all pods harvested from three plants per treatment. The mean number of seeds from all harvested pods for each treatment was taken as number of seeds per pod for that treatment. Grain size was determined by passing soybean grains through 5 mm and 8 mm diameter sieves (Plate 3.1). Grains remaining on the sieve and those passing through were counted and their percentage determined over total number of grains per given treatment.

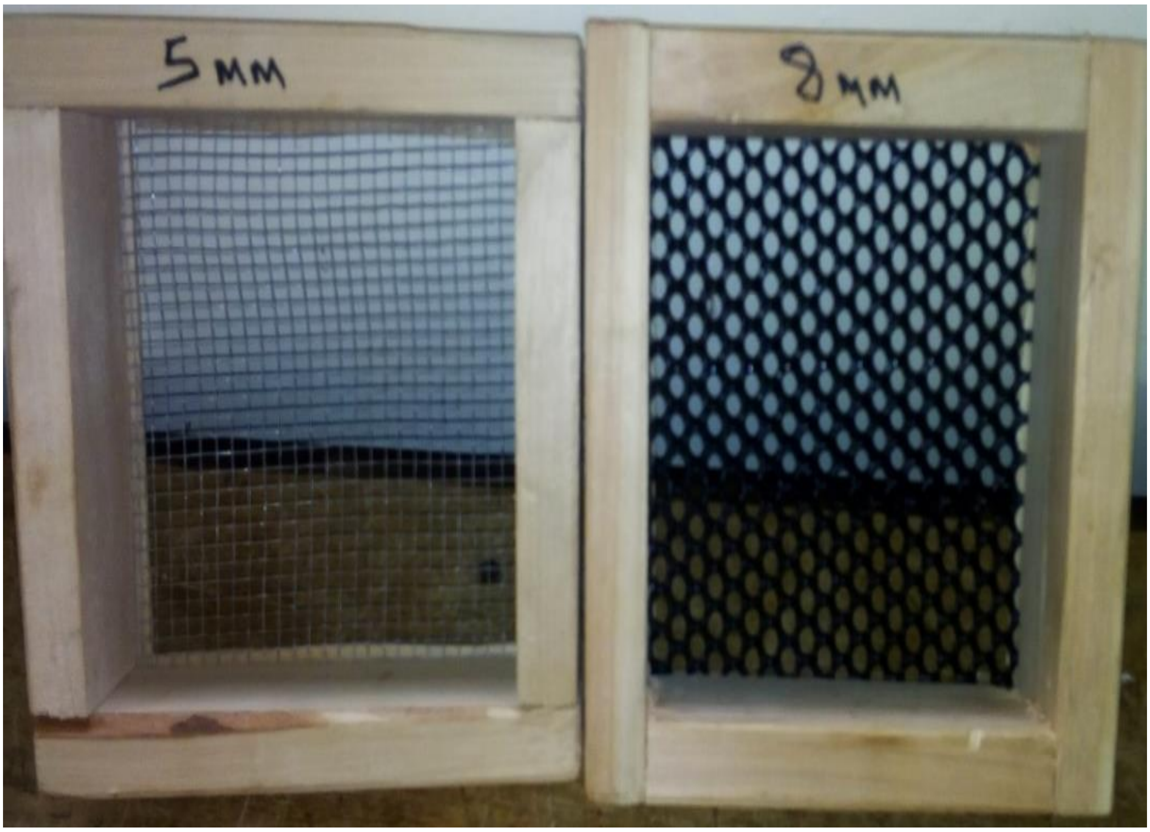



Plate 3.1 Sieves used for determination of soybean grain size

Seed weight was determined from weight of 10 seeds randomly selected from the treatments. Number of pods per node was determined from three plants per treatment at harvesting by counting number of pods per plant divided by number of pod- bearing nodes. Number of aborted pods per plant were determined from a mean of three plants per treatment at 50% physiological maturity by counting pods without any filled grain. Grain yield was obtained by harvesting 3 plants from individual treatments when 75% of pods were dry. Harvested pods were then threshed and grains separated. The obtained grains were sun dried to constant weight. Grain yield was adjusted to soybean storage moisture content of 12 % (Famurewa and Raji, 2011). Moisture content of soybean grain was determined on wet weight basis using oven drying method after placing the grain in an oven at 72- 80 $^{o}$C for 48 hours (Mloza-Banda, 2004).

Moisture content (%) = $[(w_1 - w_2)/w_1] \times 100$ Equation 3.5

Where $W_1$ = weight of seed before oven drying

$W_2$ = weight of seed after oven drying

Soybean grain yields per plant was then adjusted to 12 % storage moisture using the following formula.

Grain yield per plant = $DM_1 \times Y/DM_2$ Equation 3.6

Where $DM_1$ = dry matter content of the seed when yield was weighed, i.e. 100-initial moisture when grain was weighed.

$DM_2$ = dry matter content at which yield will be reported (12% predetermined moisture content for yield determination).

**Grain quality**

Total nitrogen (N) was determined using Kjeldahl method (Bremner and Mulvaney, 1982) and protein content calculated by multiplying N concentration by 6.25 (Rahman *et al*., 2011).

**3.3 Statistical model and data analysis**

Data obtained were checked for fulfilment of analysis of variance (ANOVA) assumption of normality by using Shapiro-Wilk normality test in Genstat release 18.1. Data were considered normally distributed when the *p*-value for Shapiro-Wilk statistic was greater than the threshold *p*-value of 0.05. Data that did not meet the aforesaid ANOVA assumption were subjected to log base 10 [log 10(x+c) ] transformation before analysis. Data were then subjected to ANOVA using the linear mixed model for RCBD with factorial treatment arrangement in Genstat (Restricted Maximum Likelihood-REML). The following statistical model was used in the analysis of experimental results:

$Y_{ijk} = \mu + V_i + ß_j + (Vß)_{ij} + R_k + \varepsilon_{ijk}$, where

$Y_{ijk}$ = $k^{th}$ observation on $i^{th}$ treatment in $j^{th}$ block; μ = overall mean; $V_i$ = effect of moisture regime at $i^{th}$ level; $ß_j$ = effect of cultivars at $j^{th}$ level; $(Vß)_{ij}$ = interaction effect of moisture regime at $i^{th}$ level and cultivars at $j^{th}$ level; $R_k$ = effect of block; $\varepsilon_{ijk}$ = random error normally distributed with mean zero.

Correlation analyses were done on individual treatment means using Genstat release 18.1 to determine inter-character associations amongst some selected quantitative traits.

## 3.4 Results

### 3.4.1 Effect of soil moisture regimes and soybean cultivars on shoot growth

***Plant height***

Plant height at 50% pod maturity stage was significantly ($p < 0.001$) influenced by the interaction of soil moisture regimes and soybean cultivars during 2017 season (Figure 3.1). In the second season, there were significant ($p < 0.001$) independent effects of soil moisture regimes and soybean cultivars (Figure 3.2). In this season, tallest plants were registered at 80% FC which was 56.22% taller than plants grown at 20% FC. Cultivars DPSB 8 and EAI 3600 had tallest (43.68 cm) and shortest (28.80 cm) plants, respectively during 2018 season.

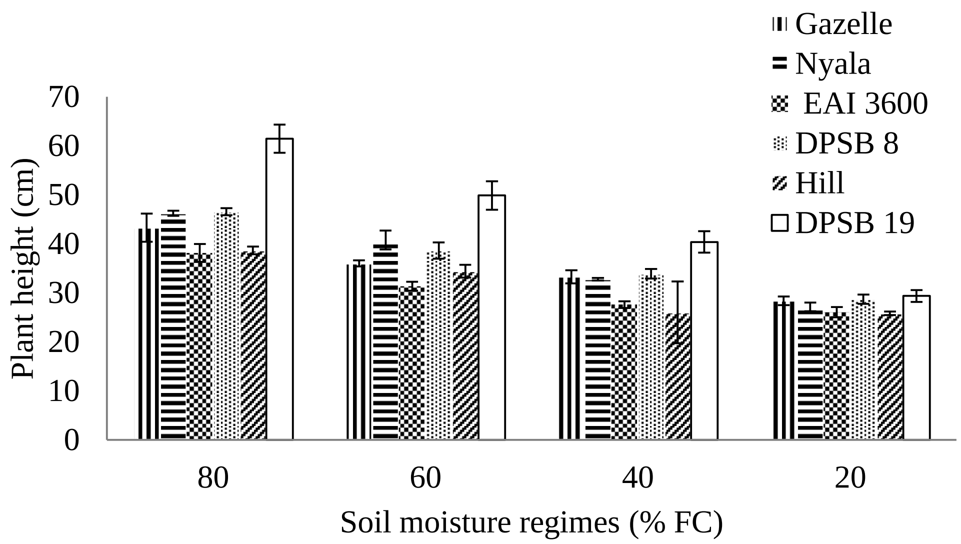



Figure 3.1 Effect of soil moisture regimes and cultivars on soybean plant height at 50% pod maturity stage during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

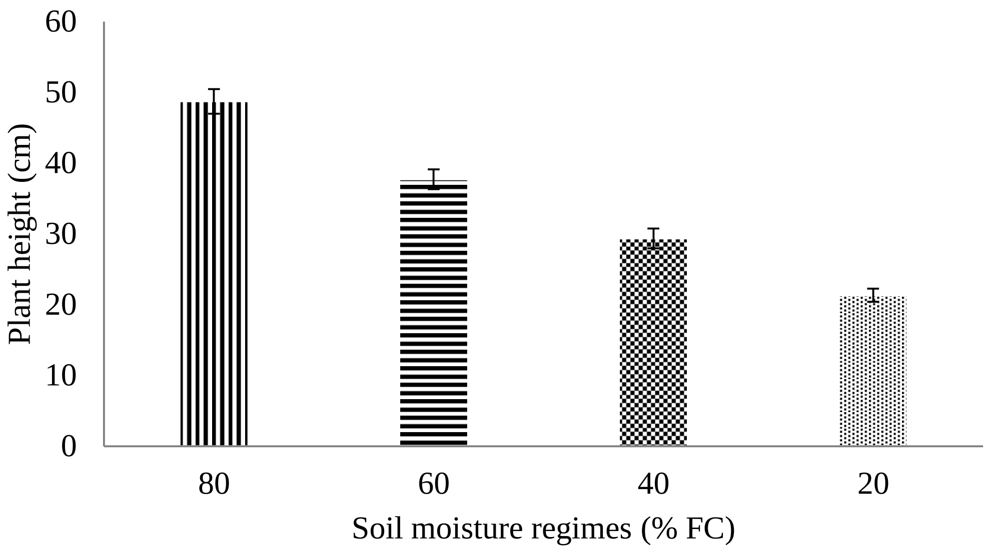



Figure 3.2 Effect of soil moisture regimes on soybean plant height at 50% pod maturity stage during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

***Internode length***

Internode length was significantly ($p < 0.001$) reduced with decreasing soil moisture levels in both 2017 and 2018 seasons and at all growth stages (Figures 3.3 and 3.4). The impact of moisture stress was more severe at 20% FC where internode length reductions of 26.36% and 43.07% were registered relative to plants grown at 80% FC in 2017 and 2018 respectively. Cultivars had a significant ($p < 0.001$) influence on internode lengths with cultivar DPSB 19 having longest internode lengths at 50% podding stage in both seasons. Shortest internode lengths were registered with cultivars EAI 3600 and Hill in 2017 and 2018 respectively.

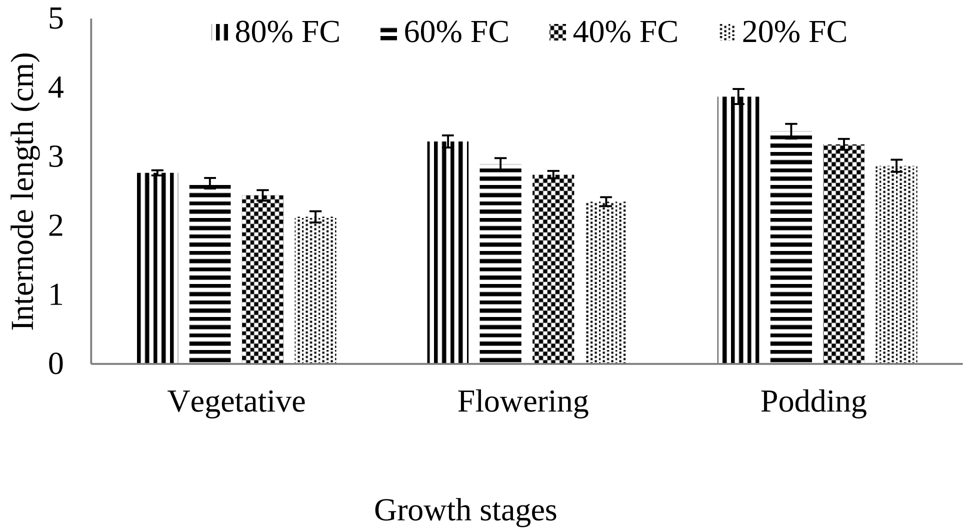



Figure 3.3 Effect of soil moisture regimes on internode length during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

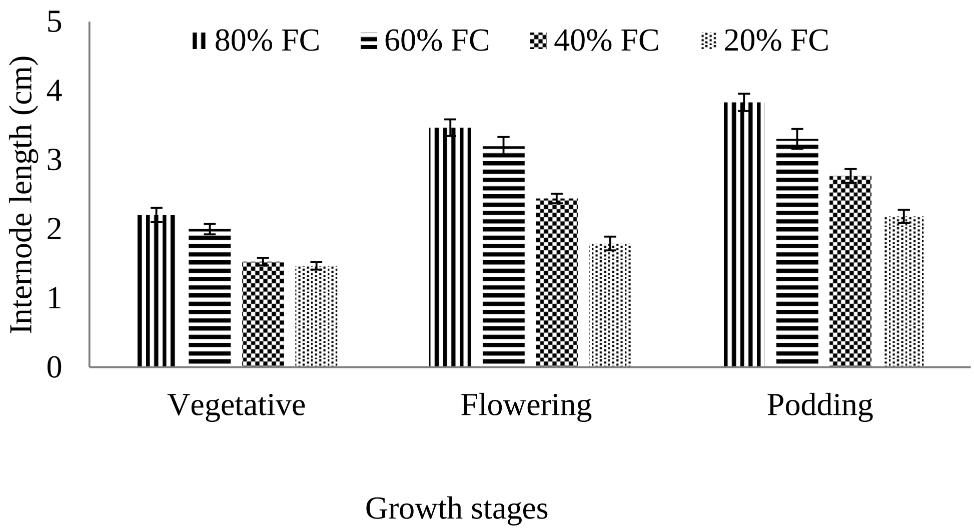



Figure 3.4 Effect of soil moisture regimes on internode length during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

***Canopy diameter***

Soil moisture levels had significant ($p < 0.001$) effect on plant canopy diameter in both seasons and at all three plant growth stages (Figures 3.5 and 3.6). Wider plant canopies in both seasons were attained at 80% FC while reduced plant canopies were registered at the lowest moisture level of 20% FC. Cultivars had significant ($p < 0.001$) influence on plant canopy diameter with a determinate cultivar Nyala having the widest canopy diameter at 50% podding stage in 2017 (30.85 cm) and 2018 (32.32 cm) seasons. Cultivars DPSB 19 and Hill had least canopy diameters of 25.27 cm and 28.54 cm at 50% podding stages in 2017 and 2018 seasons respectively.

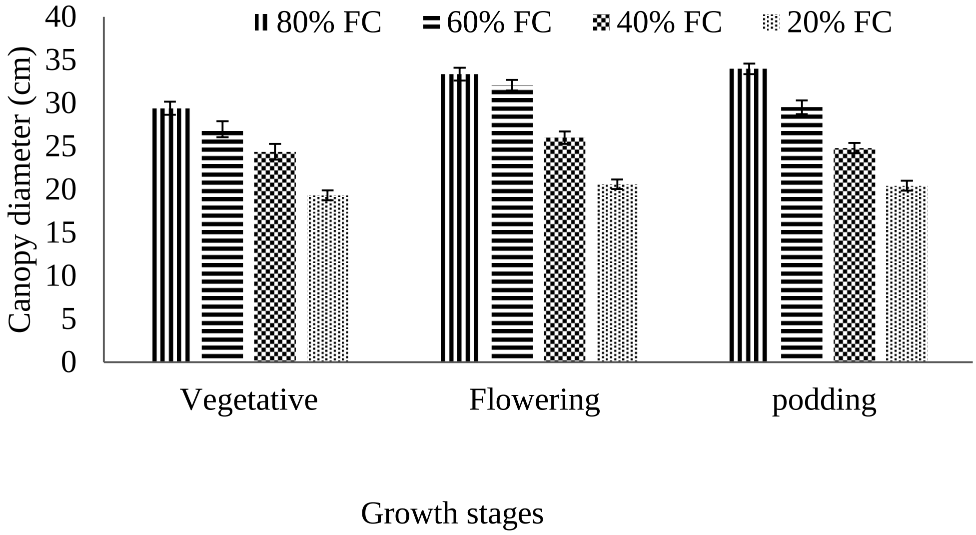



Figure 3.5 Effect of soil moisture regimes on canopy diameter during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

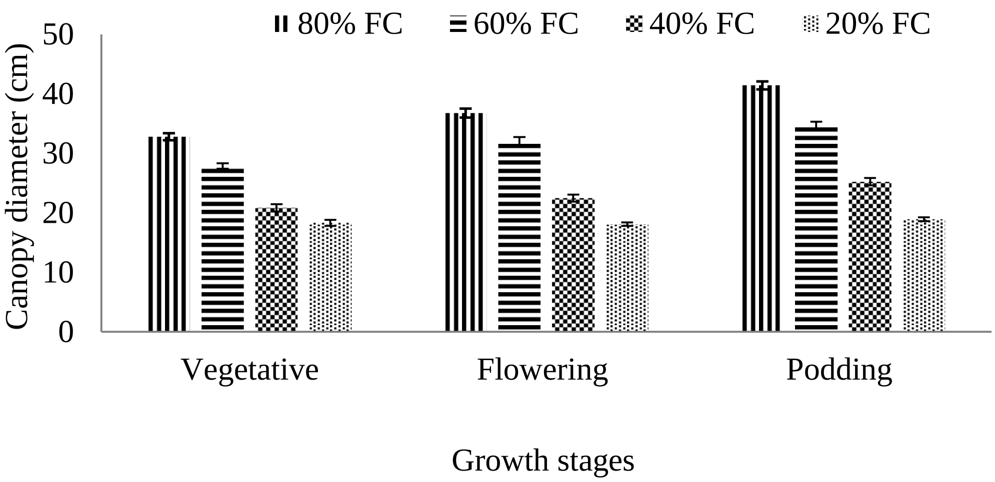



Figure 3.6 Effect of soil moisture regimes on canopy diameter during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

***Number of primary branches***

There was a significant ($p < 0.01$) interaction effect of soil moisture regimes and soybean cultivars on number of primary branches at all growth stages in 2017 season with all cultivars having more branches at highest soil moisture regime of 80% FC (Figures 3.7, 3.8

and 3.9). In 2018 season, soil moisture regimes and cultivars had significant ($p < 0.001$) independent effects on number of branches at vegetative stage (Figure 3.10). Highest number of branches was registered at 80% FC which was 78.57% more than number of branches registered at 20% FC. Cultivar DPSB 19 and Gazelle had highest (2.53) and lowest (0.89) number of branches at vegetative stage. Number of branches at 50% flowering and 50% podding stages was significantly ($p < 0.001$) responsive to interaction of soil moisture regimes and cultivars (Figures 3.11 and 3.12). All soybean cultivars registered significant increase in number of primary branches at the highest moisture regime of 80% FC.

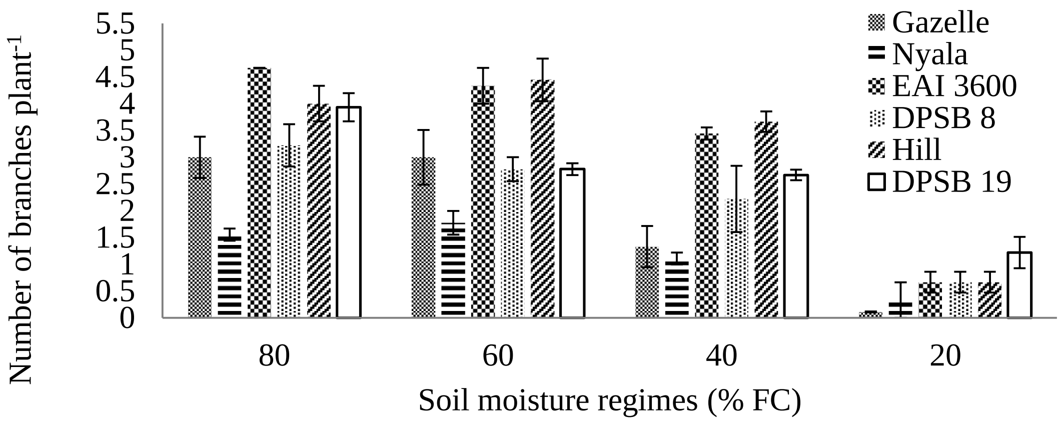



Figure 3.7 Effect of soil moisture regimes and cultivars on number of branches at vegetative stage during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.01$. FC = Field capacity.

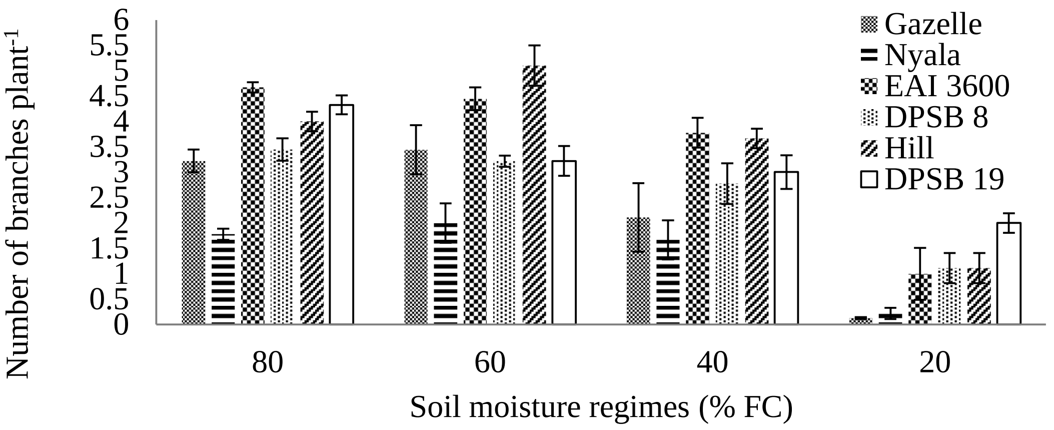



Figure 3.8 Effect of soil moisture regimes and cultivars on number of branches at 50% flowering stage during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.01$. FC = Field capacity.

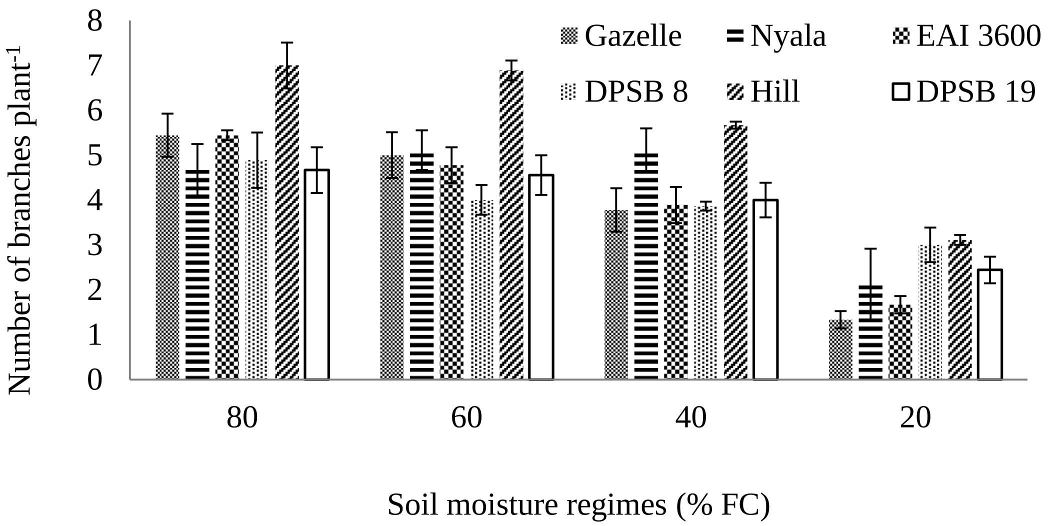



Figure 3.9 Effect of soil moisture regimes and cultivars on number of branches at 50% podding stage during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.01$. FC = Field capacity.

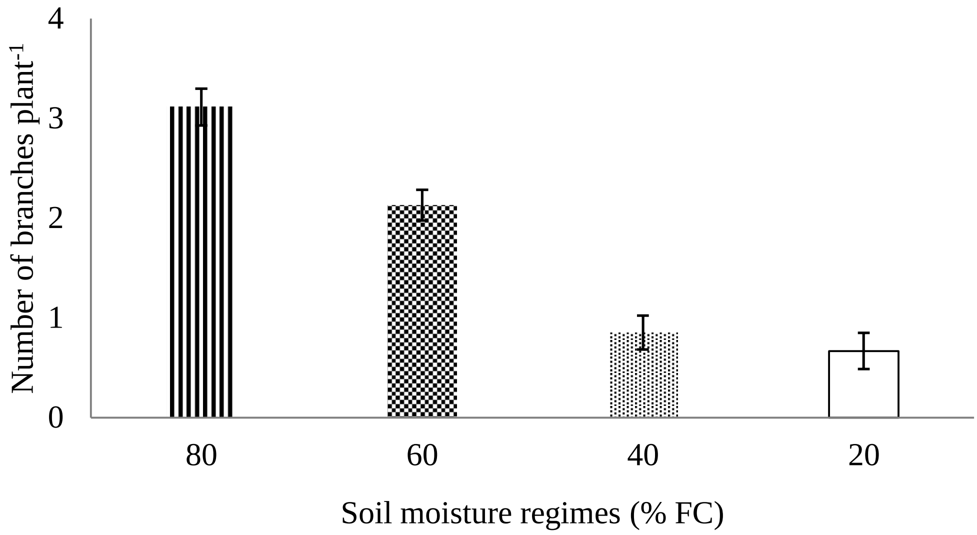



Figure 3.10 Effect of soil moisture regimes on number of branches at vegetative stage of 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

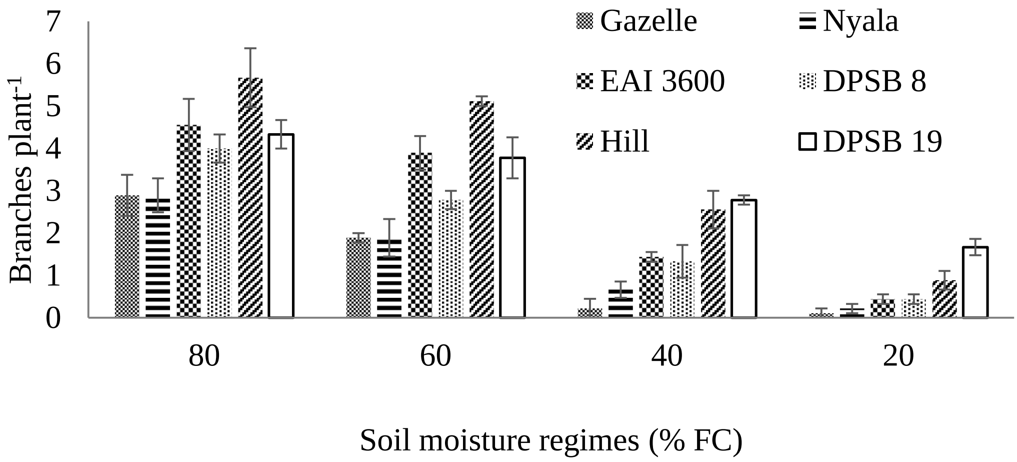



Figure 3.11 Effect of soil moisture regimes and cultivars on number of branches at 50% flowering stage of 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

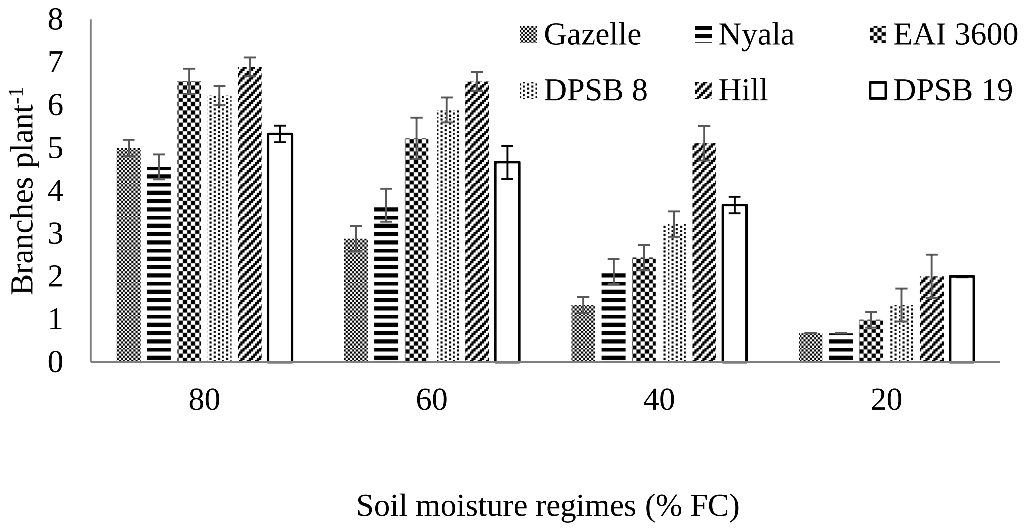



Figure 3.12 Effect of soil moisture regimes and cultivars on number of branches at 50% podding stage during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

***Stem diameter***

Stem diameter was significantly ($p < 0.001$) influenced by soil moisture regimes at vegetative growth stage of both 2017 and 2018 seasons (Table 3.2). Soil moisture level at 20% FC significantly reduced plant stem diameter compared to other treatments. Thickest stems during both seasons were registered by Gazelle though not significantly different from Nyala and DPSB 19. Cultivar DPSB 8 had thinnest stems in both seasons. Significant ($p < 0.01$) interaction effects of soil moisture and varieties on stem diameter were registered at 50% flowering and 50% podding stages in both years where all soybean cultivars had thicker stems at higher moisture level of 80% FC (Figures 3.13, 3.14, 3.15 and 3.16).

Table 3.2 Effect of soil moisture regimes and soybean cultivars on stem diameter (mm) at vegetative stage during 2017 and 2018 seasons

| | Stem diameter (mm) at vegetative stage | |
|---|---|---|
| Soil moisture (FC %) | 2017 | 2018 |
| 80 | 4.25 | 3.95 |
| 60 | 4.00 | 3.41 |
| 40 | 3.58 | 3.01 |
| 20 | 3.26 | 3.81 |
| *p*-value | < 0.001 | < 0.001 |
| SED | 0.068 | 0.078 |
| CV (%) | 5.4 | 7.1 |
| Cultivar | | |
| Gazelle | 3.99 | 3.58 |
| Nyala | 3.96 | 3.41 |
| EAI 3600 | 3.62 | 3.08 |
| DPSB 8 | 3.55 | 3.01 |
| Hill | 3.70 | 3.29 |
| DPSB 19 | 3.83 | 3.40 |
| *p*-value | < 0.001 | < 0.001 |
| SED | 0.083 | 0.095 |
| CV (%) | 5.4 | 7.1 |

SED = ± Standard error of difference of means; CV = Coefficient of variation; FC = Field capacity.

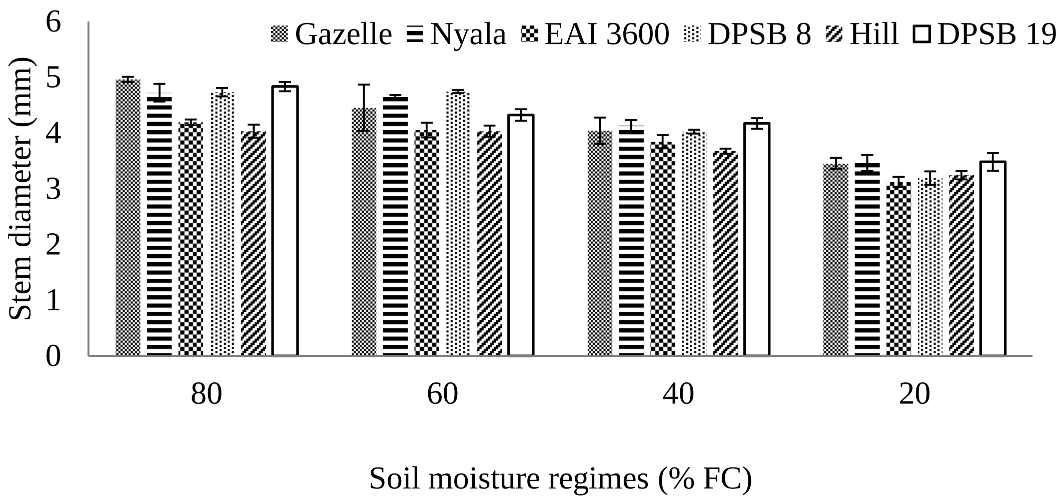



Figure 3.13 Effect of soil moisture regimes and soybean cultivars on stem diameter (mm) at 50% flowering stage during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.01$. FC = Field capacity.

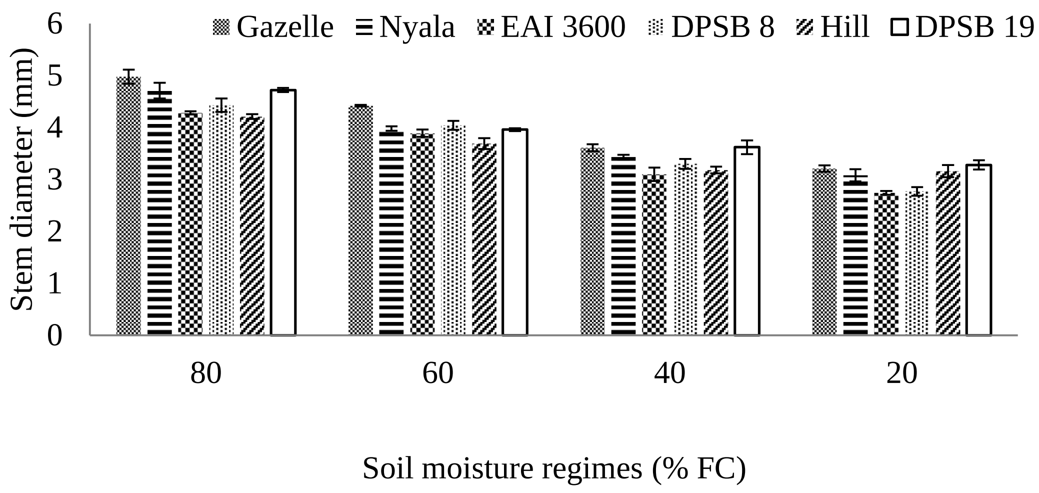



Figure 3.14 Effect of soil moisture regimes and soybean cultivars on stem diameter (mm) at 50% flowering stage during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

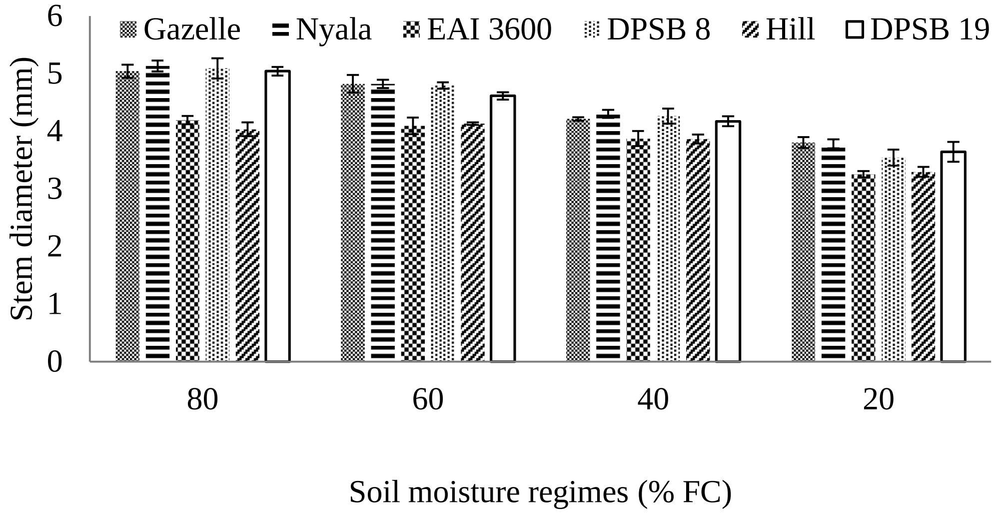



Figure 3.15 Effect of soil moisture regimes and cultivars on stem diameter (mm) at 50% podding stage during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.01$. FC = Field capacity.

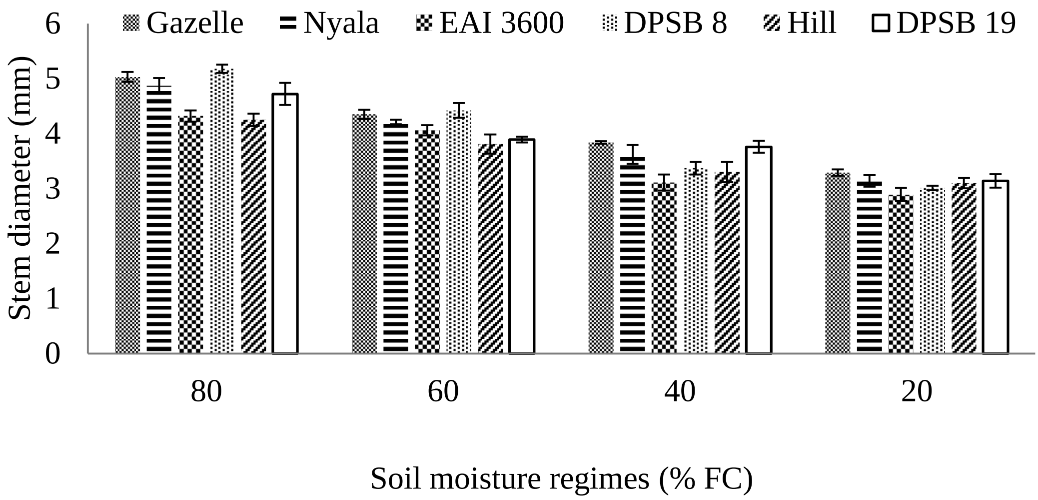



Figure 3.16 Effect of soil moisture regimes and cultivars on stem diameter (mm) at 50% podding stage during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.01$. FC = Field capacity.

***Number of leaves***

Number of leaves arising from the main stem were significantly increased with the interaction of soil moisture regimes and varieties in both years (Figures 3.17 and 3.18). Significant ($p < 0.01$) interactive effect of soil moisture regimes and soybean cultivars on number of leaves per plant was highest and lowest at 80% FC and 20% FC, respectively. Cultivar Gazelle had the lowest number of leaves at all soil moisture regimes in both seasons.

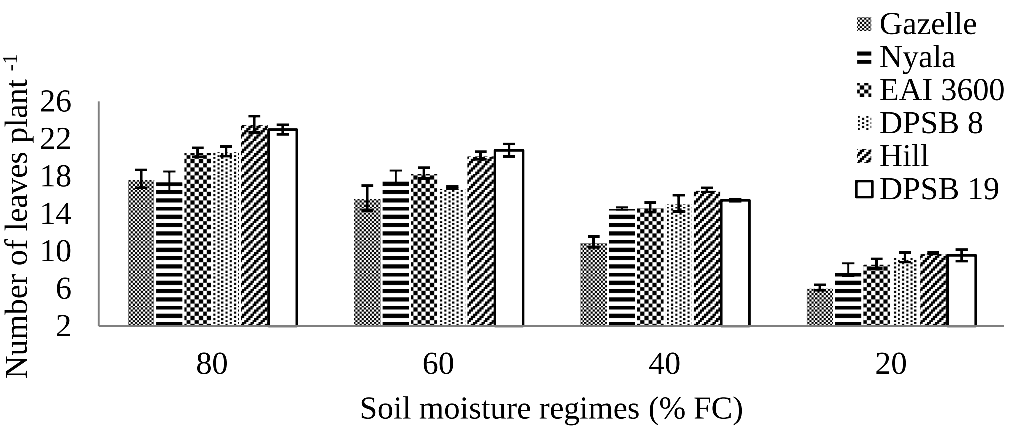



Figure 3.17 Effect of soil moisture regimes and soybean cultivars on number of leaves on primary stem at 50% podding stage during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.01$. FC = Field capacity.

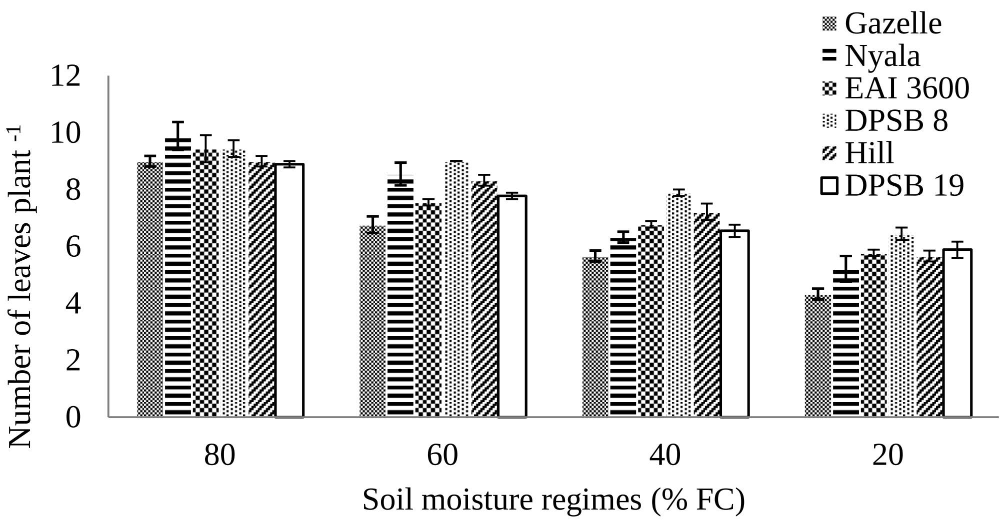



Figure 3.18 Effect of soil moisture regimes and soybean varieties on number of leaves on primary stem at 50% podding stage during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.01$. FC = Field capacity.

***Leaf area and leaf expansion rate***

Leaf area of soybean plants subjected to lower soil moisture regimes was significantly ($p < 0.001$) reduced than those grown at higher soil moisture regimes (Figures 3.19 and 3.20). At 10 weeks after planting (50% podding stage), leaf areas of soybean plants at 80% FC were 69.74% and 81.89% larger than leaf areas of plants grown at 20% FC during 2017 and 2018 seasons respectively. Cultivar DPSB 8 had largest leaf area of 542.5 $cm^2$ in 2017 and 602.8 $cm^2$ in 2018 while smallest leaf areas were registered by cultivars Gazelle (429.1 $cm^2$) in 2017 and Nyala (372.8 $cm^2$) in 2018 season. Leaf expansion rate was significantly ($p < 0.001$) reduced with reduced soil moisture levels (Figures 3.21 and 3.22). Plant leaves at 20% FC and 40% FC tended to develop a vertical leaf orientation (paraheliotropism) while a horizontal leaf orientation was observed at 80% FC (Plate 3.2).

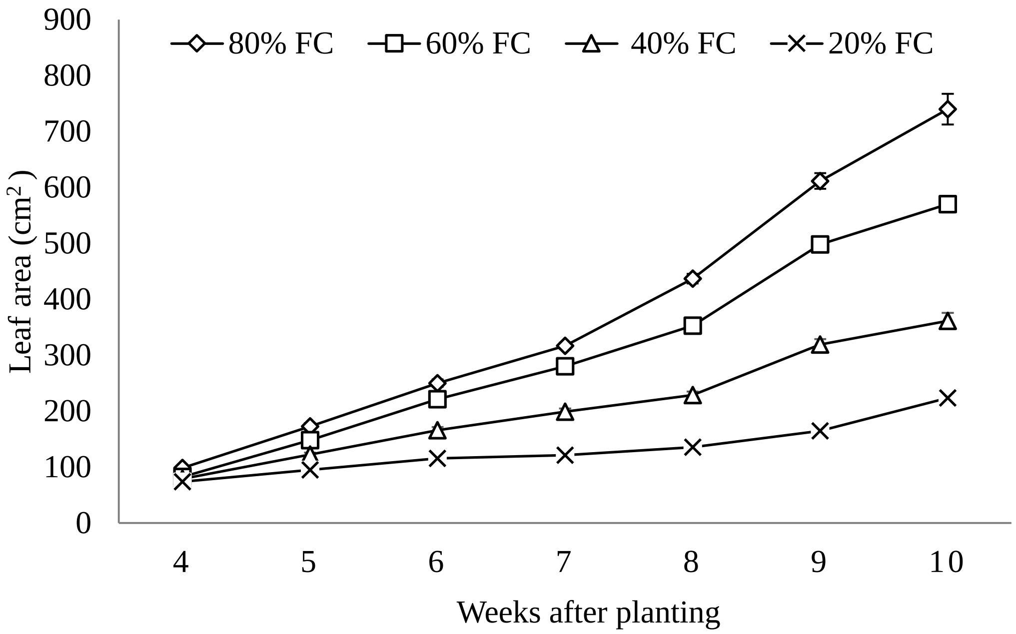



Figure 3.19 Response of leaf area to soil moisture regimes during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

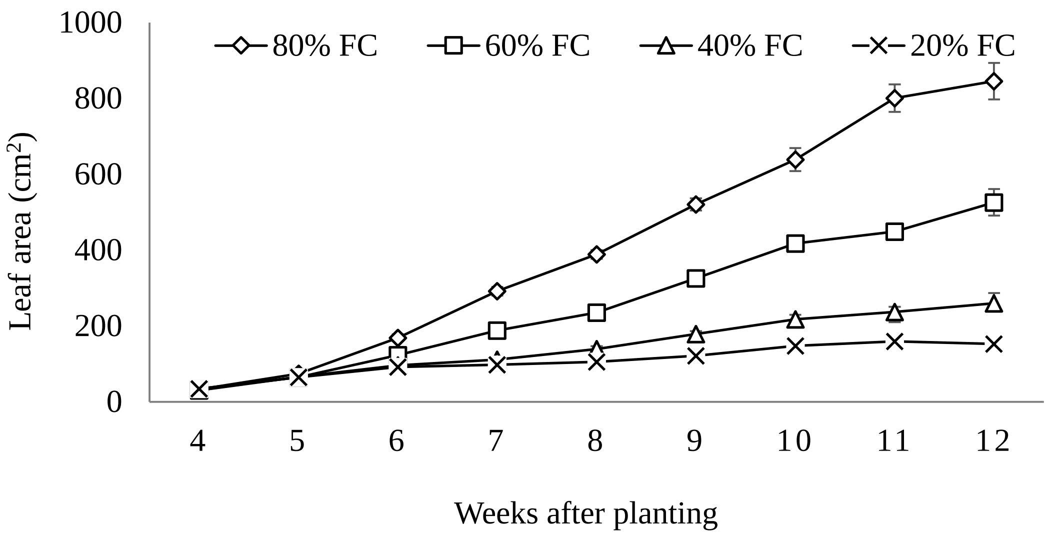



Figure 3.20 Response of leaf area to soil moisture regimes during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

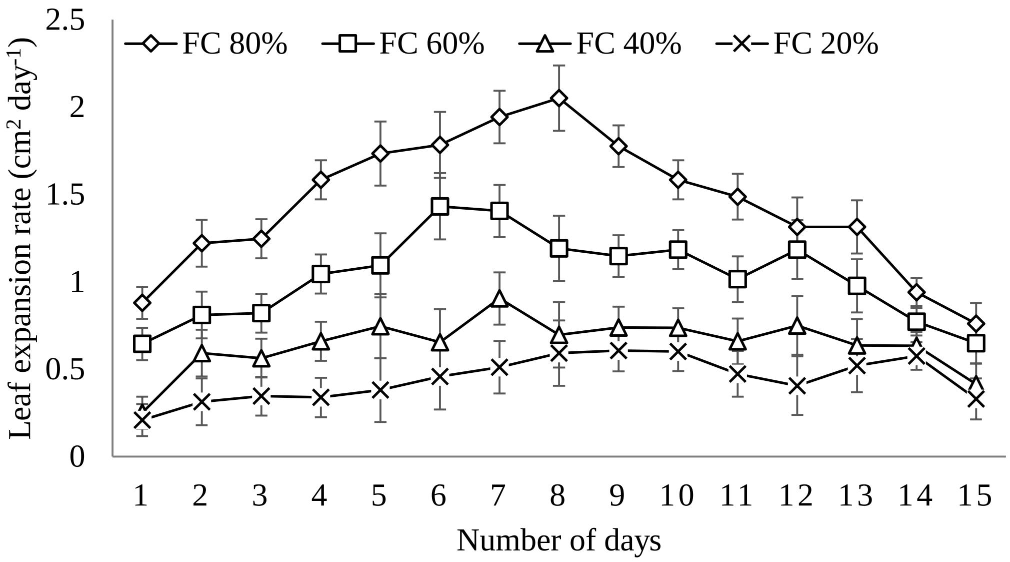



Figure 3.21 Response of leaf expansion rate to soil moisture regimes during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

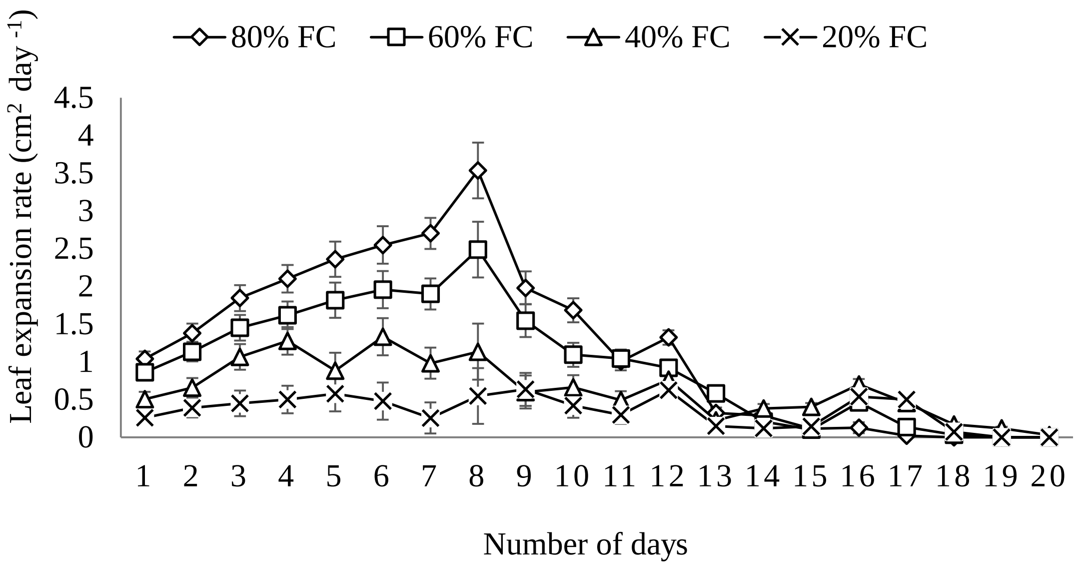
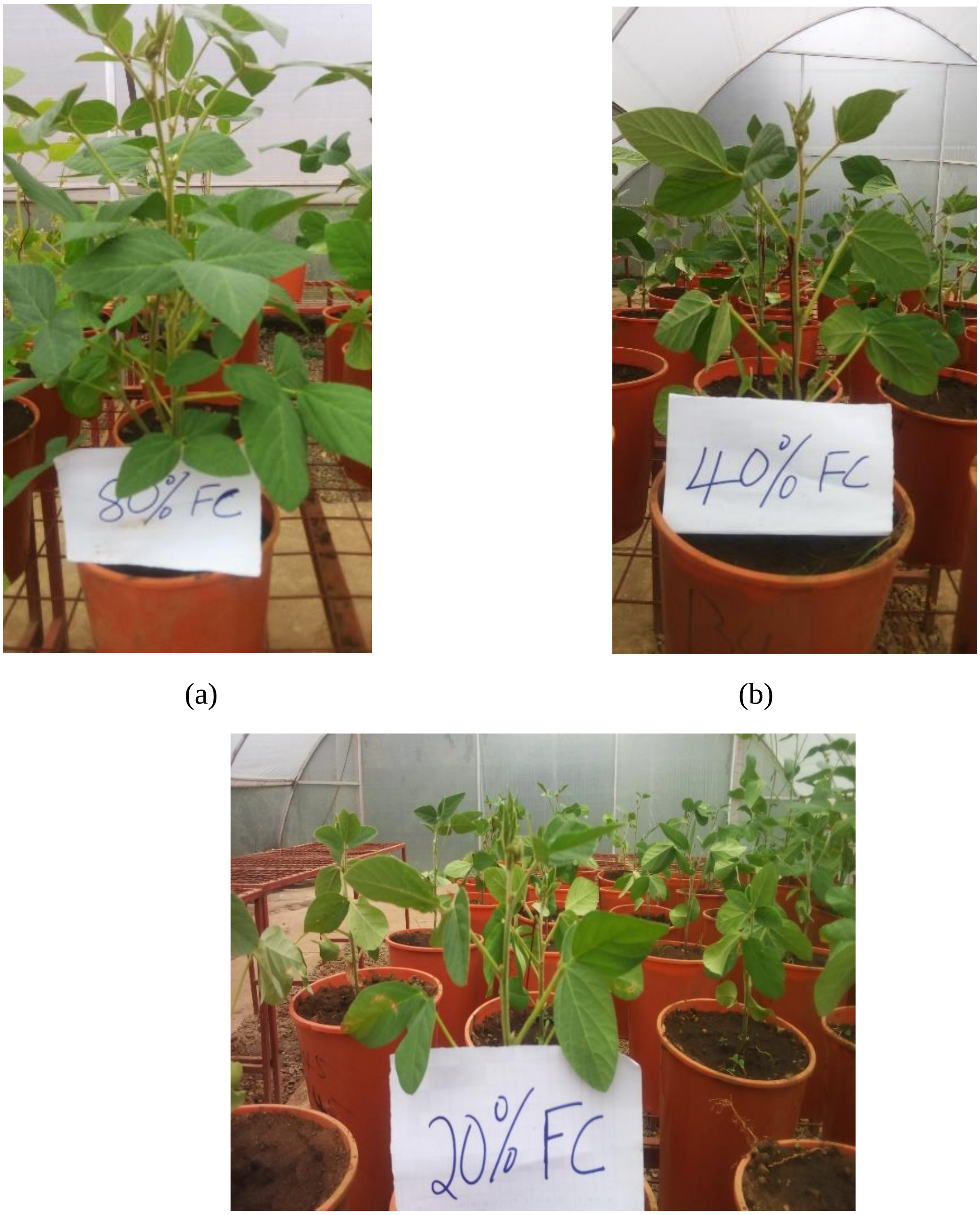



Figure 3.22 Response of leaf expansion rate to soil moisture regimes during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.




(a) (b)

(c)

Plate 3.2 Soybean canopy architecture in response to soil moisture regimes during 2018 season.

***Leaf biomass***

Leaf biomass was significantly ($P < 0.001$) reduced with increasing soil moisture stress in 2017 (Table 3.3). The highest leaf biomass of 3.12 g per plant was attained at 80% FC while the lowest leaf biomass of 0.975 g per plant was at 20% FC representing a 68.49% reduction. In 2018, there was a significant ($p < 0.001$) interaction of soil moisture regimes and cultivars on leaf biomass with all varieties accumulating more leaf biomass at the highest moisture regime of 80% FC (Table 3.4).

Table 3.3 Effect of soil moisture regimes on soybean leaf biomass during 2017 season

| Soil moisture (FC %) | Leaf biomass (g plant $^{-1}$) |
|---|---|
| 80 | 3.12 |
| 60 | 2.59 |
| 40 | 1.77 |
| 20 | 0.98 |
| *p*-value | < 0.001 |
| SED | 0.077 |
| CV (%) | 10.9 |
| Cultivar | |
| Gazelle | 2.04 |
| Nyala | 2.19 |
| EAI 3600 | 2.20 |
| DPSB 8 | 1.97 |
| Hill | 2.15 |
| DPSB 19 | 2.07 |
| *p*-value | 0.145 |
| SED | 0.094 |
| CV (%) | 10.9 |

SED = ± Standard error of difference of means; CV = Coefficient of variation; FC = Field capacity.

Table 3.4 Effect of soil moisture regimes and soybean cultivars on soybean leaf biomass (g plant $^{-1}$) during 2018 season

| | Leaf biomass (g plant $^{-1}$) | | | | |
|---|---|---|---|---|---|
| Cultivar | 80% FC | 60% FC | 40% FC | 20% FC | Mean |
| Gazelle | 5.03 | 2.94 | 1.41 | 1.11 | 2.62 |
| Nyala | 5.83 | 2.93 | 1.44 | 1.04 | 2.81 |
| EAI 3600 | 4.14 | 3.14 | 1.61 | 1.18 | 2.52 |
| DPSB 8 | 6.87 | 3.64 | 1.97 | 0.89 | 3.34 |
| Hill | 5.20 | 3.20 | 1.49 | 1.34 | 2.81 |
| DPSB 19 | 5.83 | 3.01 | 1.98 | 0.93 | 2.94 |
| Mean | 5.48 | 3.14 | 1.65 | 1.08 | |
| *p*-value | 0.007 | | | | |
| SED | 0.418 | | | | |
| CV (%) | 18.0 | | | | |

SED = ± Standard error of difference of means CV = Coefficient of variation; FC = Field capacity.

### 3.4.2 Effect of soil moisture regimes and soybean cultivars on plant water status

***Leaf relative water content***

Soil moisture regimes significantly influenced leaf relative water content (LRWC) in both 2017 and 2018 seasons (Figure 3.23). In 2017, moisture regimes at 80% FC and 60% FC registered LRWC which were significantly ($p < 0.001$) higher compared to LRWC registered at 40% FC and 20% FC. In 2018, 20% FC moisture regime significantly ($p < 0.01$) reduced LRWC while non-significant differences were observed amongst soil moisture regimes at 80% FC, 60% FC and 40% FC. While LRWC did not significantly differ amongst soybean cultivars during 2017 season, LRWC significantly varied amongst soybean cultivars during 2018 season. Cultivars DPSB 8 had highest LRWC (78.93%) though not significantly different from cultivars Nyala (78.93%), Gazelle (77.69%) and DPSB 19 (73.93%). Lowest LRWC of 68.91% during 2018 season was registered with cultivar Hill.

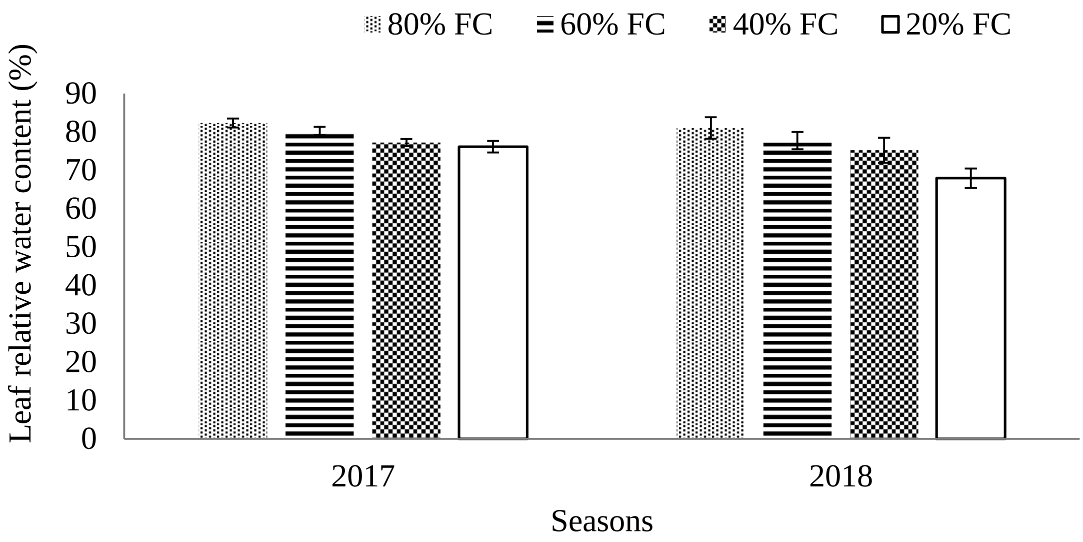



Figure 3.23 Response of leaf relative water content to soil moisture regimes during 2017 and 2018 seasons. Error bars represent ± standard error. Values significantly different at $p < 0.001$ (2017) and $p < 0.01$ (2018). FC = Field capacity.

### 3.4.3 Effect of soil moisture regimes and soybean cultivars on chlorophyll content and leaf gas exchange

***Chlorophyll content***

Significant interactive effects of soil moisture regimes and cultivars on chlorophyll 'a' content was observed in both 2017 (Table 3.5) and 2018 (Table 3.6) seasons. Soybean cultivars had highest ($p < 0.001$) chlorophyll 'a' content at lower soil moisture regimes of 40% FC and 20% FC during both seasons. While significant ($p < 0.001$) interactive effects of soil moisture regimes and cultivars for chlorophyll 'b' content was registered during 2017 season, soil moisture regimes, cultivars and their interactions were not significantly different for chlorophyll 'b' content during 2018 season. Overall, interaction of soil moisture regimes and soybean cultivars significantly ($p < 0.001$) influenced total chlorophyll concentration in soybean leaves in both seasons. Cultivar EAI 3600 had highest total chlorophyll content at the lowest soil moisture regime of 20% FC in both seasons.

Table 3.5 Effect of soil moisture regimes and soybean cultivars on leaf chlorophyll content (mg $g^{-1}$ fresh wt.) at 50% flowering stage during 2017 season

| | | Leaf chlorophyll content (mg $g^{-1}$ fresh wt.) | | |
|---|---|---|---|---|
| Soil moisture (FC %) | Cultivar | Chlorophyll a | Chlorophyll b | Total chlorophyll |
| 80 | Gazelle | 0.97 | 0.12 | 1.09 |
| | Nyala | 0.92 | 0.12 | 1.04 |
| | EAI 3600 | 1.03 | 0.12 | 1.15 |
| | DPSB 8 | 0.86 | 0.11 | 0.99 |
| | Hill | 0.85 | 0.12 | 0.97 |
| | DPSB 19 | 0.85 | 0.11 | 0.96 |
| 60 | Gazelle | 0.87 | 0.12 | 0.99 |
| | Nyala | 1.18 | 0.12 | 1.31 |
| | EAI 3600 | 0.88 | 0.12 | 0.10 |
| | DPSB 8 | 0.95 | 0.11 | 1.07 |
| | Hill | 0.85 | 0.13 | 0.96 |
| | DPSB 19 | 0.89 | 0.11 | 1.01 |
| 40 | Gazelle | 0.87 | 0.12 | 0.99 |
| | Nyala | 0.93 | 0.12 | 1.06 |
| | EAI 3600 | 0.87 | 0.11 | 0.98 |
| | DPSB 8 | 0.92 | 0.13 | 1.05 |
| | Hill | 1.19 | 0.12 | 1.30 |
| | DPSB 19 | 2.25 | 0.13 | 2.38 |
| 20 | Gazelle | 0.89 | 0.11 | 1.00 |
| | Nyala | 0.88 | 0.11 | 0.99 |
| | EAI 3600 | 3.79 | 0.03 | 3.82 |
| | DPSB 8 | 1.68 | 0.10 | 1.79 |
| | Hill | 1.04 | 0.13 | 1.16 |
| | DPSB 19 | 0.87 | 0.10 | 0.96 |
| *p*-value | | < 0.001 | 0.004 | < 0.001 |
| SED | | 0.256 | 0.015 | 0.255 |
| CV (%) | | 27.6 | 16.2 | 24.9 |

SED = ± Standard error of difference of means; CV = Coefficient of variation; FC = Field capacity.

Table 3.6 Effect of soil moisture regimes and soybean cultivars on leaf chlorophyll content (mg $g^{-1}$ fresh wt.) at 50% flowering stage during 2018 season

| | | Leaf chlorophyll content (mg $g^{-1}$ fresh wt.) | | |
|---|---|---|---|---|
| Soil moisture (FC %) | Cultivar | Chlorophyll a | Chlorophyll b | Total chlorophyll |
| 80 | Gazelle | 0.82 | 0.10 | 0.92 |
| | Nyala | 0.38 | 0.06 | 0.45 |
| | EAI 3600 | 0.84 | 0.10 | 0.94 |
| | DPSB 8 | 0.58 | 0.12 | 0.70 |
| | Hill | 0.30 | 0.06 | 0.35 |
| | DPSB 19 | 0.58 | 0.07 | 0.66 |
| 60 | Gazelle | 0.88 | 0.11 | 0.99 |
| | Nyala | 1.24 | 0.12 | 1.36 |
| | EAI 3600 | 0.49 | 0.09 | 0.58 |
| | DPSB 8 | 0.64 | 0.07 | 0.71 |
| | Hill | 0.53 | 0.09 | 0.61 |
| | DPSB 19 | 0.53 | 0.07 | 0.61 |
| 40 | Gazelle | 0.42 | 0.62 | 0.48 |
| | Nyala | 0.49 | 0.07 | 0.56 |
| | EAI 3600 | 0.73 | 0.10 | 0.83 |
| | DPSB 8 | 0.89 | 0.08 | 0.98 |
| | Hill | 1.51 | 0.11 | 1.62 |
| | DPSB 19 | 1.98 | 0.15 | 2.13 |
| 20 | Gazelle | 0.58 | 0.72 | 0.65 |
| | Nyala | 0.65 | 0.07 | 0.72 |
| | EAI 3600 | 2.77 | 0.08 | 2.85 |
| | DPSB 8 | 2.21 | 0.07 | 2.29 |
| | Hill | 054 | 0.06 | 0.60 |
| | DPSB 19 | 0.65 | 0.08 | 0.72 |
| *p*-value | | < 0.001 | 0.650 | < 0.001 |
| SED | | 0.226 | 0.066 | 0.231 |
| CV (%) | | 30.8 | 27.8 | 29.8 |

SED = ± Standard error of difference of means; CV = Coefficient of variation, FC = Field capacity.

***Stomata conductance***

There was an independent and significant ($p < 0.001$) influence of soil moisture regimes and soybean cultivars on stomata conductance at vegetative stage of 2017 season (Figure 3.24). Stomata conductance at 80% FC was 90.44% greater than the lowest stomata conductance of 2.25 mmol $m^{-2}$ $s^{-1}$ registered at 20% FC. Except for variety Gazelle which had significantly lower stomata conductance (6.49 mmol $m^{-2}$ $s^{-1}$) at vegetative stage, all other cultivars had non-significant stomata conductance. Interaction of soil moisture regimes and cultivars significantly increased stomata conductance at 50% flowering ($p < 0.05$) and 50% podding ($p < 0.001$) stages of 2017 season and also at all growth stages ($p < 0.001$) during 2018 season

(Figures 3.25; 3.26; 3.27; 3.27; 3.28 and 3.29). All cultivars attained highest levels of stomata conductance at the least stressing moisture regime of 80% FC. Overall, indeterminate cultivars DPSB 19 and DPSB 8 had relatively higher stomata conductance at the lowest soil moisture level of 20% FC.

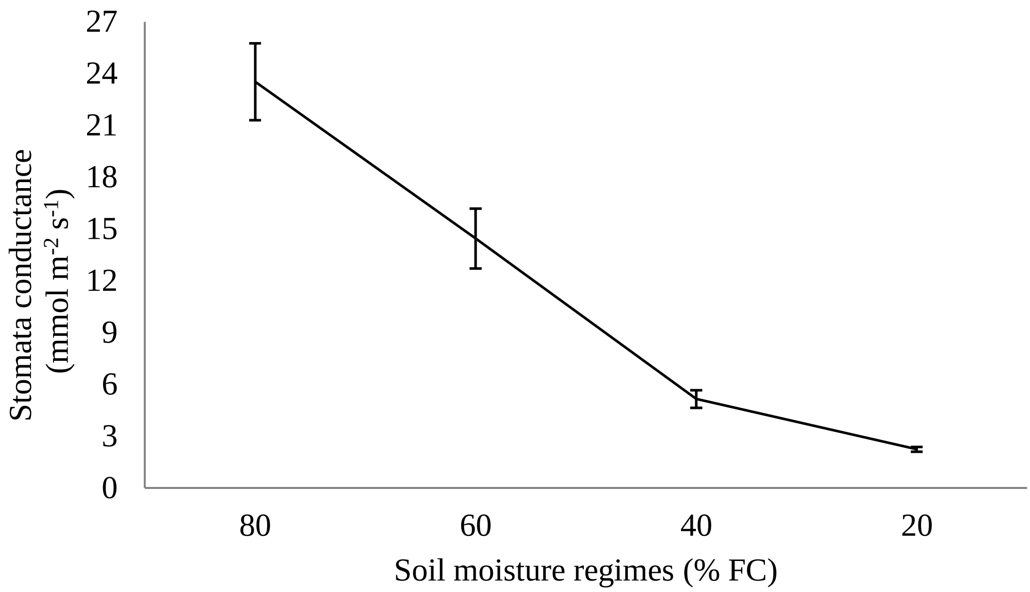



Figure 3.24 Effect of soil moisture regimes on stomata conductance at vegetative stage during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$.

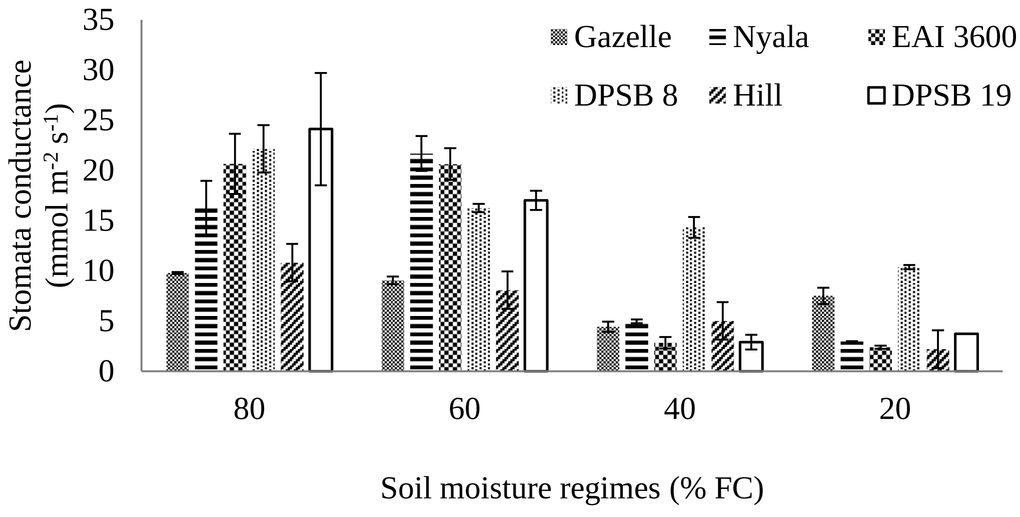



Figure 3.25.Effect of soil moisture regimes on stomata conductance at vegetative stage during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

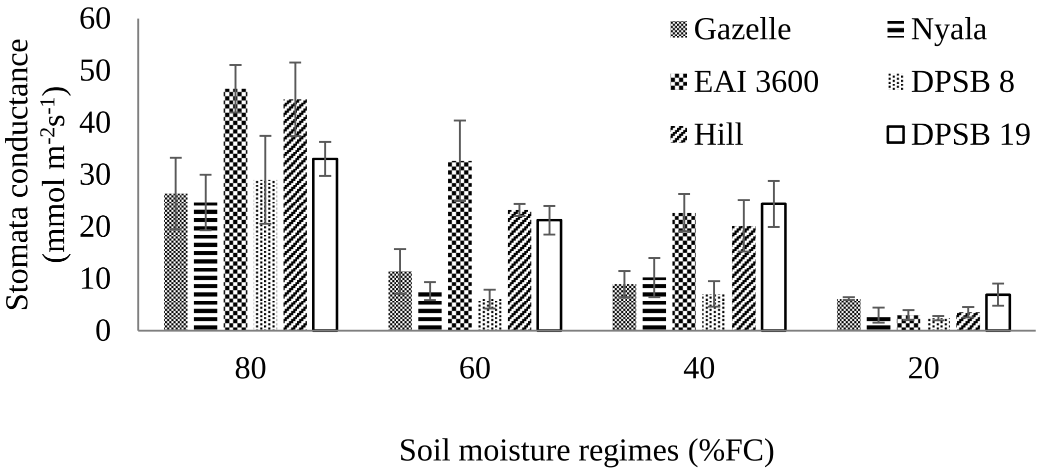



Figure 3.26 Effect of soil moisture regimes on stomata conductance at 50% flowering stage during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.05$. FC = Field capacity.

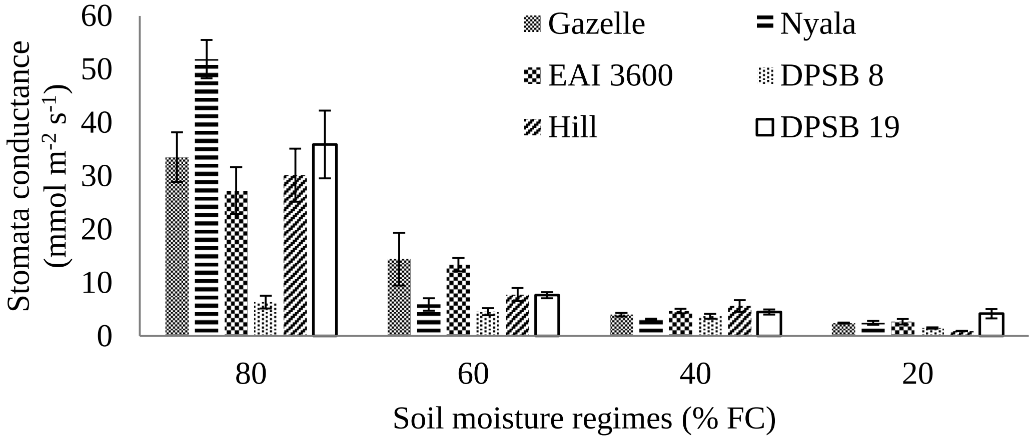



Figure 3.27 Effect of soil moisture regimes on stomata conductance at 50% flowering stage during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

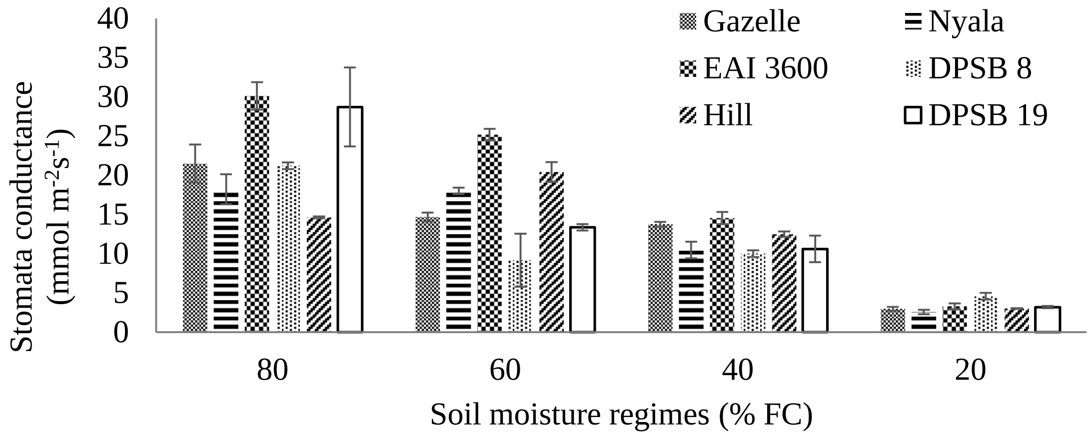



Figure 3.28 Effect of soil moisture regimes on stomata conductance at 50% podding stage during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

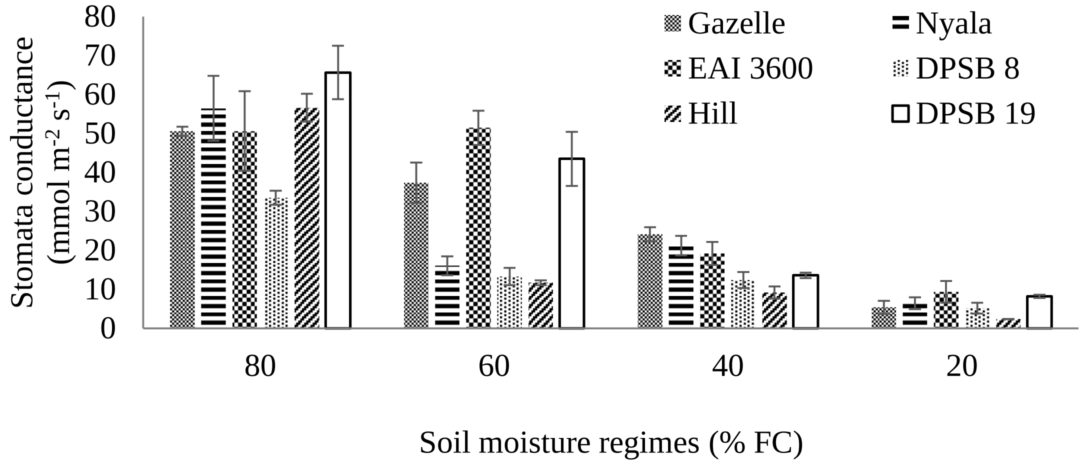



Figure 3.29 Effect of soil moisture regimes and cultivars on stomata conductance at 50% podding stage during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

***Stomata resistance***

Main effects of soil moisture regimes and cultivars significantly influenced stomata resistance at vegetative ($p < 0.05$) and 50% flowering ($p < 0.01$) stages of 2017 season (Table 3.7). At these stages, stomata resistance increased with increasing soil moisture stress. At 50% podding stage of 2017 season, stomata resistance was influenced ($p < 0.001$) by the interaction of soil moisture regimes and cultivars (Table 3.8). Second season results show that significant

($p < 0.001$) interaction of soil moisture regimes and cultivars was apparent at all three growth stages where all soybean cultivars registered increased stomata resistance at the lowest soil moisture level of 20% FC (Table 3.9).

Table 3.7 Effect of soil moisture regimes and soybean cultivars on stomata resistance (s $cm^{-1}$) at vegetative and flowering stages during 2017 season

| | Stomata resistance (s $cm^{-1}$) | |
|---|---|---|
| Soil moisture (FC %) | Vegetative | Flowering |
| 80 | 0.050 | 0.033 |
| 60 | 0.080 | 0.084 |
| 40 | 0.251 | 0.092 |
| 20 | 0.471 | 0.324 |
| *p*-value | < 0.001 | < 0.001 |
| SED | 0.029 | 0.051 |
| CV (%) | 17.5 | 36.7 |
| Cultivar | | |
| Gazelle | 0.222 | 0.107 |
| Nyala | 0.184 | 0.178 |
| EAI 3600 | 0.164 | 0.088 |
| DPSB 8 | 0.137 | 0.190 |
| Hill | 0.156 | 0.078 |
| DPSB 19 | 0.171 | 0.418 |
| *p*-value | 0.032 | 0.002 |
| SED | 0.035 | 0.063 |
| CV (%) | 17.5 | 36.7 |

SED = ± Standard error of difference of means; CV = Coefficient of variation, FC = Field capacity.

Table 3.8 Effect of soil moisture regimes and soybean cultivars on stomata resistance (s $cm^{-1}$) at 50% podding stage during 2017 season

| | Stomata resistance (s $cm^{-1}$) | | | | |
|---|---|---|---|---|---|
| Cultivar | 80% FC | 60% FC | 40% Fc | 20% FC | Mean |
| Gazelle | 0.048 | 0.068 | 0.073 | 0.340 | 0.132 |
| Nyala | 0.056 | 0.056 | 0.098 | 0.399 | 0.152 |
| EAI 3600 | 0.033 | 0.040 | 0.069 | 0.310 | 0.113 |
| DPSB 8 | 0.047 | 0.138 | 0.100 | 0.022 | 0.127 |
| Hill | 0.068 | 0.049 | 0.080 | 0.332 | 0.132 |
| DPSB 19 | 0.037 | 0.075 | 0.099 | 0.314 | 0.131 |
| Mean | 0.048 | 0.071 | 0.087 | 0.319 | |
| *p*-value | < 0.001 | | | | |
| SED | 0.024 | | | | |
| CV (%) | 22.3 | | | | |

SED = ± Standard error of difference of means; CV = Coefficient of variation; FC = Field capacity.

Table 3.9 Effect of soil moisture regimes and soybean cultivars on stomata resistance (s $cm^{-1}$) during 2018 season

| | | Stomata resistance (s $cm^{-1}$) | | |
|---|---|---|---|---|
| Soil moisture (FC %) | Cultivar | Vegetative | Flowering | Podding |
| 80 | Gazelle | 0.102 | 0.030 | 0.020 |
| | Nyala | 0.065 | 0.019 | 0.018 |
| | EAI 3600 | 0.051 | 0.039 | 0.021 |
| | DPSB 8 | 0.051 | 0.170 | 0.030 |
| | Hill | 0.125 | 0.035 | 0.018 |
| | DPSB 19 | 0.048 | 0.030 | 0.016 |
| 60 | Gazelle | 0.111 | 0.107 | 0.028 |
| | Nyala | 0.047 | 0.185 | 0.064 |
| | EAI 3600 | 0.049 | 0.076 | 0.020 |
| | DPSB 8 | 0.094 | 0.229 | 0.079 |
| | Hill | 0.104 | 0.137 | 0.086 |
| | DPSB 19 | 0.059 | 0.132 | 0.024 |
| 40 | Gazelle | 0.233 | 0.251 | 0.042 |
| | Nyala | 0.202 | 0.323 | 0.048 |
| | EAI 3600 | 0.389 | 0.218 | 0.054 |
| | DPSB 8 | 0.071 | 0.276 | 0.084 |
| | Hill | 0.223 | 0.194 | 0.114 |
| | DPSB 19 | 0.416 | 0.227 | 0.074 |
| 20 | Gazelle | 0.137 | 0.412 | 0.237 |
| | Nyala | 0.336 | 0.424 | 0.174 |
| | EAI 3600 | 0.425 | 0.409 | 0.132 |
| | DPSB 8 | 0.097 | 0.677 | 0.231 |
| | Hill | 0.465 | 1.074 | 0.423 |
| | DPSB 19 | 0.268 | 0.259 | 0.122 |
| *p*-value | | < 0.001 | < 0.001 | 0.022 |
| SED | | 0.023 | 0.055 | 0.05 |
| CV (%) | | 39.1 | 27.0 | 23.9 |

SED = ± Standard error of difference of means; = CV = Coefficient of variation; FC = Field capacity.

***Sub- stomata carbon dioxide concentration***

Sub-stomatal carbon dioxide concentration significantly ($p < 0.001$) varied with changes in soil moisture regime and cultivar at 50% flowering stage during 2017 season. The highest sub-stomatal carbon dioxide concentration of 238.70 µmol $mol^{-1}$ was attained at the highest soil moisture regime of 80% FC and carbon dioxide concentration progressively declined with increased soil moisture stress (Figure 3.30). Cultivar EAI 3600 had highest sub-stomatal carbon dioxide concentration (242.42 µmol $mol^{-1}$) though not statistically different from sub-stomatal carbon dioxide concentration levels registered by cultivar Gazelle (178.83

µmol mol$^{-1}$) and DPSB 19 (148.11 µmol mol$^{-1}$). While higher soil moisture levels significantly ($p < 0.05$) increased sub-stomatal carbon dioxide concentration at flowering stage of 2018 season, soybean cultivars did not have any significant influence on this (Figure 3.31). At 50% podding stage of both seasons, soil moisture regimes significantly increased sub-stomatal carbon dioxide concentration with the highest and lowest levels achieved at 80% FC and 20% FC respectively. Type of cultivar used did not yield any significant effects.

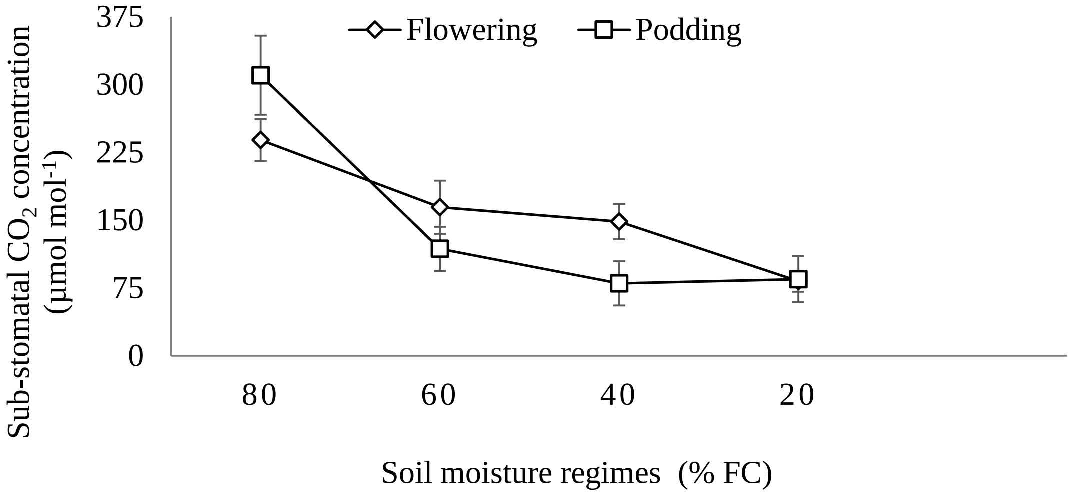



Figure 3.30 Response of sub-stomatal carbon dioxide concentration in soybean leaves to soil moisture regimes during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

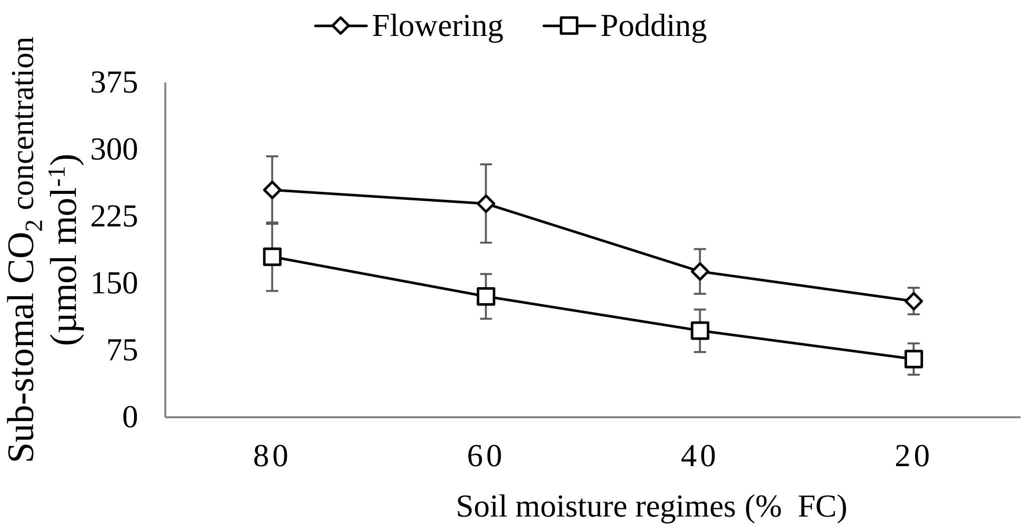



Figure 3.31 Response of sub-stomatal carbon dioxide concentration in soybean leaves to soil moisture regimes during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.05$. FC = Field capacity.

***Photosynthetic rate***

The rate of phosynthesis significantly ($p < 0.05$) increased with reduced soil moisture stress at 50% flowering stage of both seasons. In both cases, 80% FC had highest photosynthetic rate representing 64.46% (2017) and 63.27% (2018) increases over the lowest photosynthetic rates attained at 20% FC (Figure 3.32 and 3.33). Use of different soybean cultivars did not significantly influence photosynthetic rate at 50% flowering stage in both seasons. At 50% podding stage, both soil moisture regimes and cultivars did not significantly influence rate of photosynthesis.

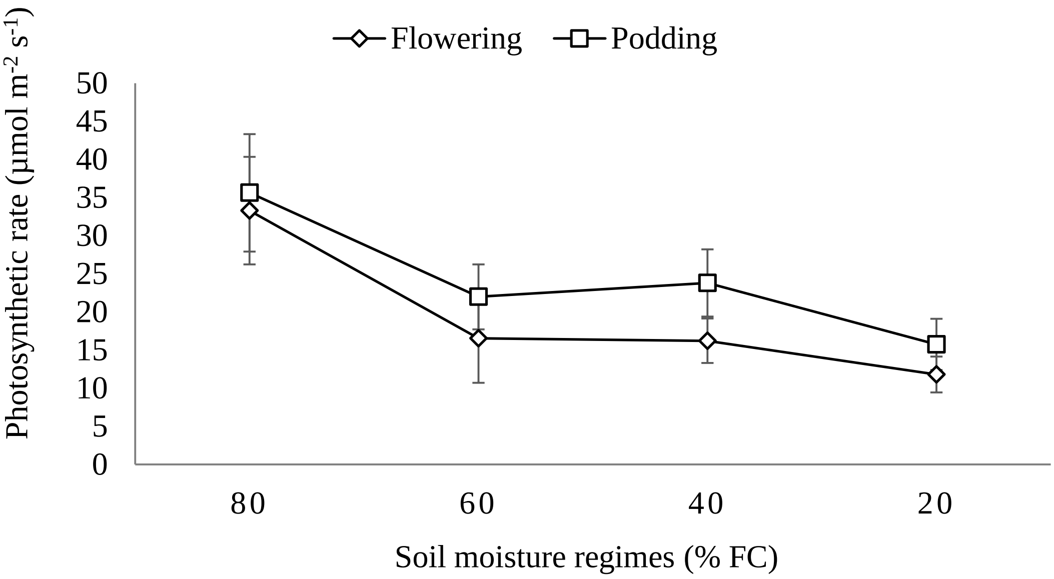



Figure 3.32 Soybean photosynthetic rate as influenced by soil moisture regimes during 2017 season. Error bars represent ± standard error. Values at flowering stage significantly different at $p < 0.05$ and values at podding stage were not significantly different. FC = Field capacity.

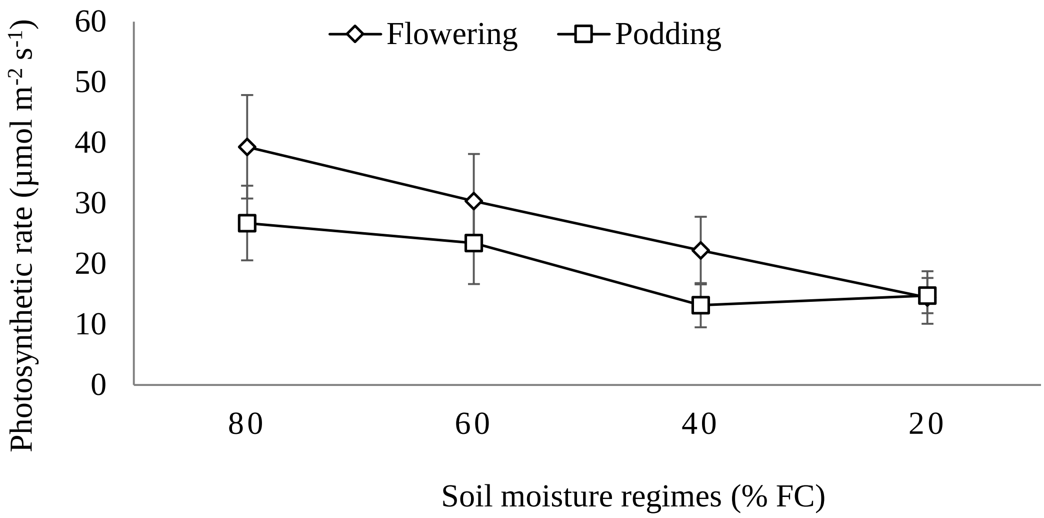



Figure 3.33 Soybean photosynthetic rate as influenced by soil moisture regimes during 2018 season. Error bars represent ± standard error. Values at flowering stage significantly different at $p < 0.05$, values at podding stage not significantly different. FC = Field capacity.

***Correlation between sub-stomatal carbon dioxide concentration and rate of photosynthesis***

Sub-stomatal carbon dioxide concentration and photosynthetic rate of soybean cultivars showed a positive association (Figures 3.34 and 3.35). A linear relationship between carbon dioxide concentration and photosynthesis at 50% flowering stage indicates that the higher the concentration of sub-stomatal carbon dioxide, the greater the photosynthetic rate. Coefficient of determination ($r^2$) indicate that 87.75% and 93.42% of variations in photosynthetic rates at different soil moisture regimes in 2017 and 2018 respectively were as a result of differences in sub-stomatal carbon dioxide concentrations.

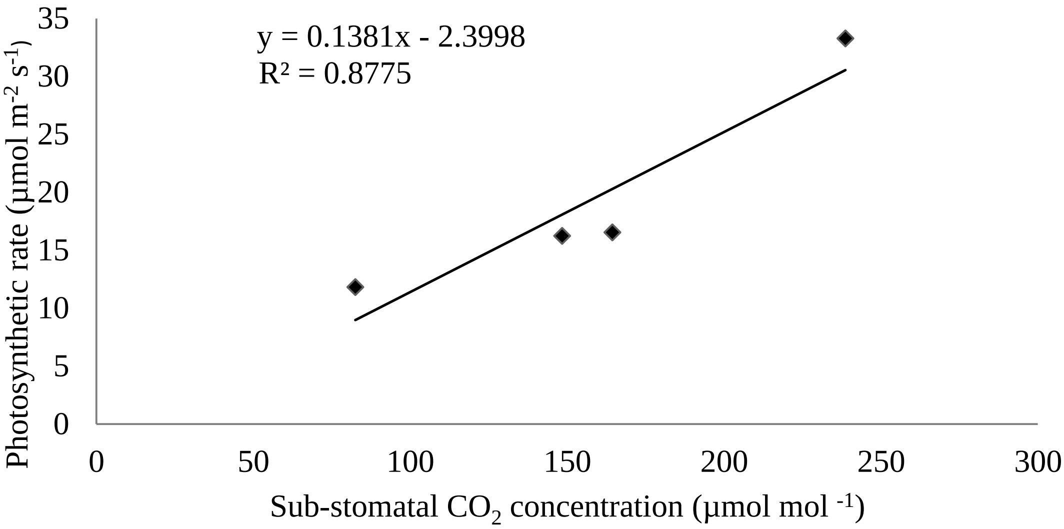



Figure 3.34 Correlation of sub-stomatal carbon dioxide concentration and rate of photosynthesis at 50% flowering stage during 2017 season.

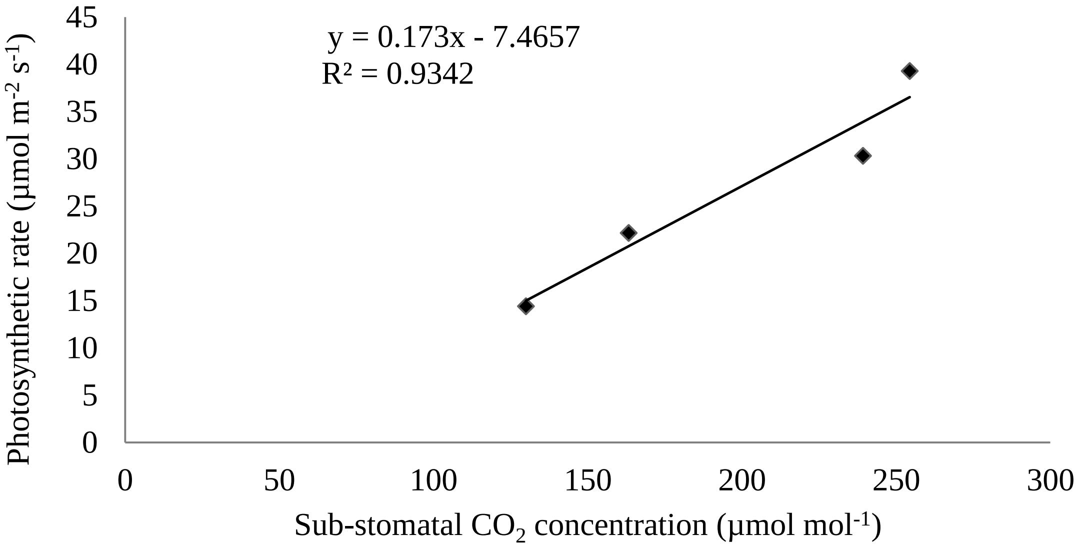



Figure 3.35 Correlation of sub-stomatal carbon dioxide concentration and photosynthetic rate at 50% flowering stage during 2018 season.

### 3.4.4 Effect of soil moisture regimes and soybean cultivars on root growth of soybean

***Root diameter***

Root diameter was significantly ($p < 0.001$) influenced by the interaction of soil moisture regimes and soybean varieties (Table 3.10). In the two seasons, all soybean cultivars had thicker roots at higher soil moisture regime of 80% FC with root diameter progressively decreasing with soil moisture limitation.

Table 3.10 Effect of soil moisture regimes and soybean cultivars on root diameter (mm) during 2017 and 2018 seasons

| | | Root diameter (mm) | |
|---|---|---|---|
| Soil moisture (FC %) | Cultivar | 2017 | 2018 |
| 80 | Gazelle | 0.82 | 0.69 |
| | Nyala | 0.95 | 0.85 |
| | EAI 3600 | 0.77 | 0.63 |
| | DPSB 8 | 0.84 | 0.80 |
| | Hill | 0.63 | 0.68 |
| | DPSB 19 | 0.81 | 0.62 |
| 60 | Gazelle | 0.66 | 0.68 |
| | Nyala | 0.75 | 0.69 |
| | EAI 3600 | 0.71 | 0.72 |
| | DPSB 8 | 0.75 | 0.69 |
| | Hill | 0.66 | 0.64 |
| | DPSB 19 | 0.74 | 0.65 |
| 40 | Gazelle | 0.62 | 0.56 |
| | Nyala | 0.62 | 0.55 |
| | EAI 3600 | 0.64 | 0.54 |
| | DPSB 8 | 0.68 | 0.67 |
| | Hill | 0.61 | 0.55 |
| | DPSB 19 | 0.62 | 0.60 |
| 20 | Gazelle | 0.61 | 0.49 |
| | Nyala | 0.54 | 0.54 |
| | EAI 3600 | 0.52 | 0.52 |
| | DPSB 8 | 0.66 | 0.58 |
| | Hill | 0.54 | 0.55 |
| | DPSB 19 | 0.52 | 0.50 |
| *p*-value | | 0.007 | 0.009 |
| SED | | 0.049 | 0.044 |
| CV (%) | | 8.8 | 8.6 |

SED = ± Standard error of difference of means CV = Coefficient of variation. FC = Field capacity.

***Root surface area***

Soil moisture regimes significantly ($p < 0.001$) influenced root surface area both in 2017 and 2018 (Figure 3.36). Highest root surface area of 829 $cm^2$ in 2017 and 1079 $cm^2$ in 2018 were achieved at 80% FC representing 69.60% and 82.02% increase over lowest root surface areas of 252 $cm^2$ (2017) and 194 $cm^2$ (2018) attained at 20% FC. Soybean cultivars did not have a significant effect on root surface area in both seasons.

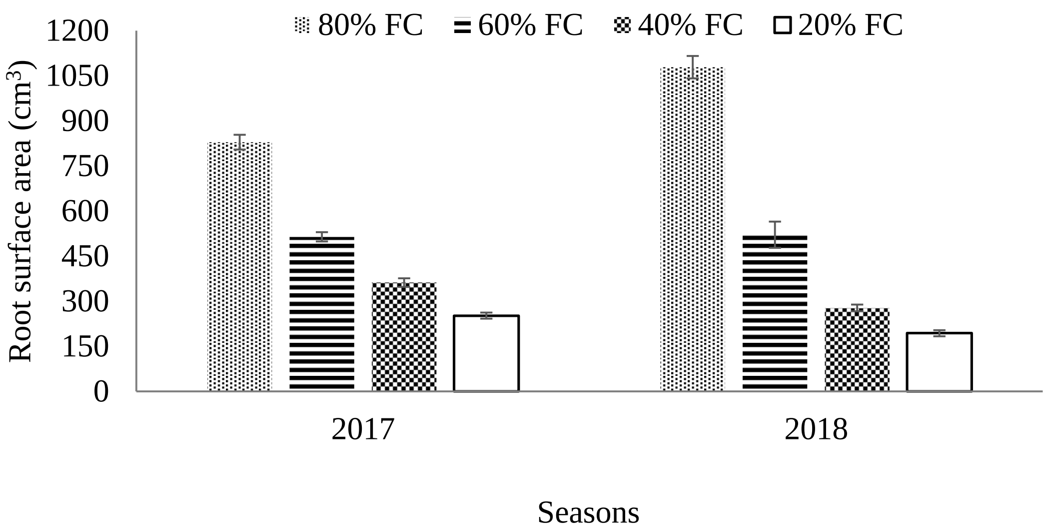



Figure 3.36 Response of root surface area to soil moisture regimes during 2017 and 2018 seasons. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

***Root length***

Soil moisture regimes significantly ($p < 0.001$) increased soybean root length in both seasons. In either case, root length significantly increased with reduced soil moisture stress (Figure 3.37). The effect of soybean cultivars on root length varied with seasons. In 2017 season, cultivars did not have a significant influence on root length. In 2018, root length was significantly dependent on cultivar type. Cultivar EAI 3600 had longest root length (29.57 m) while cultivar Nyala had shortest root length of 22.32 m.

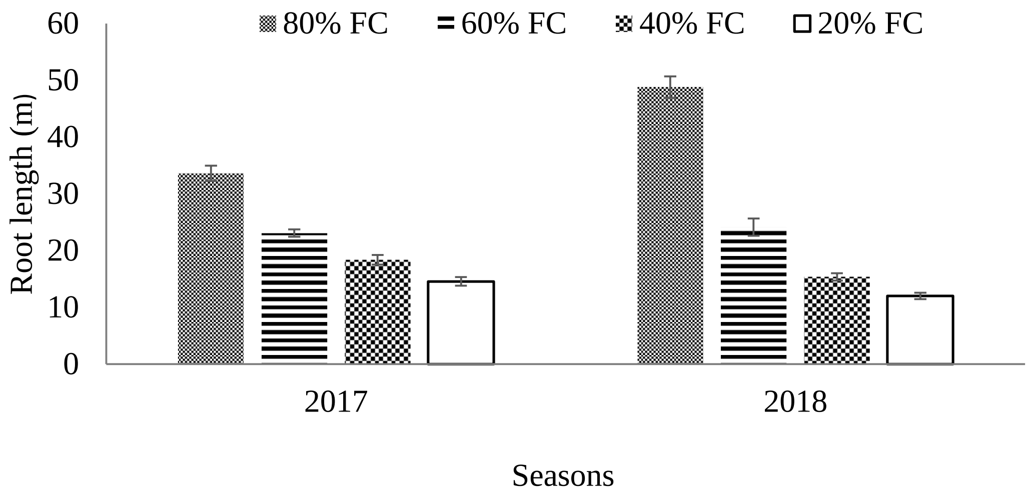



Figure 3.37. Response of root length to soil moisture regimes during 2017 and 2018 seasons. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

***Root volume***

Interaction of soil moisture regimes and cultivars had a significant ($p < 0.001$) effect on volume of soybean roots during both seasons (Figures 3.38; 3.39 and plate 3.3). The interaction of the highest soil moisture regime of 80% FC and all soybean cultivars led to a significant increase in root volume. Cultivar Nyala had highest percent reduction in root volume at the lowest soil moisture regime of 20% FC both in 2017 (85.47%) and 2018 (91.39%) seasons. On the other hand, cultivars DPSB 19 and EAI 3600 maintained highest root volume at lowest soil moisture level in 2017 and 2018 respectively.

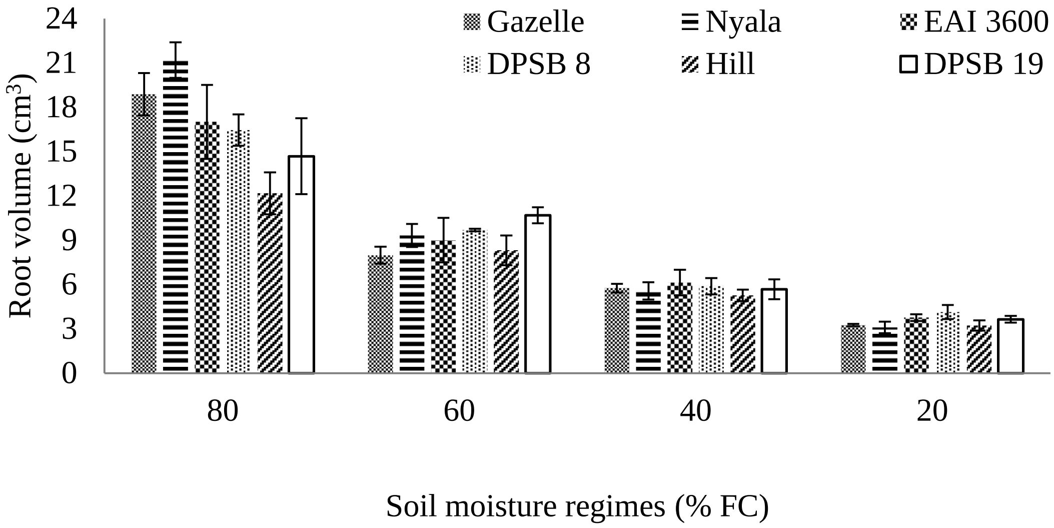



Figure 3.38 Effect of soil moisture regimes and soybean cultivars on root volume during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

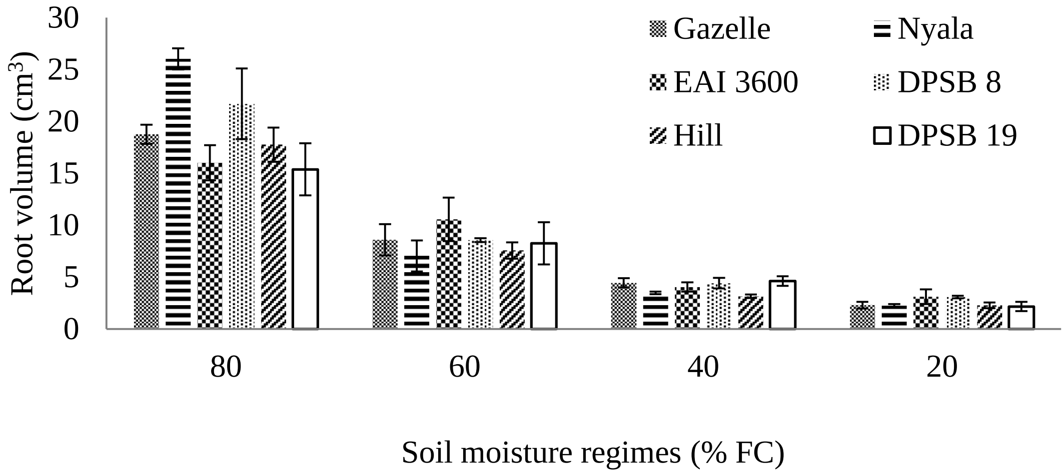



Figure 3.39 Effect of soil moisture regimes and soybean cultivars on root volume during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

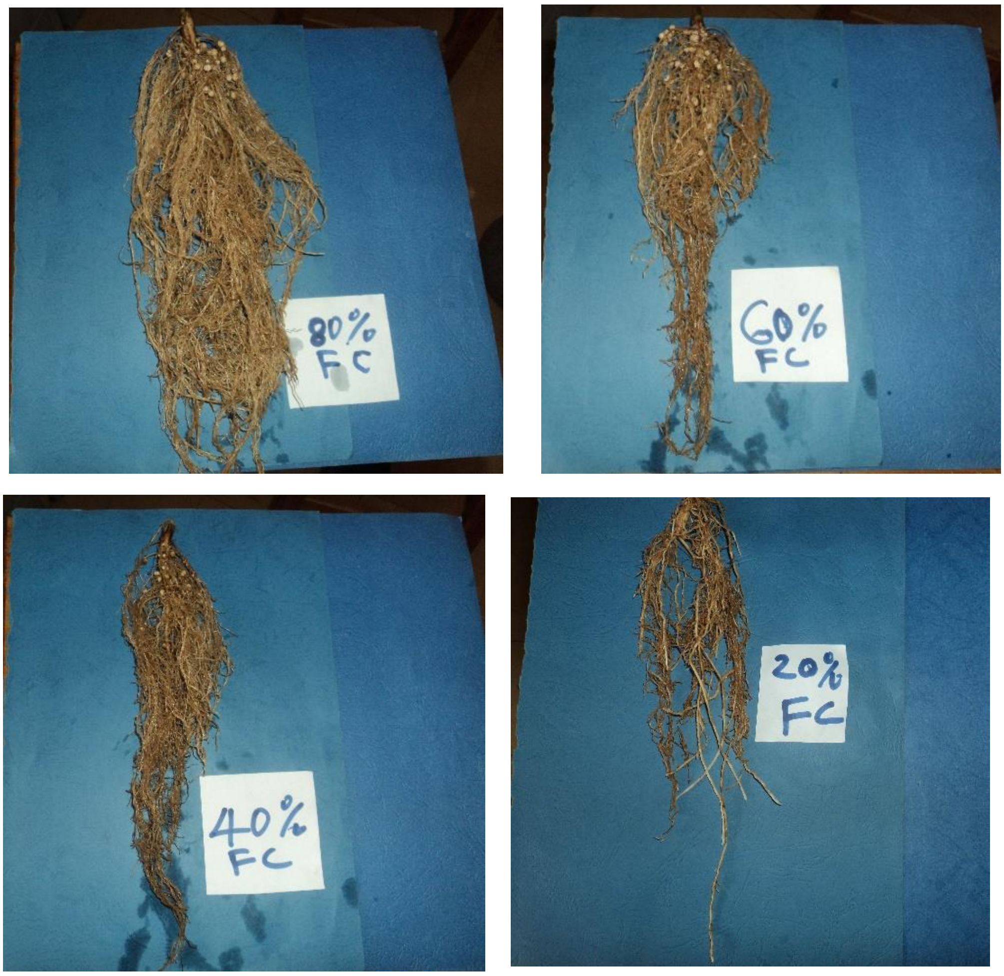



Plate 3.3 Soybean root density in response to soil moisture regimes at 50% flowering stage during 2018 season

***Root biomass***

Root biomass was significantly ($p < 0.001$) influenced by the interaction of soil moisture regimes and soybean cultivars (Table 3.11). In both seasons, all soybean cultivars accumulated more root biomass at higher soil moisture regime of 80% FC with root biomass decreasing with increasing soil moisture stress. Cultivar Nyala had highest percent reduction in root biomass accumulation in 2017 (76.23%) and 2018 (85.49%) seasons.

Table 3.11 Effect of soil moisture regimes and soybean cultivars on soybean root biomass (g $plant^{-1}$) during 2017 and 2018 seasons

| | | Root biomass (g $plant^{-1}$) | |
|---|---|---|---|
| Soil moisture (FC %) | Cultivar | 2017 | 2018 |
| 80 | Gazelle | 2.85 | 3.00 |
| | Nyala | 3.24 | 3.17 |
| | EAI 3600 | 2.72 | 2.19 |
| | DPSB 8 | 2.89 | 3.61 |
| | Hill | 2.09 | 2.22 |
| | DPSB 19 | 2.50 | 2.38 |
| 60 | Gazelle | 1.72 | 1.35 |
| | Nyala | 2.26 | 1.25 |
| | EAI 3600 | 1.90 | 1.91 |
| | DPSB 8 | 2.46 | 1.69 |
| | Hill | 1.47 | 1.20 |
| | DPSB 19 | 2.15 | 1.39 |
| 40 | Gazelle | 1.24 | 0.82 |
| | Nyala | 1.21 | 0.64 |
| | EAI 3600 | 1.22 | 0.81 |
| | DPSB 8 | 1.31 | 0.83 |
| | Hill | 1.34 | 0.63 |
| | DPSB 19 | 1.18 | 0.68 |
| 20 | Gazelle | 0.84 | 0.50 |
| | Nyala | 0.77 | 0.46 |
| | EAI 3600 | 0.73 | 0.60 |
| | DPSB 8 | 0.77 | 0.58 |
| | Hill | 0.69 | 0.49 |
| | DPSB 19 | 0.81 | 0.40 |
| *p*-value | | < 0.001 | < 0.001 |
| SED | | 0.158 | 0.19 |
| CV (%) | | 11.5 | 17.0 |

SED = ± Standard error of difference of means; CV = Coefficient of variation; FC = Field capacity.

***Number of nodules, nodule efficiency and nodule biomass***

Figures 3.40; 3.41and 3.42 present results on the total number of nodules, number of effective nodules and nodule biomass per plant. The number of nodules per plant, nodule efficiency and nodule biomass were significantly responsive to variations in soil moisture regimes ($p < 0.001$) and type of cultivar ($p < 0.05$) used. Total number of nodules per plant at 80% FC were 91.57% (2017) and 90.13% (2018) higher compared to number of nodules registered at 20% FC. Cultivar Hill consistently gave the lowest number of nodules per plant in both seasons. All other cultivars were not significantly different. Number of effective nodules and nodule biomass followed a similar trend to total number of nodules per plant. In both seasons, moisture stress significantly decreased both number of effective nodules and nodule biomass.

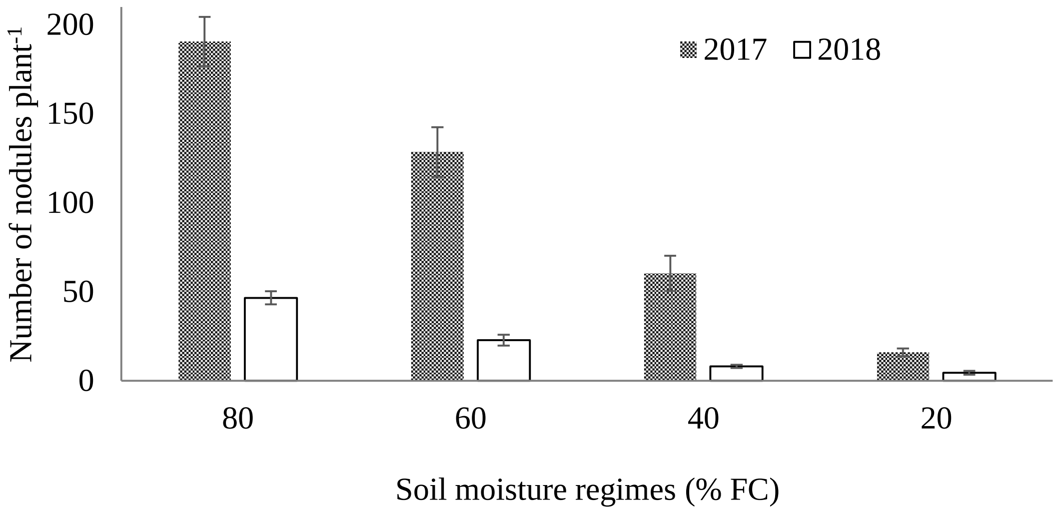



Figure 3.40 Effect of soil moisture regimes on number of soybean root nodules during 2017 and 2018 seasons. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

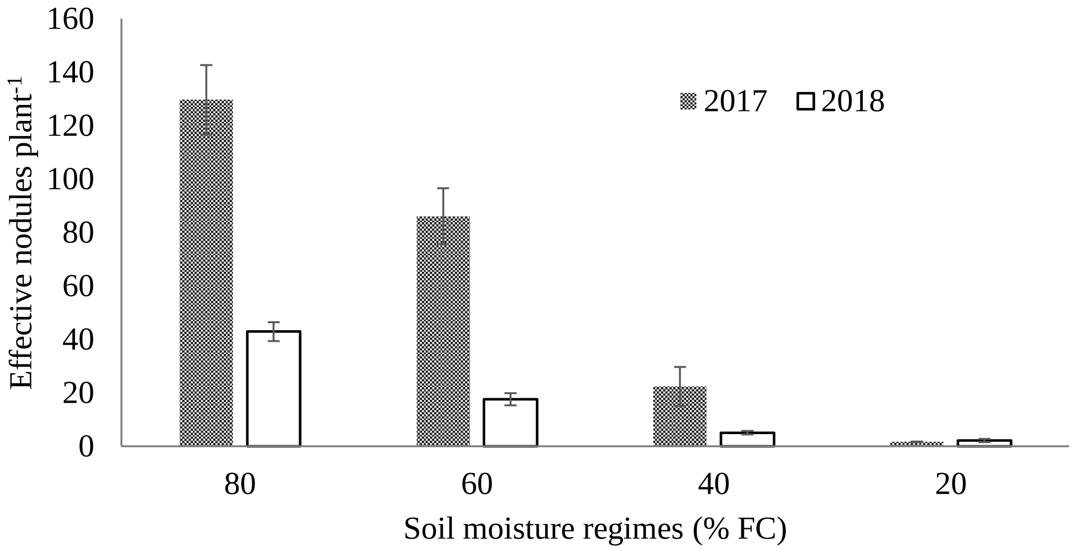



Figure 3.41 Effect of soil moisture regimes on number of effective nodules during 2017 and 2018 seasons. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

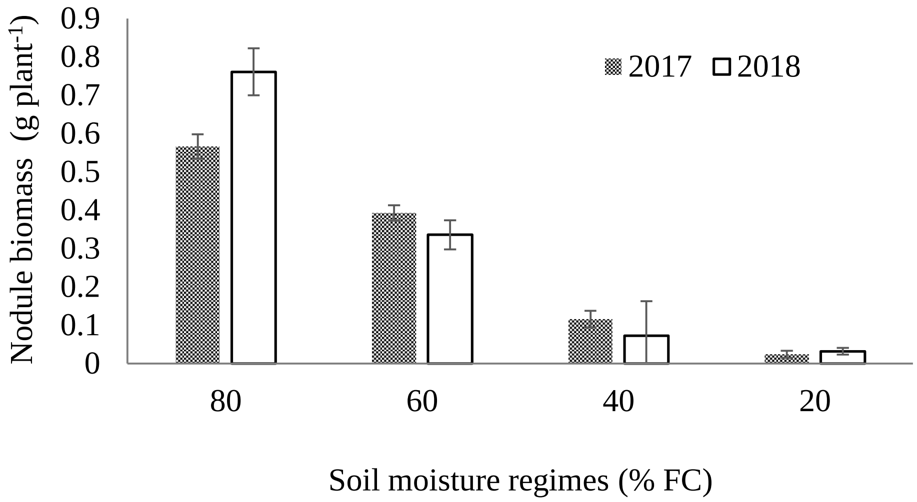



Figure 3.42 Effect of soil moisture regimes on nodule biomass during 2017 and 2018 seasons. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

### 3.4.5. Effect of soil moisture regimes and soybean cultivars on dry matter partitioning

***Shoot to root ratio***

Main effects of soil moisture regimes and cultivars played a significant ($p < 0.001$) role in determining shoot to ratio in both seasons (Figure 3.43). In both seasons, shoot to root ratio was significantly higher at 80% FC compared to shoot to root ratios obtained at 60% FC, 40% FC and 20% FC. Soil moisture regime at 40% FC had the least shoot to root ratio in 2017 season. During 2018 season, non-significant differences were registered amongst 60% FC, 40% FC and 20% FC. Though cultivar DPSB 8 (0.48) had the highest shoot to root ratio in 2017, this was not statistically different from cultivars Gazelle (0.45), EAI 3600 (0.43), DPSB 19 (0.43) and Nyala (0.42). Cultivar Hill (0.37) had the lowest shoot to root ratio in 2017. In 2018, cultivar EAI 3600 had highest (0.32) shoot to root ratio with cultivar DPSB 19 having the lowest (0.23). Overall, results indicate that there was a preferential allocation of biomass to root system over shoot system at lower soil moisture regimes and by all soybean cultivars.

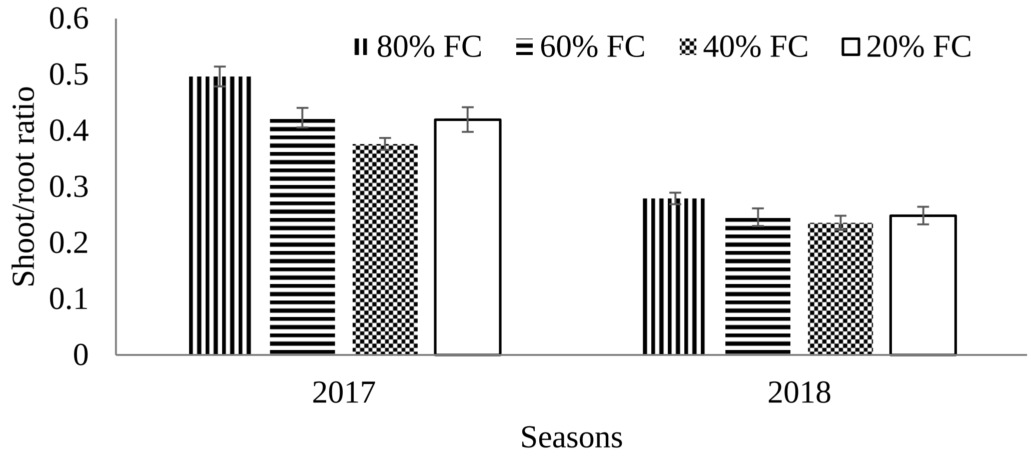



Figure 3.43 Response of shoot to root ratio in soybean to soil moisture regimes during 2017 and 2018 seasons. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

***Specific leaf mass***

Specific leaf mass had a negative but significant response to increased soil moisture regimes during 2017 ($p < 0.05$) and 2018 ($p < 0.001$) seasons. In the two seasons, soil moisture regime at 20% FC registered highest specific leaf mass compared to 80% FC (Figure 3.44). Specific leaf mass also varied with type of cultivar with cultivar DPSB 8 having lowest specific leaf mass of 0.47g $dm^2$ in 2017 and 0.56g $dm^2$ in 2018. All other cultivars had a non-significant specific leaf mass amongst them.

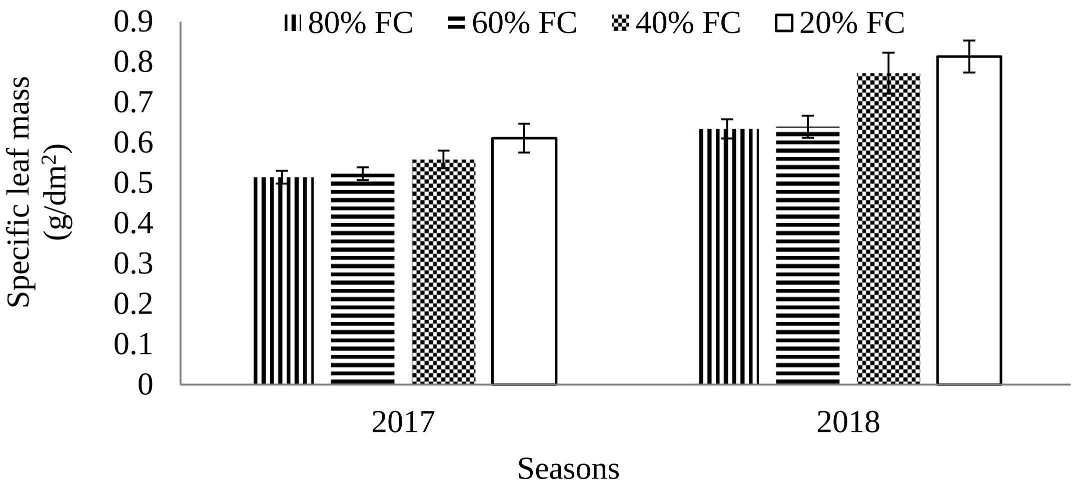



Figure 3.44 Effect of soil moisture regimes on specific leaf mass of soybeans during 2017 and 2018 seasons. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

### 3.4.6 Effect of soil moisture regimes on reproductive growth

***Number of days to flowering and pod maturity***

Number of days taken by soybean plants to attain 50% flowering were significantly ($p < 0.01$) influenced by interactive effects of soil moisture regimes and soybean cultivars in both seasons (Figure 3.45 and 3.46). Number of days taken from pod set to pod maturity were significantly ($p < 0.001$) influenced by main effects of soil moisture regimes and cultivar used (Figure 3.47). While moisture stress delayed soybean flowering, pod maturity was hastened by limited soil moisture levels from pod initiation during both seasons. Overall, soybean plants took fewer days to mature at 20% FC compared to all other moisture regimes.

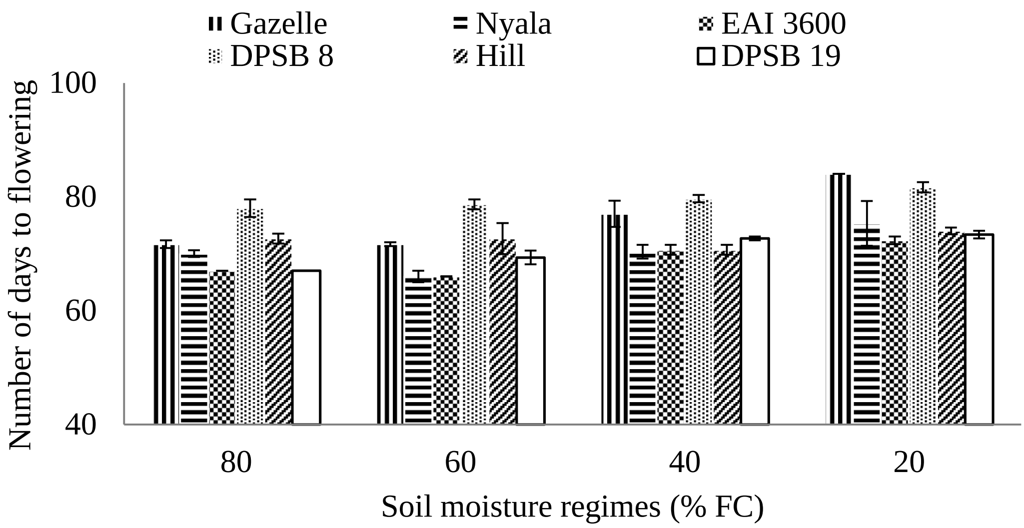



Figure 3.45 Effect of soil moisture regimes and soybean cultivars on number of days to 50% flowering during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.01$. FC = Field capacity.

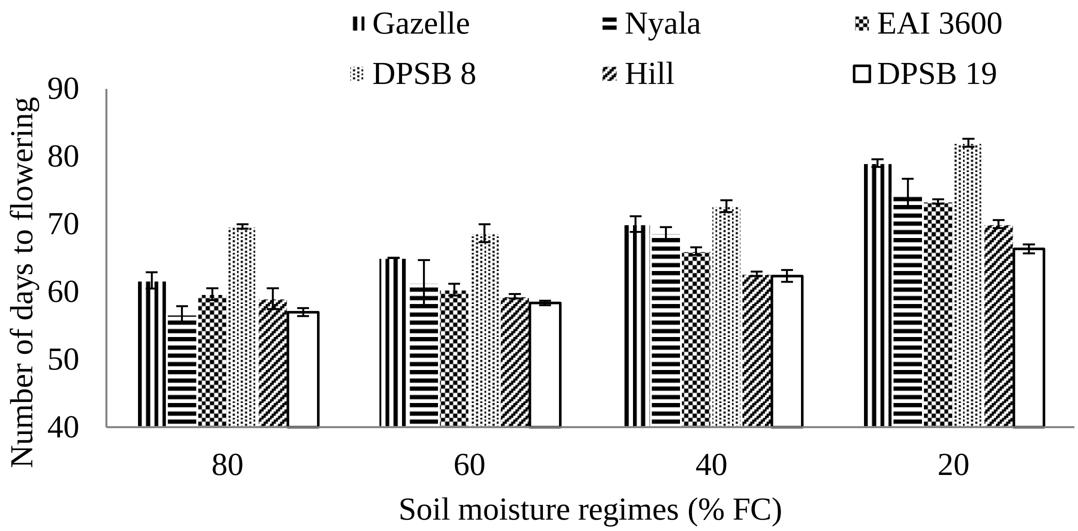



Figure 3.46 Effect of soil moisture regimes and soybean cultivars on number of days to 50% flowering during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.01$. FC = Field capacity.

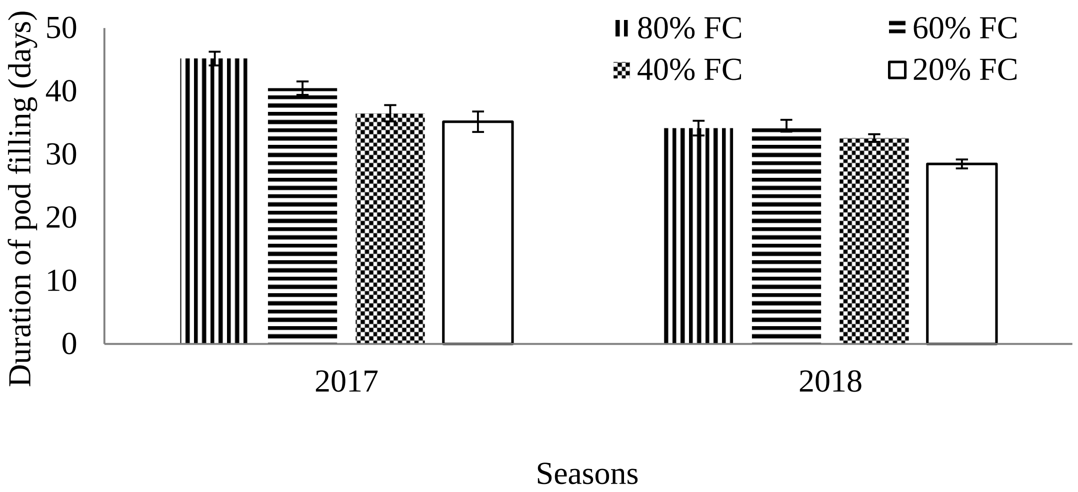



Figure 3.47 Effect of soil moisture regimes on duration of pod filling in soybeans. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

### 3.4.7 Effect of soil moisture regimes and soybean cultivars on yield components and yield

***Number of pods per plant***

There was a significant ($p < 0.001$) interaction of soil moisture regimes and soybean cultivars on total number of pods borne per plant in both seasons (Figures 3.48 and 3.49). The interaction of cultivar DPSB 19 and 80% FC soil moisture regime gave highest number of pods both in 2017 and 2018 seasons. Cultivars Gazelle and DPSB 8 had lowest number of pods per plant at the lowest moisture level of 20% in both seasons.

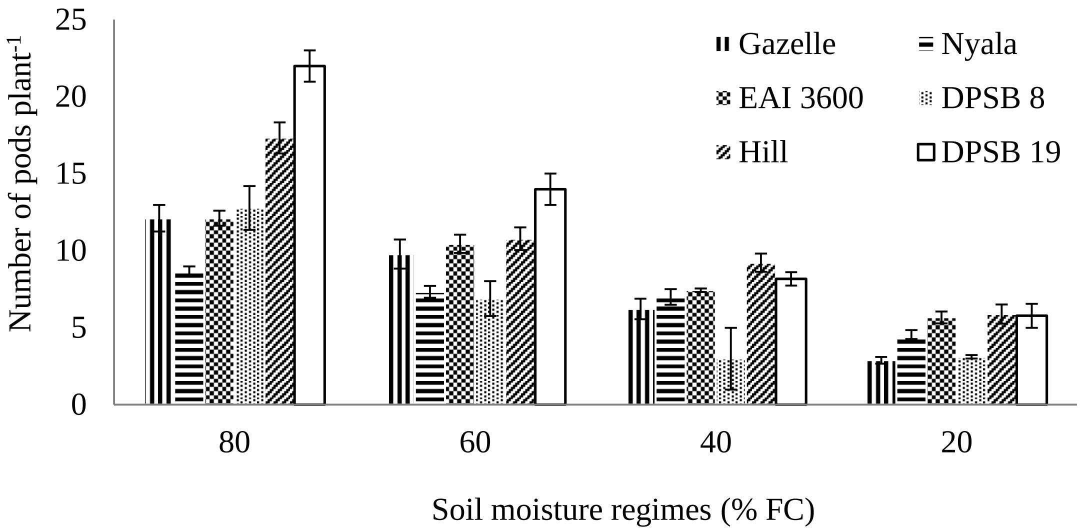



Figure 3.48 Effect of soil moisture regimes and soybean cultivars on number of pods per plant during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. FC = Field capacity.

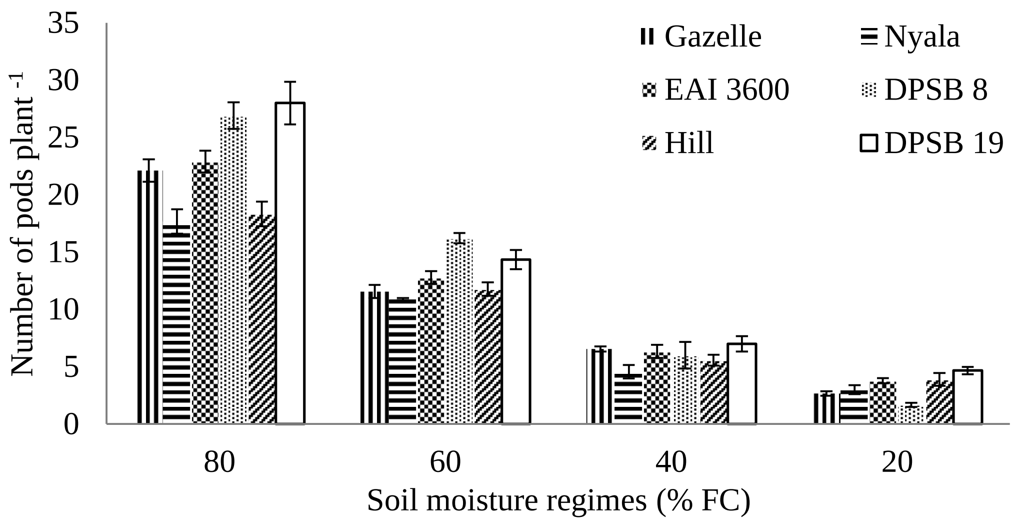



Figure 3.49 Effect of soil moisture regimes and soybean cultivars on number of pods per plant during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.001$. Field capacity.

***Number of aborted pods***

Number of aborted pods per plant was significantly ($p < 0.01$) influenced by interaction of soil moisture regimes and soybean cultivars in both seasons (Figures 3.50 and 3.51). Cultivars Gazelle and Hill had highest number of pod abortions at 20% FC during 2017 and 2018 seasons respectively. Cultivar EAI 3600 had the least number of aborted pods at the lowest soil moisture regimes of 20% in both seasons.

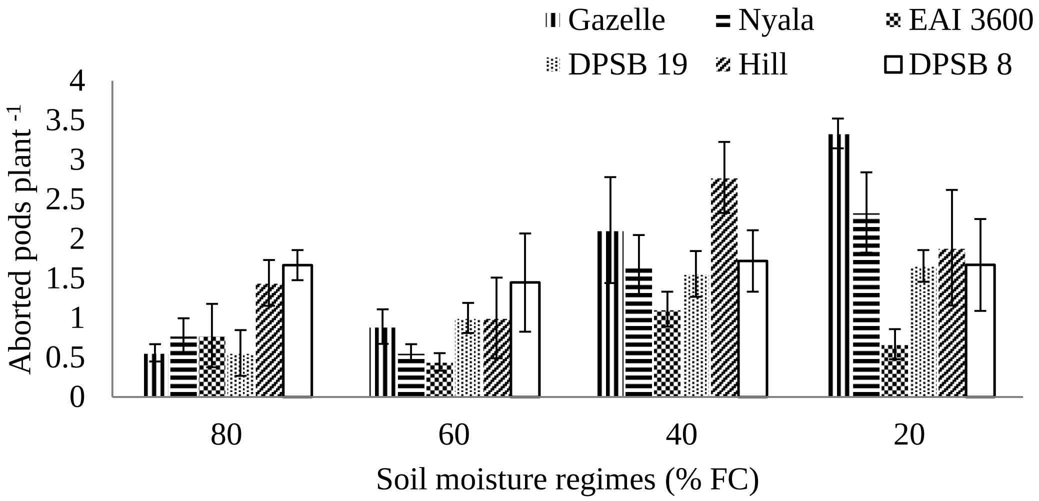



Figure 3.50 Effect of soil moisture regimes and cultivars on number of aborted pods during 2017 season. Error bars represent ± standard error. Values significantly different at $p < 0.01$. FC = Field capacity.

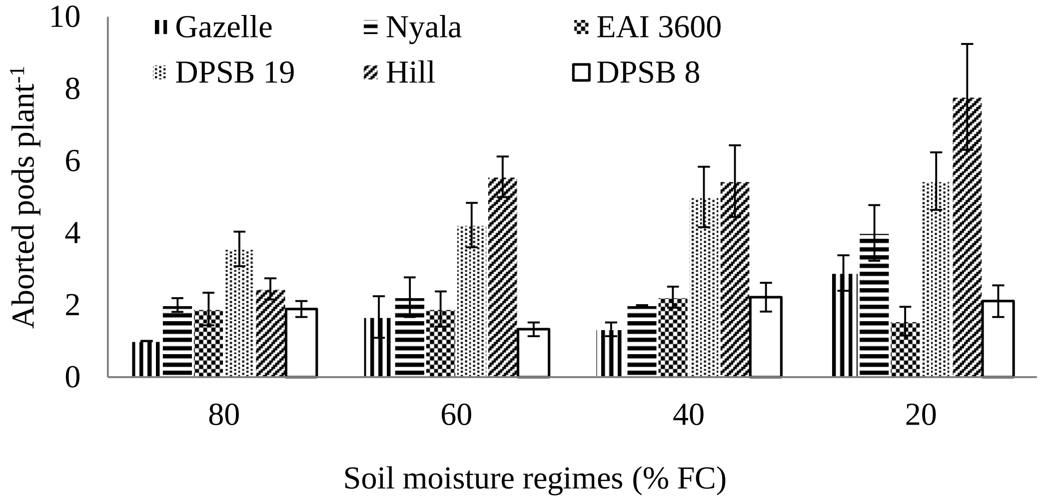



Figure 3.51 Effect of soil moisture regimes and soybean cultivars on number of aborted pods during 2018 season. Error bars represent ± standard error. Values significantly different at $p < 0.01$. FC = Field capacity.

***Number of pods per node***

Number of pods per node was affected ($p < 0.001$) by main effects of soil moisture regimes and cultivars during 2017 season (Table 3.12). Soil moisture regime at 80% FC had highest number of pods per node compared to all other three treatments which, amongst them, registered a non-significant effect. Cultivar DPSB 19 had the highest number of pods per node during 2017 season. During 2018 season, there was a significant ($p < 0.05$) interaction of soil moisture regimes and cultivars on number of pods per plant with all soybean cultivars having more pods per node at the highest soil moisture regime of 80% FC (Table 3.13).

***Number of seeds per pod***

Number of seeds per pod was significantly ($p < 0.001$) responsive to soil moisture regimes and cultivars during 2017 season (Table 3.12) while interaction of soil moisture regimes and cultivars significantly ($p < 0.05$) influenced number of seeds per pod during 2018 season (Table 3.13). The highest number of seeds per pod in 2017 was registered at the highest soil moisture level of 80% FC which was 20.95% more than number of seeds per pod registered at 20% FC. Cultivars EAI 3600 had highest number of seeds per pod representing 14.48% increase over cultivar Nyala which had lowest number of seeds per pod. All cultivars had highest number of seeds per pod at 80% FC during 2018 season. Nonetheless, cultivar Nyala had highest reduction (42.8%) in number of seeds per pod between 80% FC and 20% FC.

Table 3.12 Effect of soil moisture regimes and soybean cultivar on number of pods per node and number of seeds per pod during 2017 season

| Soil moisture (FC %) | Number of pods per node | Number of seeds per pod |
|---|---|---|
| 80 | 1.25 | 2.54 |
| 60 | 1.12 | 2.46 |
| 40 | 1.12 | 2.14 |
| 20 | 1.11 | 2.01 |
| *p*-value | < 0.001 | < 0.001 |
| SED | 0.035 | 0.057 |
| CV (%) | 9.0 | 7.4 |
| Cultivar | | |
| Gazelle | 1.09 | 2.17 |
| Nyala | 1.07 | 2.16 |
| EAI 3600 | 1.17 | 2.53 |
| DPSB 8 | 1.10 | 2.41 |
| Hill | 1.16 | 2.28 |
| DPSB 19 | 1.32 | 2.18 |
| *p*-value | < 0.001 | < 0.001 |
| SED | 0.042 | 0.079 |
| CV (%) | 9.0 | 7.4 |

SED = ± Standard error of difference of means; CV = Coefficient of variation; FC = Field capacity.

Table 3.13 Effect of soil moisture regimes and soybean cultivars on number of pods per node and number of seeds per pod during 2018 season

| Soil moisture (FC %) | Cultivars | Number of pods per node | Number of seeds per pod |
|---|---|---|---|
| | Gazelle | 2.05 | 2.43 |
| | Nyala | 1.82 | 2.50 |
| | EAI 3600 | 2.07 | 2.57 |
| 80 | DPSB 8 | 2.15 | 2.53 |
| | Hill | 1.82 | 2.27 |
| | DPSB 19 | 2.13 | 2.67 |
| | Gazelle | 1.49 | 2.20 |
| | Nyala | 1.24 | 2.33 |
| | EAI 3600 | 1.51 | 2.43 |
| 60 | DPSB 8 | 1.56 | 2.37 |
| | Hill | 1.24 | 2.13 |
| | DPSB 19 | 1.82 | 2.37 |
| | Gazelle | 1.13 | 1.90 |
| | Nyala | 1.00 | 2.13 |
| | EAI 3600 | 1.35 | 2.40 |
| 40 | DPSB 8 | 1.11 | 2.20 |
| | Hill | 1.18 | 2.23 |
| | DPSB 19 | 1.35 | 2.23 |
| | Gazelle | 1.00 | 1.57 |
| | Nyala | 1.00 | 1.43 |
| 20 | EAI 3600 | 1.11 | 2.10 |
| | DPSB 8 | 1.00 | 1.83 |
| | Hill | 1.06 | 1.88 |
| | DPSB 19 | 1.17 | 1.88 |
| *p*-value | | 0.022 | 0.022 |
| SED | | 0.094 | 0.122 |
| CV (%) | | 8.1 | 6.8 |

SED = ± Standard error of difference of means; CV = Coefficient of variation; FC = Field capacity.

***Pod length***

Interaction of soil moisture regimes and soybean cultivars significantly ($p < 0.05$) increased soybean pod lengths during 2017 season with all cultivars having longer pod lengths at 80% FC (Table 3.14). In the second season, pod lengths were significantly ($p < 0.001$) influenced by independent effects of soil moisture regimes and cultivars (Table 3.15). Soybean pods were 33.05% longer at 80% FC relative to the shortest pod length of 2.88 cm registered at 20% FC. Cultivar EAI 3600 had longest pods (4.06 cm) with shortest pod length of 3.46 cm registered by cultivar DPSB 8.

Table 3.14 Effect of soil moisture regimes and soybean cultivar on pod length (cm) during 2017 season

| | Pod length (cm) | | | | |
|---|---|---|---|---|---|
| Cultivar | 80 | 60 | 40 | 20 | Mean |
| Gazelle | 3.81 | 3.71 | 3.48 | 3.28 | 3.57 |
| Nyala | 4.25 | 4.07 | 3.57 | 3.17 | 3.76 |
| EAI 3600 | 4.14 | 4.20 | 3.85 | 3.53 | 3.93 |
| DPSB 8 | 3.90 | 3.56 | 3.54 | 3.37 | 3.59 |
| Hill | 4.16 | 4.09 | 3.75 | 3.40 | 3.85 |
| DPSB 19 | 3.84 | 3.81 | 3.22 | 3.08 | 3.49 |
| Mean | 4.02 | 3.91 | 3.57 | 3.31 | |
| *p*-value | 0.015 | | | | |
| SED | 0.121 | | | | |
| CV (%) | 4.0 | | | | |

SED = ± Standard error of difference of means; CV = Coefficient of variation FC = Field capacity.

Table 3.15 Effect of soil moisture regimes and cultivars on soybean pod length (cm) during 2018 season

| Soil moisture (FC %) | Pod length (cm) |
|---|---|
| 80 | 4.30 |
| 60 | 4.05 |
| 40 | 3.65 |
| 20 | 2.88 |
| *p*-value | < 0.001 |
| $HSD_{(0.05)}$ | 0.149 |
| CV (%) | 6.0 |
| Variety | |
| Gazelle | 3.66 |
| Nyala | 3.74 |
| EAI 3600 | 4.06 |
| DPSB 8 | 3.46 |
| Hill | 3.77 |
| DPSB 19 | 3.64 |
| *p*-value | < 0.001 |
| $HSD_{(0.05)}$ | 0.183 |
| CV (%) | 6.0 |

HSD = Tukey's honestly significant difference; CV = Coefficient of variation; FC = Field capacity.

***Seed weight and seed size***

Significant interaction effect of soil moisture regimes and soybean cultivars on seed weight was observed both in 2017 ($p < 0.001$) and 2018 ($p < 0.05$) seasons (Table 3.16). In either season, the interactive effect of soil moisture regimes and cultivars had more pronounced influence at the highest soil moisture regime of 80% FC than at lower ones. While interaction of soil moisture regimes and cultivars had a positive and significant ($p$ < 0.001) effect on soybean seed size in 2017, seed size was significantly ($p$ < 0.001) influenced by independent effects of soil moisture regimes and cultivars in 2018 season (Table 3.16). During 2018 season, 86.3% of soybean seeds at 80% FC were greater than 5 mm but less than 8 mm in diameter. Cultivars Gazelle (89.7%), Nyala (87.29%) and DPSB 19 (80.52%) had more seeds greater than 5 mm in diameter compared to other cultivars.

Table 3.16 Effect of soil moisture regimes and cultivars on seed weight (g) and seed size of soybeans during 2017 and 2018 seasons

| Soil moisture (FC %) | Cultivar | 2017 | | 2018 | |
|---|---|---|---|---|---|
| | | 10 seed weight (g) | Seed size >5 mm (%) | 10 seed weight (g) | Seed size > 5mm (%) |
| 80 | Gazelle | 1.23 | 80.4 | 1.48 | 99.5 |
| | Nyala | 1.33 | 90.5 | 1.73 | 98.4 |
| | EAI 3600 | 1.08 | 49.4 | 1.25 | 86.2 |
| | DPSB 8 | 1.16 | 46.2 | 1.19 | 67.2 |
| | Hill | 1.01 | 44.6 | 1.23 | 82.6 |
| | DPSB 19 | 1.25 | 74.7 | 1.19 | 83.6 |
| 60 | Gazelle | 1.25 | 93.0 | 1.54 | 99.6 |
| | Nyala | 1.33 | 83.4 | 1.64 | 95.3 |
| | EAI 3600 | 0.97 | 45.4 | 1.40 | 85.3 |
| | DPSB 8 | 1.00 | 38.6 | 0.99 | 50.9 |
| | Hill | 1.01 | 44.5 | 1.08 | 72.2 |
| | DPSB 19 | 1.04 | 55.0 | 1.25 | 87.7 |
| 40 | Gazelle | 1.11 | 88.9 | 1.40 | 87.9 |
| | Nyala | 1.06 | 58.9 | 1.53 | 82.4 |
| | EAI 3600 | 0.88 | 29.9 | 1.27 | 83.3 |
| | DPSB 8 | 0.72 | 15.7 | 0.83 | 39.0 |
| | Hill | 0.84 | 36.3 | 1.07 | 82.6 |
| | DPSB 19 | 1.01 | 55.1 | 1.06 | 77.8 |
| 20 | Gazelle | 0.60 | 36.5 | 1.10 | 71.8 |
| | Nyala | 1.19 | 27.7 | 1.09 | 73.1 |
| | EAI 3600 | 0.72 | 21.1 | 0.90 | 48.4 |
| | DPSB 8 | 0.53 | 6.6 | 0.44 | 7.0 |
| | Hill | 0.68 | 29.0 | 0.83 | 55.2 |
| | DPSB 19 | 0.77 | 26.4 | 0.98 | 72.9 |
| *p*-value | | < 0.001 | 0.001 | 0.041 | 0.114 |
| SED | | 0.069 | 8.54 | 0.099 | 9.19 |
| CV (%) | | 8.6 | 20.5 | 10.2 | 15.1 |

SED = ± Standard error of difference of means; CV = Coefficient of variation. Seed > 5 mm % = Percent soybean seeds greater than 5 mm but less than 8 mm in diameter. FC = Field capacity.

***Grain yield***

Significant ($p$ < 0.001) interactive effects of soil moisture regimes and cultivars on soybean grain yield was observed in both 2017 and 2018 seasons (Table 3.17). Grain yield of all soybean cultivars significantly increased at higher soil moisture regimes of 80% with a progressive reduction at lower soil moisture levels. Cultivar DPSB 8 had highest mean reduction (93.62%) in grain yield between 80% FC and 20% FC.

Table 3.17 Effect of soil moisture regimes and soybean cultivars on soybean grain yield during 2017 and 2018 seasons

| | | Grain yield (g plant$^{-1}$) | |
|---|---|---|---|
| Soil moisture (FC %) | Cultivar | 2017 | 2018 |
| | Gazelle | 3.01 | 6.85 |
| | Nyala | 2.44 | 7.02 |
| | EAI 3600 | 3.00 | 6.13 |
| 80 | DPSB 8 | 3.79 | 7.12 |
| | Hill | 3.53 | 4.53 |
| | DPSB 19 | 6.16 | 7.19 |
| | Gazelle | 2.89 | 3.85 |
| | Nyala | 1.98 | 3.91 |
| | EAI 3600 | 2.82 | 3.86 |
| 60 | DPSB 8 | 1.79 | 4.01 |
| | Hill | 2.42 | 2.62 |
| | DPSB 19 | 3.85 | 3.95 |
| | Gazelle | 1.50 | 1.68 |
| | Nyala | 1.49 | 1.37 |
| | EAI 3600 | 1.63 | 1.64 |
| 40 | DPSB 8 | 0.54 | 1.24 |
| | Hill | 1.25 | 1.29 |
| | DPSB 19 | 1.64 | 1.45 |
| | Gazelle | 0.59 | 0.50 |
| | Nyala | 0.99 | 0.52 |
| 20 | EAI 3600 | 1.03 | 0.73 |
| | DPSB 8 | 0.34 | 0.27 |
| | Hill | 0.94 | 0.69 |
| | DPSB 19 | 0.83 | 0.79 |
| *p*-value | | < 0.001 | < 0.001 |
| SED | | 0.267 | 0.265 |
| CV (%) | | 15.6 | 10.6 |

SED = ± Standard error of difference of means; CV = Coefficient of variation FC = Field capacity.

***Grain yield correlations***

Yield and yield components correlation results indicate that increases in seed weight, pod length, number of pods per node, number of pods per plant and number of seeds per pod positively increased soybean grain yield in both seasons. Number of aborted pods however negatively correlated with grain yield both in 2017 and 2018 seasons (Tables 3.18 & 3.19). Coefficients of determination ($r^2$) indicate that 36.81%, 30.91%, 62.09%, 89.17%, 29.69% of variations in soybean grain yield among different soil moisture regimes in 2017 may be attributed to differences in seed weight, pod length, number of pods per node, number of pods per plant and number of seeds per pod, respectively. On other hand, 28.64%, 56.12%, 83.67%, 92.70% and 53.24% of variations in soybean grain yield among different soil moisture regimes in 2018 may be attributed to differences in seed weight, pod length, number of pods per node, number of pods per plant and number of seeds per pod, respectively.

Table 3.18 Correlation of soybean grain yield with selected soybean yield components during 2017 season

| | Grain yield | Seed weight | Pod length | Pods aborted | Pods node$^{-1}$ | Pods plant$^{-1}$ | Seeds pod$^{-1}$ |
|---|---|---|---|---|---|---|---|
| Grain yield | - | - | - | - | - | - | - |
| Seed weight | 0.607*** (0.368) | - | - | - | - | - | - |
| Pod length | 0.556*** (0.309) | 0.442*** (0.195) | - | - | - | - | - |
| Pods abort | -0.346** (0.120) | -0.376** (0.141) | -0.475*** (0.226) | - | - | - | - |
| Pods node$^{-1}$ | 0.621*** (0.386) | 0.163ns (0.027) | 0.120ns (0.014) | -0.0461ns (0.0021) | - | - | - |
| Pods plant$^{-1}$ | 0.944*** (0.892) | 0.506*** (0.256) | 0.533*** (0.284) | -0.2667* (0.0711) | 0.645*** (0.416) | - | - |
| Seeds pod$^{-1}$ | 0.545*** (0.297) | 0.228ns (0.052) | 0.825*** (0.680) | -0.4448*** (0.1978) | 0.1751ns (0.0301) | 0.477*** (0.228) | - |

*, **, *** = significant at $p < 0.05$, $p < 0.01$, $p < 0.001$, respectively; ns = not significant. Figures in parentheses represent coefficient of determination, $r^2$

Table 3.19 Correlation of soybean grain yield with selected soybean yield components during 2018 season

| | Grain yield | Seed weight | Pod length | Pods aborted | Pods node$^{-1}$ | Pods plant$^{-1}$ | Seeds pod$^{-1}$ |
|---|---|---|---|---|---|---|---|
| Grain yield | - | - | - | - | - | - | - |
| Seed weight | 0.5352*** (0.2864) | - | - | - | - | - | - |
| Pod length | 0.7491*** (0.5612) | 0.5896*** (0.3476) | - | - | - | - | - |
| Pods abort | -0.3809*** (0.1451) | -0.5924*** (0.3509) | -0.4433*** (0.1965) | - | - | - | - |
| Pods node$^{-1}$ | 0.9158*** (0.8367) | 0.3487** (0.1216) | 0.6751*** (0.4558) | -0.3646** (0.1329) | - | - | - |
| Pods plant$^{-1}$ | 0.9628*** (0.9270) | 0.3848** (0.1189) | 0.6997*** (0.4896) | -0.3180** (0.1011) | 0.9389*** (0.8815) | - | - |
| Seeds pod$^{-1}$ | 0.7297*** (0.5324) | 0.3629** (0.1317) | 0.8393*** (0.7044) | 0.3606** (0.1300) | 0.7004*** (0.4906) | 0.7133*** (0.5088) | - |

**, *** = significant at $p < 0.01$, $p < 0.001$, respectively. Figures in parentheses represent coefficient of determination, $r^2$.

### 3.4.8. Effect of soil moisture regimes on grain quality

***Protein content***

Seed protein content was significantly ($p < 0.001$) influenced by soil moisture regimes during 2017 season. The highest protein content of 28.39% was attained at the highest soil moisture regime of 80% FC representing 18.0% increase over the lowest moisture level of 20% FC (Table 3.20). In 2018, protein content was significantly ($p < 0.01$) influenced by soil moisture regimes and cultivars. Increased moisture stress reduced seed protein content while cultivars DPSB 19 and DPSB 8 had highest and lowest protein contents of 30.14% and 26.88% respectively.

Table 3.20 Effect of soil moisture regimes and cultivars on soybean grain protein content during 2017 and 2018 seasons.

| | Grain protein content (%) | |
|---|---|---|
| Soil moisture (FC %) | 2017 | 2018 |
| 80 | 28.39 | 29.89 |
| 60 | 27.31 | 28.20 |
| 40 | 26.44 | 27.55 |
| 20 | 26.59 | 27.35 |
| *p*-value | < 0.001 | 0.010 |
| SED | 0.495 | 0.796 |
| CV (%) | 5.5 | 8.5 |
| Cultivar | | |
| Gazelle | 27.70 | 26.92 |
| Nyala | 26.55 | 28.38 |
| EAI 3600 | 27.85 | 28.95 |
| DPSB 8 | 27.71 | 26.88 |
| Hill | 26.85 | 28.21 |
| DPSB 19 | 26.45 | 30.14 |
| *p*-value | 0.068 | 0.014 |
| SED | 0.606 | 0.975 |
| CV (%) | 5.5 | 8.5 |

SED = ± Standard error of difference of means; CV = Coefficient of variation; FC = Field capacity.

### 3.5 Discussion

**Effects of moisture stress on shoot growth**

Results have shown that soil moisture stress retarded shoot growth by reducing soybean plant height, internode length, canopy diameter, number of branches per plant, stem diameter, number of leaves per plant, leaf area, leaf expansion rate and leaf biomass. Inhibitory effects of water stress on soybean plant growth and development have previously been reported by Chaves *et al*. (2002) Atti *et al*. (2004) and Amira and Qados (2014).

In this study, moisture stress suppressed photosynthetic rate which might have led to a reduction in production, transportation and assimilation of photosynthates required for plant growth. Reduced root length and root volume under moisture stress might have contributed to limited uptake of essential mineral nutrients required for plant growth. Limitations in the uptake of mineral nutrients, and in production, transportation and assimilation of photosynthates reduces cell division and elongation which leads to reduced shoot growth (Hossain *et al*., 2014). Declines in plant height at reduced soil moisture levels may be linked to decreases in cell elongation emanating from the inhibitory effect of water shortage on growth promoting hormones (Taiz and Zeiger, 2006). A reduction in internode length at lower moisture regimes led to a related reduction in soybean plant height. Similarly, reduced leaf expansion rate at limited soil moisture regimes gave a corresponding reduction on soybean total leaf area which, coupled with lower number of leaves per plant, translated into lower leaf biomass at lower moisture regimes. Reduction in leaf area under soil moisture stress as portrayed in this study is not surprising as it is considered a prominent morphological response plants employ to minimize adverse effects of moisture stress (Catuchi *et al*., 2011). At lower soil moisture regimes soybean plants tended to develop a vertical leaf orientation (paraheliotropism) as mechanism to limit heat load and in the process minimize water loss through transpiration (Pastenes *et al*., 2004). Reduced shoot growth at lower soil moisture regimes may also be attributed to a secondary effect of increased production of abscisic acid and reactive oxygen species (ROS) which inhibit growth and causes oxidative damage and death of plant cells (Azadeh *et al*., 2014).

Overall, indeterminate cultivars had taller plants (DPSB 8), longer internode length (DPSB 19), highest number of leaves (Gazelle) and larger leaf area (DPSB 8) compared to determinate cultivars. On the other hand, determinate cultivars had bushier canopy (Nyala), more number of branches and thicker stems (Hill) relative to indeterminate cultivars. Unlike determinate growth habit which has terminal leaf growth upon flowering, indeterminate growth habit is characterized by continuous production of leaves upon flowering which leads to more leaves per plant, larger leaf area, taller plants and increased internode length (Tanaka and Shiraiwa, 2009) which concurs with findings of this study.

**Effect of soil moisture stress on plant water status**

Relative water content measures the dehydration status of plants relative to the maximum water holding capacity at full turgidity. A cultivar with the ability to minimize stress by maintaining turgid leaves under limited soil moisture conditions may be considered drought tolerant. Results of the study have shown that soil moisture stress reduced leaf relative water content with cultivars DPSB 8, Nyala, Gazelle and DPSB 19 maintaining higher percent leaf relative water contents than cultivars EAI 3600 and Hill. This signifies moisture stress tolerance potential of these cultivars. Previous studies on soybean also demonstrated that soil moisture stress reduces leaf relative water content with a pronounced effect on moisture stress susceptible cultivars (Amira and Qados, 2014; Hossain *et al.,* 2014). Under limited soil moisture conditions, there is lower cell water potential which may lead to reduced leaf relative water content in plants grown under such conditions (Rahman *et al*., 2004; Cheruiyot *et al*., 2010., Hossain *et al*., 2015). In drought tolerant soybean cultivars, high leaf relative water content is maintained by the increased expression of P5CS gene resulting in increased biosynthesis of proline which helps in cell stabilization and maintenance of cell turgidity (Hayat *et al.*, 2012).

**Effect of moisture stress on chlorophyll content and leaf gas exchange**

Chlorophyll ‘a’ is the principal photosynthesis pigment that interacts directly in the light requiring processes of photosynthesis. Chlorophyll ‘b’, on the other hand, is an accessory photosynthetic pigment and it acts indirectly in the photosynthetic process by transferring light it absorbs to chlorophyll ‘a’. A combination of chlorophylls ‘a’ and ‘b’ constitute total chlorophyll content in plant leaves (Scheer, 1991). This study has shown that chlorophyll ‘a’ and total chlorophyll content of soybean leaves increased with increased soil moisture stress in both seasons. Higher soil moisture level increased chlorophyll ‘b’ content during 2017 season while chlorophyll ‘b’ content was not significantly responsive to different soil moisture levels during 2018 season. There was no obvious effect of soybean cultivars on chlorophyll content. In 2017 season, chlorophylls ‘a’ and ‘b’ including total chlorophyll concentration varied with soybean cultivars used. In 2018, however, all chlorophyll components were not significantly influenced by soybean cultivars. Contradicting results on effect of soil moisture stress on leaf chlorophyll content have been reported from previous studies. Significant decreases in chlorophyll ‘a’, ‘b’ and total chlorophyll content in leaves of soybean plants grown under drought stress were reported by Amira and Qados, (2014); Atti *et al*. (2014) and Mannan *et al*. (2016). Nonetheless, a study on maize by Rahman *et al.* (2004) indicated an increase in total chlorophyll and carotene contents with increase in water stress, with maize cultivars showing an inverse relationship between Chlorophylls ‘a’ and ‘b’. High chlorophyll content due to reduced drip irrigation frequency was also reported by Muhumed *et al*. (2014) in a study with maize.

Higher chlorophyll contents at increased soil moisture levels as reported from studies by Amira and Qados (2014), Atti *et al*. (2004) and Mannan *et al*. (2016) were attributed to application of nitrogen fertilizers which was not the case with this study. Adequate soil moisture levels in those studies meant efficient utilization of applied nitrogen fertilizer by plants grown at optimum soil moisture level which was not the case with plants grown at lower soil moisture levels where plants could not effectively benefit from applied nitrogen fertilizers due to moisture limitation to facilitate dissolution and uptake of nitrates. Maintaining high soil moisture regimes in this study required frequent application of water which might have led to leaching of nutrients from growth medium. This might have deprived soybean plants of the required nitrogen to sustain high chlorophyll levels. Reduced nitrogen contents in maize leaves and roots as a result of increased irrigation frequencies were reported by Muhumed *et al*. (2014).

Increased levels of stomata conductance, sub-stomatal carbon dioxide concentration and photosynthetic rate were attained at highest soil moisture regime of 80% FC. Stomatal resistance was highest at lower soil moisture regimes with varied responses from cultivars at different plant growth stages. Rate of photosynthesis was positively correlated with sub-stomatal carbon dioxide concentration. These results are in agreement with observations by Atti *et al*. (2004), Makbul *et al.* (2011), Hossain *et al*. (2015) and Chowdhury *et al*. (2016) who reported reductions in stomata conductance, sub-stomatal carbon dioxide concentration and rate of photosynthesis due to moisture stress in soybean plants grown under greenhouse conditions or related structures. Increased stomata resistance at lower soil moisture levels was reported by Kimurto (2008) in a study with bread wheat. Indeterminate varieties DPSB 19 and DPSB 8 had higher stomata conductance at lower soil moisture regimes compared to determinate varieties.

Plants close stomata at limited soil moisture levels to prevent excessive water loss to the environment which leads to reduction in stomata conductance (Catuchi *et al.,* 2011). Results of this study have shown that leaf relative water content was reduced at lower soil moisture regimes which also led to reduction in stomata conductance. Higher stomata conductance amongst indeterminate cultivars may be associated with increased number of stomata per unit area in indeterminate cultivars compared to soybean varieties with determinate growth habit (Tanaka and Shiraiwa, 2009). Considering that stomata conductance indicates a degree of exchange of carbon dioxide and water vapour between ambient and inner leaf, reduced stomata conductance due to stomata closure could have led to minimal diffusion of carbon dioxide from the atmosphere to plant cells leading to low concentrations of sub-stomatal carbon dioxide. It has been observed from this study that photosynthetic rate was strongly correlated with sub-stomatal carbon dioxide concentrations which implies that lower photosynthetic rate at lower soil moisture regimes could have been a result of reduced sub-stomatal carbon dioxide diffusion to carboxylation site of ribulose 1,5 bisphosphate carboxylase oxygenase (Rubisco). Moisture stress also reduces photosynthesis metabolites and enzyme activity translating into reduced rate of photosynthesis (Lisar *et al.,* 2012). Furthermore, reductions in photosynthesis at lower soil moisture regimes might also have been caused by decreases in leaf area and associated reduction in carbohydrate production as energy source for optimal photosynthesis to take place. This concurs with an observation by Makbul *et al.* (2011) who also linked reduced photosynthesis rate under moisture stress to decline in in leaf size, damaged photosynthetic apparatus and diminishing activities of Calvin cycle enzymes.

**Effect of moisture stress on root growth**

Roots play an important role in plant survival under moisture stress via a combination of morphological, osmotic and cell wall adaptations (Wu and Cosgrove, 2002). Results of the study have indicated that root surface area, root diameter, root length, root volume and root biomass were all reduced under moisture stress. These root characteristics varied with soybean cultivars but growth habit seemed to have non-significant influence on root surface area, root diameter, root length, root biomass, number of nodules per plant and nodule efficiency. Visual observations on root architecture showed a uniform root density across the root profile at 80% FC compared to roots under stress which had a higher root concentration at upper root profile as opposed to lower profile. These findings are in agreement with observations by Sartori *et al.*

(2016) who reported an increase in soybean root length, root diameter, root surface area and root volume in irrigated soybean plants compared to non- irrigated plants. While results of this study have shown that root biomass was significantly affected by moisture stress, Machado *et al*. (2017) reported that root dry matter accumulation amongst determinate and indeterminate soybean cultivar was not affected by moisture stress. Unlike results of this study which have indicated reduced root diameter at lower moisture levels, Foloni *et al.* (2006) reported increased root diameter at lower soil moisture levels as a result of increased force exerted in the process of stretching root meristem cell to penetrate compacted soil. Studies on wheat by Saidi *et al.* (2010) indicated that moisture stress did not have significant effect on wheat root length unlike root surface area which was significantly reduced at lower moisture levels. Number of soybean nodules per plant, nodule biomass and efficiency of nodules to fix nitrogen were all significantly dependent on available soil moisture. Increases in number of soybean nodules per plant, nodule efficiency and nodule biomass at minimal moisture stress were reported by Streeter (2003) and Madhu and Hartfield (2015).

Masoumi *et al*. (2014) attributed reduced root length at low soil moisture levels to inadequate allocation of photosynthates to root system. Reduced root growth at lower soil moisture regimes may also arise from suppressed division, elongation and expansion of root cells coupled with increased root penetration resistance offered by drier soil (Bengough *et al*., 2005). Arrese-Igor *et al*. (2011) and Kunert *et al*. (2016) indicated that exposure of soybean roots to moisture stress impairs nitrogenase activity caused by either a compromised supply of photosynthates to nodules to drive symbiotic nitrogen fixation, breakdown of oxygen diffusion barrier or loss of leghemoglobin. Moisture deficit promotes accumulation of ureides in soybean shoot system causing a feedback reduction in the efficiency with which root nodules fix nitrogen (Purcell *et al*., 2000; Kunert *et al*., 2016). These observations are in line with findings of this study which have shown that moisture stress reduced photosynthesis rate which might have led to limited supply of carbohydrates for root growth leading to reductions in root sizes, number of nodules, nodule efficiency and a related reduction in nodule biomass.

**Effect of moisture stress on dry matter partitioning**

Shoot to root ratio decreased with increased soil moisture stress amongst soybean plants during both seasons. Much as shoot to root ratio varied with type of cultivar used, no cultivar had a distinct advantage over others in dry matter partitioning to shoot and root systems. Previous studies under growth chambers and greenhouse conditions have reported significant reductions in shoot to root ratio at lower soil moisture levels (Said *et al*., 2010; Dos Santos *et al*., 2018) which are in agreement with findings of this study. Soil moisture limitation reduces shoot growth and increases allocation of dry matter to roots for optimization of root growth resulting in reduced shoot to root ratio (Kage *et al*., 2004). Specific leaf mass increased with an increase in soil moisture stress which implies that soybean leaves were thicker at lower soil moisture levels. Cultivar DPSB 8 had the lowest specific leaf mass in both seasons indicating the likelihood of the cultivar being rapidly dehydrated from increased transpiration due to thinner leaves should soil moisture become limiting. Thicker leaves at reduced moisture could be viewed as an adaptive strategy by plants to limit water loss via transpiration. Thicker leaves increase the length of the pathway (apoplast length) through which water in plants has to move before it reaches leaf surfaces for evaporation to take place which in the long run reduces transpiration rate (Brodribb *et al*., 2007). An inverse relationship between leaf thickness and transpiration in rice was reported by Giuliani *et al.* (2013).

**Effect of moisture stress on reproductive growth**

Flower induction in soybean plants was attained earlier at higher soil moisture regimes in both seasons. Cultivars DPSB19 and EAI 3600 were the earliest to flower compared to cultivars Gazelle, Nyala, Hill and DPSB 8. The period between pod set and pod maturity was significantly reduced with increased soil moisture stress. Cultivar DPSB 8 took longer time to mature compared to all other cultivars. In a study with Haricot beans, Yunusa *et al*. (2014) reported a non–significant effect of irrigation levels on days to flowering but number of days to pod maturity were enhanced with reduced soil moisture levels. El-Aal *et al*. (2011) and Tayel and Sabreen (2011) indicated that increased soil moisture levels delayed flowering in common beans and faba beans respectively. Higher moisture regimes might also have led to high plant water status which led to a continued vegetative growth and delayed attainment of physiological maturity of the pods (El-Aal, *et al*., 2011). Accelerated pod maturity at reduced soil moisture regimes as is the case in this study may be attributed to increased leaf senescence which might have deprived soybean pods of the required photosynthates to sustain prolonged pod development.

**Effect of moisture stress on yield components and yield**

During the two seasons the study was conducted, soil moisture stress reduced number of pods per plant, number of pods per node, number of seeds per pod, pod length, seed weight, grain size, yield and seed protein content. Number of aborted pods per plant increased at reduced soil moisture regimes. Soybean grain yield was positively correlated with seed weight, pod length, number of pods per node, number of pods per plant and number of seeds per pod during both seasons. Number of aborted pods per plant was negatively correlated with grain yield. Cultivar DPSB 19 had the highest number of pods per plant, number of pods per node and grain yield in both seasons. Cultivar EAI 3600 registered highest number of seeds per pod and longest pod lengths while the highest number of aborted pods per plant was registered by cultivar Hill in both years. Cultivar Nyala had largest grain size which also led the same cultivar having more grains greater than 5 mm in diameter in either season. Previous studies by Dos Santos *et al*. (2010), Amira and Qados (2014), Madhu and Hartfield (2015) reported reductions in soybean number of pods per plant, number of pods per node, number of seeds per pod, pod length, seed weight, seed size, grain yield and seed protein content in response to reduced soil moisture levels under greenhouse conditions.

It has been shown from this study that soil moisture stress reduced soybean plant height, number of branches, plant canopy, number of leaves, leaf area and sub-stomatal carbon dioxide concentration which might have contributed to a reduction in photosynthesis and the supply of carbon assimilates for increased soybean seed development. Increased pod abortions at reduced soil moisture levels may also explain why soybean yield was significantly decreased at lower soil moisture regimes. Retarded root system development at low soil moisture regimes also meant that there was limited uptake of growth nutrients from the growth medium to support pod development and maturity. As regards seed protein content, increased numbers of effective nodules at higher soil moisture regimes might have led to increased biological nitrogen fixation. Higher biological nitrogen fixation means increased concentrations of nitrogen in seeds translating into significantly higher protein contents in soybean grains. Number of days from pod setting to pod maturity was significantly lower at reduced soil moisture levels compared to higher soil moisture levels. This accelerated drying of soybean grains at lower soil moisture regimes which might have also contributed to reduction in grain size and protein content.

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## CHAPTER FOUR

## EFFECT OF SOIL MOISTURE REGIMES ON CARBON DIOXIDE ASSIMILATION, GROWTH AND YIELD OF SELECTED SOYBEAN CULTIVARS UNDER FIELD CONDITIONS

**Abstract**

Climate change due to global warming is contributing to upward shifts in temperatures and reductions in rainfall leading to increased incidences of soil moisture stress. A study to determine effect of soil moisture regimes on shoot growth and carbon dioxide assimilation in soybean [*Glycine max* (L.) Merrill] was conducted under field conditions at Kenya Agricultural and Livestock Research Organization in Njoro, Nakuru County. The experiment was laid out in a randomized complete block design (RCBD) using a split plot treatment arrangement and was replicated three times. Treatments of soil moisture regimes which were evaluated at 100, 75, 50 and 25% of crop water requirement (CWR) formed main plot treatments while cultivars Gazelle, Nyala, EAI 3600, DPSB 8, Hill and DPSB 19 formed sub plot treatments. Collected data were subjected to analysis of variance (ANOVA) using Linear Mixed Model in GENSTAT. Soil moisture stress reduced soybean shoot growth by suppressing plant height, number of branches, stem diameter, leaf area and canopy development. Photosynthetically active radiation, leaf chlorophyll content and sub-stomatal $CO_2$ concentration declined ($p < 0.05$) with increasing soil moisture limitation. Soil moisture regime at 25% CWR reduced ($p < 0.05$) photosynthetic rate and stomata conductance by 86.45% and 36.64%, respectively, compared to optimal CWR of 100%. Leaf temperature was significantly ($p < 0.001$) increased with increasing soil moisture stress. Soybean grain yield at 25% CWR was 58.87% lower than yields obtained at 100% CWR. Cultivars Nyala and DPSB 19 gave highest soybean yields during 2018 and 2019 respectively. Cultivar DPSB 19 had both highest stomata conductance and lowest transpiration rates at reduced CWR of 25% indicating drought tolerance potential of the cultivar and therefore recommended for production under soil moisture limiting conditions.

### 4.1 Introduction

Soybean [*Glycine max* (L) Merrill] is an important legume crop as it contributes 29% of global edible oil and 70% of protein meal consumption (Soystats, 2016). Soybean diets help reduce risks of breast cancer, cardiovascular diseases, osteoporosis, diabetes and obesity (Kirnak *et al*., 2010). Soybean is a good source of biofuel (Qi and Lee, 2014), and helps improve soil fertility through biological nitrogen fixation (Layzell, 1990). The potential of soybean to significantly contribute to food and income security is however constrained by low yields. Low soybean yields are attributed to several biotic and abiotic constraints including soil moisture stress (Sentelhas *et al.,* 2015). In soybeans, soil moisture stress may interfere with seed germination, uptake of mineral nutrients, plant water relations, photosynthetic rates and partitioning of photoassimilates leading to low grain yields (Pedersen and Lauer, 2004). Mangena (2018) reported that soil moisture stress may also lead to increased incidences of pests and diseases such as soybean cyst nematodes (*Heterodera glycine*) and phytophthora root and stem rots (*Phytophthora sojae*).

Many African countries have, in the recent past, experienced severe effects of droughts which have caused food crises in countries such as Ethiopia, Somalia and Kenya (Managena, 2018). Soil moisture stress arising from such recurring droughts due to climate change has become a key limiting factor to crop productivity and ultimately to attainment of food security (Lesk *et al.,* 2016). Reduction in quantities of rainfall and associated unpredictable rainfall patterns are catalysts of reduced crop yields due to negative impacts of soil moisture stress on morphological, physiological and biochemical processes in crops (Barnabas *et al*., 2008). Considering that reduction in rainfall is expected to continue due to global warming (Rosenzweig and Colls, 2005), it is necessary to continuously understand morphological and physiological responses in plants which may act as a basis for generation of mitigation measures to limit adverse effects of soil moisture limitation on plant growth and yields. Key in soil moisture stress mitigation is the identification of crop varieties that can tolerate negative effects of soil moisture limitation. In order to foster attainment of food self-sufficiency at household level and limit huge importations of soybean in the country, the Kenyan Government is promoting soybean production through use of high yielding cultivars to meet food requirements of growing population. Limited information is however available on the performance of current soybean cultivars under soil moisture stress. It is with this understanding that a study was undertaken to determine effect of varying soil moisture regimes on carbon dioxide assimilation, growth and yield of selected soybean cultivars under field conditions in Kenya.

### 4.1.1 Effect of soil moisture stress on shoot growth

A study in Turkey by Candoğan and Yazgan (2015) indicated that water deficit imposed at flowering and pod filling stages of soybean decreased leaf area, leaf area index (LAI) and plant height of soybean plants. Iqbal *et al*. (2018) reported reductions in soybean plant height, stem diameter, number of branches and nodes per plant in response to water deficit. The level of response varied with cultivars used. Studying effect of drip irrigation intensity on soybean yield and quality, Kirnak *et al.* (2010) indicated that water stress suppressed vegetative growth of soybean plants by reducing number of branches per plant, leaf production, stem thickness and number of nodes per plant. Reductions in leaf production led to related reductions in leaf area and LAI. Similar results were reported by Karam *et al*. (2005) and Maleki *et al*. (2013) who indicated reductions in plant height, LAI of soybean plants due to soil water limitation.

Moisture stress studies with common beans (Emam *et al*., 2010) and faba beans (Tayel and Sabreen, 2011) showed reductions in plant height, number of leaves and leaf area of the crops due to water stress. A study in Iran by Dahmardeh *et al.* (2015) reported that water stress reduced plant height of forage sorghum (*Sorghum bicolor* (L.) Moench).

### 4.1.2 Effect of soil moisture stress on reproductive growth

Jha *et al*. (2018) reported delayed flowering and extended periods of pod filling and physiological maturity of soybean plants grown at optimal soil moisture levels than under soil moisture limitation. A study with common beans by Rezene *et al*. (2013) reported that soil moisture stress did not have a significant influence on number of days to attain 50% flowering. Soil moisture stress however hastened pod maturity of common bean plants. Results of the study also indicated that days to flowering and pod maturity varied with type of bean genotype used. Similarly, results from a study by Ntukamazina *et al.* (2017) showed accelerated flowering and pod maturity of bush and climbing beans under soil moisture stress. Number of days to flowering and pod maturity were nonetheless not significantly dependent on growth habit of common bean cultivars used.

### 4.1.3 Effect of soil moisture stress on leaf gaseous exchange

In a study to determine the response of soybean to water stress and supplementary irrigation, Jha *et al.* (2018) reported reductions in photosynthetic and transpiration rates, stomata conductance and sub-stomatal carbon dioxide concentration in soybean plants grown under water stress compared to those grown under supplementary irrigation. Water stress however increased leaf temperature of soybean plants. In china, Zhang *et al*. (2016) reported reduced photosynthetic and transpiration rates, stomata conductance and leaf relative water content (LRWC) in soybean plants in response to water deficit under high and low light intensity. Water deficit increased sub-stomatal carbon dioxide concentration, chlorophyll 'a', chlorophyll 'b' and total chlorophyll contents of soybean leaves. Studying effects of drought stress on physiological responses of soybean, Kirnak *et al.* (2010), Krivosudska and Filova (2013) and Sepanlo *et al*. (2014) reported decreased LRWC and chlorophyll contents in soybean plants grown under soil moisture limitation compared to soybean plants grown either at optimal soil moisture levels or under supplementary irrigation. Nonetheless, Silvente *et al*. (2012) indicated that soil moisture stress did not have significant effect on chlorophyll contents of drought tolerant and sensitive soybean cultivars.

Moisture stress study with faba beans (*Vicia faba* L.) by Girma and Haile (2014) indicated that supplementary irrigation at anthesis stage significantly improved transpiration rate, internal carbon dioxide concentration, stomata conductance and leaf temperature whereas supplementary irrigation did not have significant effect on photosynthetic rate and chlorophyll fluorescence. Types of faba bean cultivars used did not have a significant influence on studied physiological parameters. Similarly, Mathobo *et al*. (2017) reported reduced photosynthetic and transpiration rates, intercellular carbon dioxide concentration, stomata conductance and leaf chlorophyll content of dry bean (*Phaseolus vulgaris* L.) in response to drought stress in South Africa. A study with maize (*Zea mays*) by Parthasarathi *et al*. (2012) and with wheat (*Triticum aestivum*) by Yordanov *et al*. (2001) reported reductions in photosynthetic and transpiration rates, sub-stomatal carbon dioxide concentration, stomata conductance and chlorophyll content of the crops at lower soil moisture levels.

### 4.1.4 Effect of soil moisture stress on yield and yield components

A study on quality and yield responses of soybean to drought stress in sub-humid environment of Western Turkey (Demirtas *et al.*, 2010) indicated that drought stress reduced number of pods per plant, seeds per plant, 1000 seed weight, grain yield and protein content of soybean. Ghassemi-Golezani and Lotfi (2012) reported that water stress imposed at reproductive stage of soybean reduced number of pods per plant, 100 seed weight and grain yield. Number of seeds per pod did not significantly differ amongst irrigation treatments. Studies in Lebanon (Karam *et al*., 2005), Northern Iran (Chafi and Gohari, 2013) and China (Iqbal *et al*., 2018) reported reductions in number of pods per plant, 100 seed weight, number of grains per plant and grain yield of soybean plants grown under soil moisture stress. Soil moisture limitation however increased protein content of soybean grains (Iqbal *et al*., 2018). Soil moisture studies with mung beans (Sadeghipour, 2008), common beans (Simsek *et al.*, 2011) and faba beans (Ghassemi-Golezani *et al*., 2009) showed reduced pod lengths, number of pods per plant, seed weight, pod and grain yields of the crops.

It is evident from the literature review that varied and often contradicting results exist on the response of soybean to soil moisture stress. Variations and contradictions in results may emanate from either differences in environmental conditions of the regions where the studies were conducted or from genetic differences of soybean cultivars used in the respective studies. This limits cross-utilization of production recommendations amongst regions and necessitates the need for localized studies to mitigate local crop production challenges. It has been found from the literature review that limited soil moisture stress studies have been conducted on soybean in Kenya in the recent past which makes the current study relevant to ascertain the response of soybean cultivars to soil moisture limitation and identify soil moisture stress tolerant cultivars for production in the country.

## 4.2 Materials and methods

### 4.2.1 Site description

The experiment was conducted under irrigation at Kenya Agricultural and Livestock Research Organization (KALRO) in Njoro (0º 20' S; 35º 56' E), which is at 2120 meters above sea level. The experiment was conducted over two seasons during months of November 2017 to March 2018 and from November 2018 to March 2019. Soils at the site are classified as *mollic andosols* in agro ecological zone III (Jaetzold *et al*., 2006).

### 4.2.2 Experimental design and treatments

The experiment was conducted using the randomized complete block design (RCBD) in a split plot arrangement with three replicates. Treatments of soil moisture regimes were evaluated at 100, 75, 50 and 25% of crop water requirement (CWR) and formed main plot treatments while cultivars; Gazelle, Nyala, EAI 3600, DPSB 8, Hill and DPSB 19, formed sub plot treatments. Gross plot sizes were 4.5 m long and 4 m wide (18 $m^2$) with an inter row spacing of 45 cm. Net plots were 2.25 m by 3 m (6.75 $m^2$) with inter row spacing of 45 cm. Moisture regimes treatments were separated by 2 m wide path. Growth habits and phenology of soybean varieties used in the study are as described in table 3.1 of experiment 1.

### 4.2.3 Planting and crop management

Planting of first season experiment was done on 8th November 2017 while second season experiment was planted on 6th November 2018. Soybean seeds were inoculated with BIOFIX *(Bradyrhizobium japonicum)* inoculant strain USD 110 from Mea Limited–Kenya at the rate of 10 g $kg^{-1}$ of seed prior to planting. Triple Super Phosphate and Muriate of Potash fertilizers were applied at the rates of 30 kg $P_2O_5$ $ha^{-1}$ and 30 kg $K_2O$ $ha^{-1}$ respectively as basal dressing fertilizers. Planting was done at inter and intra row spacing of 45 cm and 10 cm respectively.

### 4.2.4 Determination of crop water requirement and irrigation frequency

Crop water requirement ($ET_{crop}$) on daily basis was determined according to Savva and Frenken (2002) as follows:

$ET_c = K_c \times ET_o \times K_s$ Equation 4.1

Where:

$ET_c$ = Crop water requirement/crop evapotranspiration (mm/day)

Kc = crop factor

$ET_o$ = reference evapotranspiration (mm/day).

$K_s$ = coefficient for each irrigation treatment in the experiment

Reference crop evapotranspiration was determined using pan evaporation method (Savva and Frenken, 2002) as indicated below.

$ET_o = E_{pan} \times K_{pan}$ Equation 4.2

Where:

$ET_o$ = reference crop evapotranspiration (mm/day)

$E_{pan}$ = evaporation pan reading (mm/day)

$K_{pan}$ = pan coefficient (0.70 for class A pan)

For purposes of the study, weather data of 20 years (1997-2017) was used and was collected from Egerton University meteorological station. Crop factors ($K_c$) used at different stages of soybean growth stages as provided by FAO, (2012) were 0.35 for initial stage (0-25 days), 0.75 for crop development stage (26-60-days), 1.10 for mid-season stage (61-100 days) and 0.60 for late season stage (101-120 days). Crop water requirement on daily basis was translated into volume of water per unit area using the following equation (Brouwer and Heibloem, 1985).

1 mm = 1 litre (L)/$m^2$ Equation 4.3

Respective soil moisture regimes were initiated 30 days after planting and after depletion of soil moisture to 50% of field capacity (Chafi and Gohari, 2013). Irrigation frequency (IF) was determined using the following equation (Savva and Frenken, 2002).

$IF = SM_{ta} \times P \times RZD / ET_c$ Equation 4.4

Where:

IF = irrigation frequency (days)

$SM_{ta}$ = total available soil moisture [= Field capacity (FC) - Permanent wilting point (PWP) mm/m)

P = allowable depletion (0.5 for soybeans)

RZD = effective root zone depth (m)

$ET_c$ = crop water requirement (mm/day)

### 4.2.5 Data collection

**Determination of morphological parameters**

Plant height, canopy diameter and number of branches per plant were determined from five plants from each treatment per replicate. Plant height was measured using a measuring tape from the soil surface to the last node of soybean plant. Soybean plant canopy diameter was measured using a measuring tape on the widest part of plant shoot. Stem diameter was determined from five plants with measurements taken from the bottom, middle and top positions of soybean plant's primary stem using a 0-150 millimetre digital calliper (09070705763-Mars). Number of branches per plant was determined by making individual counts of branches arising from primary stem of soybean plant. Leaf area was determined at 50% poding stage of plant growth on one tagged plant per treatment. Leaf area was measured using manual method as described under section 3.3.5 of experiment 1.

**Determination of physiological parameters**

***Intercepted photosynthetically active radiation (IPAR)***

Intercepted photosynthetically active radiation (IPAR) was measured at 50% flowering stage using an AccuPar Ceptometer (LP-80 PAR/LAI Decagon Devices). Measurements were done above and below canopy of soybean plants. Calculation of percent IPAR used the following formula (Purcell, 2000).

$IPAR (\%) = [1-(PAR_b / PAR_a)] \times 100$ Equation 4.6

Where:

IPAR = intercepted photosynthetically active radiation (PAR); $PAR_a$ is PAR (µmol $m^{-2}$ $s^{-1}$) measured above soybean canopy and $PAR_b$ is PAR (µmol $m^{-2}$ $s^{-1}$) measured below soybean canopy.

***Transpiration rate and leaf temperature***

Transpiration rate and leaf temperature were determined at vegetative and flowering stages of soybean growth on a middle leaflet of a third trifoliate leaf from top of the plant. The parameters were measured between 12.00 - 14.00 hours during sunny days using a TPS-2 portable photosynthesis system (V2.02-PP systems Inc., USA).

Photosynthetic rate, sub-stomatal carbon dioxide concentration, leaf chlorophyll determination, stomata conductance and relative water content were determined as described under section 3.3.5 of experiment 1.

***Yield components and yield***

Number of pods per plant were determined from an average number of pods borne on 10 plants harvested per treatment. Pod length was measured using a 30 cm ruler on 20 pods randomly picked from harvested pods. Number of seeds per pod were determined by counting number of fully developed seeds from 20 pods randomly picked per treatment. The mean number of seeds from 20 pods for each treatment was taken as number of seeds per pod for that treatment. Seed weight was determined from weight of 100 seeds randomly selected from the treatments. Number of pods per node was determined from 10 plants per treatment at harvesting by counting number of pods per plant divided by number of pod- bearing nodes. Grain yield was obtained by harvesting plants from a net plot of individual treatments when 75% of pods were dry. Harvested pods were then threshed and grains separated. The obtained grains were sun dried to constant weight and yield adjusted to storage moisture level of 12% as described under section 3.3.5 of experiment 1.

## 4.3 Statistical analysis

Data obtained were checked for fulfilment of analysis of variance (ANOVA) assumption of normality by using Shapiro-Wilk normality test in Genstat release 18. Data that did not meet the aforesaid ANOVA assumption were subjected to log base 10 [log 10(x+c) ] transformation before analysis. Data were analysed using analysis of variance (ANOVA) using linear mixed model for split plot in GENSTAT (REML).

The following statistical model was used for data analysis.

$Y_{ijkm} = \mu + \alpha_i + ß_j + (\alpha\beta)_{ij} + \gamma_k + (\alpha\gamma)_{ik} + \theta_m + (\alpha\theta)_{im} + (\gamma\theta)_{km} + (\alpha\beta\theta)_{ijm} + (\alpha\gamma\theta)_{ikm} + \varepsilon_{ijkm}$

Where:

$Y_{ijkm}$ = observed response; $\mu$ = experimental mean; $\alpha_i$ = effect of season; $ß_j$ = block effect; $(\alpha\beta)_{ij}$ = main plot error; $\gamma_k$ = effect of soil moisture regimes; $(\alpha\gamma)_{ik}$ = interaction effect of season and moisture regimes; $\theta_m$ = effect of cultivar; $(\alpha\theta)_{im}$ = interaction effect of season and cultivar; $(\gamma\theta)_{km}$ = interaction effect of soil moisture regimes and cultivar; $(\alpha\beta\theta)_{ijm}$ = sub-plot error; $(\alpha\gamma\theta)_{ikm}$ = interaction effect of season, soil moisture regime and cultivar; $\varepsilon_{ijkm}$ = residual error randomly distributed with mean of zero. Statistically significant treatment means were separated using Least Significant Difference (LSD) test at 0.05 significance level.

## 4.4 Results

### 4.4.1 Effect of soil moisture regimes, cultivars and seasons on shoot growth

***Plant height***

Plant height was significantly affected by the interaction effects of soil moisture regimes and seasons ($p < 0.05$) and of cultivars and seasons ($p < 0.01$). Tallest soybean plants were obtained at 100% crop water requirement (CWR) during 2018 season while shortest plants were obtained at 25% CWR during 2019 season (Figure 4.1). All soybean cultivars had tallest plants during 2018 season with cultivars EAI 3600, DPSB 8 and Gazelle having relatively taller plants compared to other cultivars (Figure 4.2). Overall, there was 31.54% reduction in plant height at the lowest soil moisture regime of 25% CWR compared to plants grown at 100% CWR.

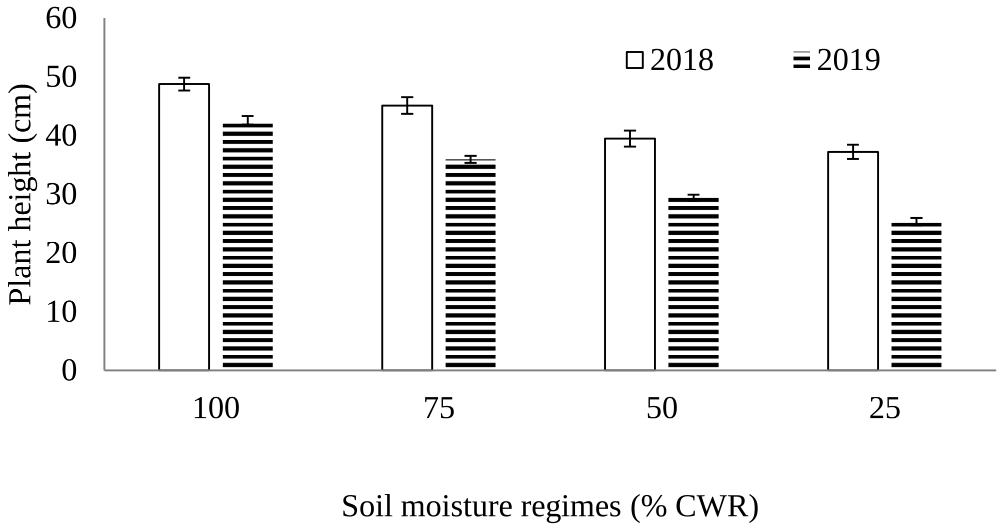


Figure 4.1 Effect of soil moisture regimes and seasons on soybean plant height at 50% podding stage Error bars represent ± standard error. Values significantly different at $p < 0.05$. CWR = Crop water requirement.

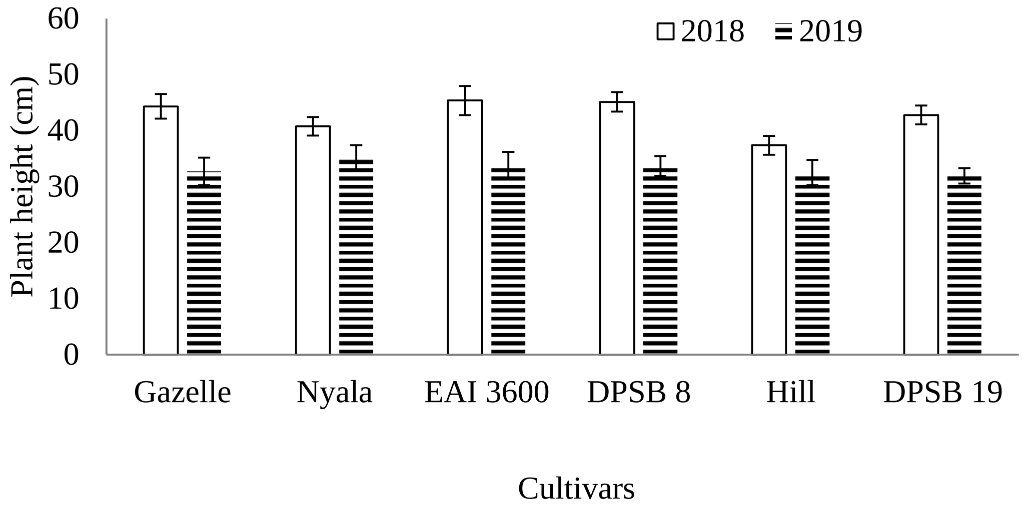


Figure 4.2 Effect of cultivars and seasons on soybean plant height at 50% podding stage. Error bars represent ± standard error. Values significantly different at $p < 0.01$.

***Internode length***

Internode length was significantly responsive to interaction effects of soil moisture regimes and seasons ($p < 0.001$) and of cultivars and seasons ($p < 0.01$). Shortest internode lengths were obtained at the most limiting soil moisture regime of 25% CWR in both seasons (Figure 4.3). Cultivar Gazelle had longest internode lengths during 2018 season which corresponded to 24.50% increase over the longest internode length registered during 2019 season by the same cultivar (Figure 4.4).

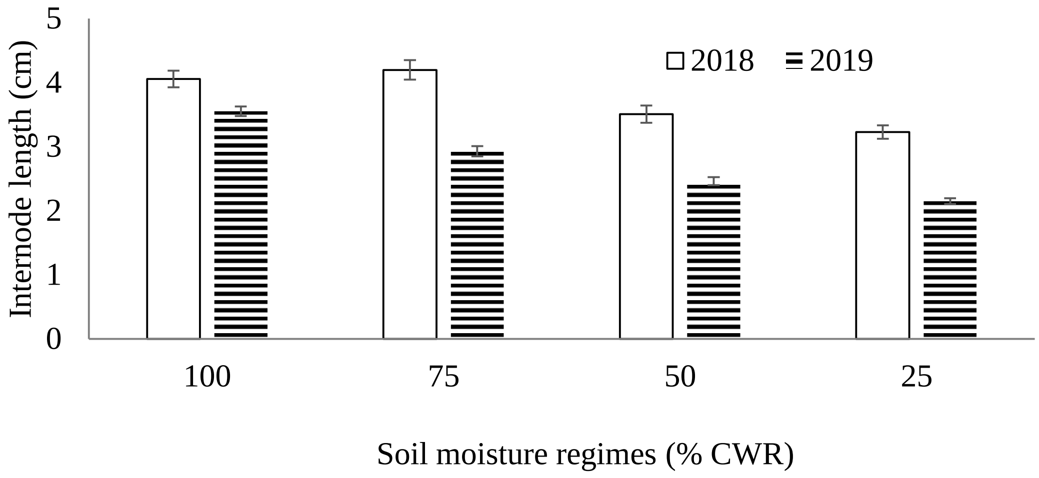


Figure 4.3 Effect of soil moisture regimes and seasons on internode length at 50% podding stage. Error bars represent ± standard error. Values significantly different at $p < 0.001$. CWR = Crop water requirement.

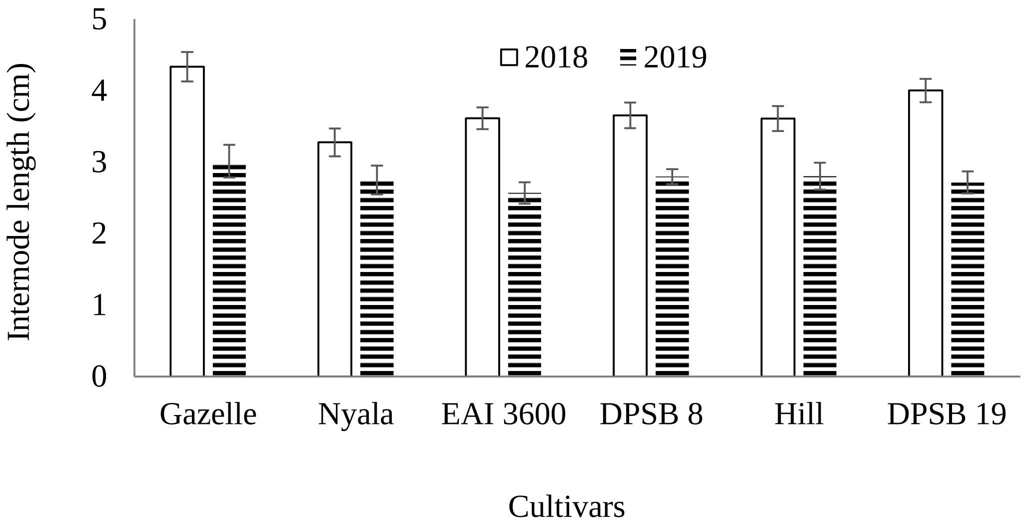


Figure 4.4 Effect of cultivars and seasons on soybean internode length at 50% podding stage. Error bars represent ± standard error. Values significantly different at $p < 0.01$.

***Plant canopy***

Results (Table 4.1) indicate that soybean canopy development significantly varied with interaction effects of soil moisture regimes and cultivars ($p < 0.05$) and of cultivars and seasons ($p < 0.001$). All soybean cultivars had wider canopy diameters at 100% CWR after which canopy diameters of all cultivars progressively decreased with an increase in soil moisture limitation. All soybean cultivars had wider canopy spread during 2018 season though cultivar DPSB 19 had the lowest canopy spread compared to other cultivars.

Table 4.1 Effect of soil moisture regimes, cultivar and season on soybean canopy diameter at 50% podding stage

| Canopy diameter (cm) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Cultivar | | | | | | |
| Soil Moisture Regimes (% CWR) | Gazelle | Nyala | EAI 3600 | DPSB 8 | Hill | DPSB 19 | Mean |
| 100 | 48.83 | 45.81 | 44.58 | 45.92 | 45.28 | 38.00 | 44.74 |
| 75 | 40.72 | 42.49 | 40.33 | 39.33 | 39.97 | 33.25 | 39.35 |
| 50 | 32.67 | 32.55 | 33.00 | 35.47 | 34.86 | 27.25 | 32.63 |
| 25 | 27.11 | 31.78 | 29.56 | 29.97 | 29.69 | 27.14 | 29.21 |
| Mean | 37.33 | 38.16 | 36.87 | 37.67 | 37.45 | 31.41 | |
| *p*-value | 0.018 | | | | | | |
| SED | 1.861 | | | | | | |
| CV (%) | 5.5 | | | | | | |
| **Seasons** | | | | | | | |
| 2018 | 42.00 | 41.88 | 41.46 | 43.62 | 43.54 | 32.75 | 40.88 |
| 2019 | 32.67 | 34.44 | 32.28 | 31.72 | 31.36 | 30.07 | 32.09 |
| *p*-value | <0.001 | | | | | | |
| SED | 1.321 | | | | | | |
| CV (%) | 9.80 | | | | | | |

CWR = crop water requirement; SED = ± Standard error of difference of means; CV = Coefficient of variation.

***Stem diameter***

Stem thickness was significantly dependent on interaction effects of soil moisture regimes and cultivars ($p < 0.05$), soil moisture regimes and seasons ($p < 0.01$) and of cultivars and seasons ($p < 0.001$). A general trend was that soybean cultivars had smallest stems at the lowest soil moisture regime of 25% CWR. Except for cultivars Hill and DPSB 19 which had thicker stems during 2019 season, all other cultivars had thicker stems during 2018 season (Table 4.2). Equally, thicker stems were attained at 100% CWR during 2018 season which was 8.0% more than stem thickness attained during 2019 season at the same soil moisture level (Table 4.3). Determinate soybean cultivars had thicker stems compared to indeterminate soybean cultivars.

Table 4.2 Effect of soil moisture regime, cultivar and season soybean on stem diameter (mm) at 50% podding stage

| Stem diameter (mm) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Cultivar | | | | | | |
| Soil Moisture Regimes (% CWR) | Gazelle | Nyala | EAI 3600 | DPSB 8 | Hill | DPSB 19 | Mean |
| 100 | 6.22 | 6.55 | 5.79 | 5.91 | 5.53 | 4.67 | 5.78 |
| 75 | 5.86 | 6.00 | 5.16 | 5.22 | 5.66 | 4.81 | 4.45 |
| 50 | 4.88 | 4.67 | 4.83 | 5.04 | 4.70 | 4.01 | 4.69 |
| 25 | 4.83 | 4.58 | 4.11 | 4.53 | 3.99 | 4.00 | 4.35 |
| Mean | 5.46 | 5.45 | 4.97 | 5.17 | 4.97 | 4.37 | |
| *p*-value | 0.024 | | | | | | |
| SED | 0.25 | | | | | | |
| CV (%) | 6.6 | | | | | | |
| **Seasons** | | | | | | | |
| 2018 | 5.48 | 5.53 | 5.18 | 5.45 | 4.93 | 3.98 | 5.09 |
| 2019 | 5.43 | 5.37 | 4.77 | 4.90 | 5.01 | 4.76 | 5.04 |
| *p*-value | <0.001 | | | | | | |
| SED | 0.19 | | | | | | |
| CV (%) | 9.1 | | | | | | |

CWR = crop water requirement; SED = ± Standard error of difference of means; CV = Coefficient of variation.

Table 4.3 Effect of soil moisture regime and season on stem diameter (mm) at 50% podding stage

| Stem diameter (mm) | | | |
|---|---|---|---|
| | Seasons | | |
| Soil moisture regimes (% CWR) | 2018 | 2019 | Mean |
| 100 | 6.02 | 5.54 | 5.78 |
| 75 | 5.53 | 5.37 | 5.45 |
| 50 | 4.77 | 4.61 | 4.69 |
| 25 | 4.53 | 4.16 | 4.35 |
| Mean | 5.21 | 4.92 | |
| *p*-value | 0.002 | | |
| SED | 0.115 | | |
| CV (%) | 9.1 | | |

CWR = crop water requirement; SED = ± Standard error of difference of means; CV = Coefficient of variation.

***Number of branches***

Number of branches borne from primary stem were significantly ($p < 0.05$) responsive to interaction effects of soil moisture regimes, cultivars and seasons (Table 4.4). Cultivars Hill and Gazelle had highest number of branches at 100% CWR during 2018 and 2019 seasons, respectively. Overall, increase in soil moisture stress negated formation of branches regardless of season and cultivar.

Table 4.4 Effect of soil moisture regime, cultivar and season on number of soybean branches at 50% podding stage

| | | Number of branches plant$^{-1}$ | |
|---|---|---|---|
| Soil moisture Regime (% CWR) | Cultivar | 2018 | 2019 |
| 100 | Gazelle | 6.67 | 7.11 |
| | Nyala | 4.83 | 6.00 |
| | EAI 3600 | 6.67 | 6.78 |
| | DPSB 8 | 5.33 | 5.33 |
| | Hill | 7.67 | 6.56 |
| | DPSB 19 | 5.00 | 7.00 |
| 75 | Gazelle | 4.83 | 5.89 |
| | Nyala | 5.17 | 5.33 |
| | EAI 3600 | 6.00 | 4.67 |
| | DPSB 8 | 6.33 | 6.22 |
| | Hill | 6.33 | 5.22 |
| | DPSB 19 | 4.33 | 4.55 |
| 50 | Gazelle | 4.17 | 1.33 |
| | Nyala | 2.50 | 3.45 |
| | EAI 3600 | 5.67 | 3.78 |
| | DPSB 8 | 4.33 | 4.56 |
| | Hill | 4.17 | 4.00 |
| | DPSB 19 | 4.00 | 4.56 |
| 25 | Gazelle | 2.33 | 2.00 |
| | Nyala | 3.17 | 3.78 |
| | EAI 3600 | 5.50 | 3.22 |
| | DPSB 8 | 4.00 | 3.66 |
| | Hill | 3.50 | 3.11 |
| | DPSB 19 | 4.67 | 4.22 |
| Mean | | 4.88 | 4.66 |
| *p*-value | | 0.019 | |
| SED | | 0.602 | |
| CV (%) | | 16.0 | |

CWR = crop water requirement; SED = ± Standard error of difference of means; CV = Coefficient of variation.

***Number of leaves***

Number of leaves arising from the main stem significantly ($p < 0.01$) varied with interaction effects of soil moisture regime, cultivars and seasons (Table 4.5). A determinate cultivar EAI 3600 had highest number of leaves at 100% CWR during 2018 season. Increase in soil moisture stress suppressed leaf production across cultivars and seasons. Indeterminate cultivar DPSB 19 had the lowest percent leaf production reduction at the highest and lowest soil moisture regimes of 100 and 25% CWR, respectively.

Table 4.5 Effect of soil moisture regime, cultivar and season on number of leaves at 50% podding stage

| | | Number of leaves plant$^{-1}$ | |
|---|---|---|---|
| Soil moisture Regime (% CWR) | Cultivar | 2018 | 2019 |
| 100 | Gazelle | 9.67 | 9.00 |
| | Nyala | 10.50 | 9.67 |
| | EAI 3600 | 11.50 | 11.00 |
| | DPSB 8 | 7.83 | 9.56 |
| | Hill | 9.50 | 9.78 |
| | DPSB 19 | 10.00 | 10.78 |
| 75 | Gazelle | 8.00 | 8.33 |
| | Nyala | 9.50 | 8.22 |
| | EAI 3600 | 10.50 | 9.12 |
| | DPSB 8 | 10.00 | 7.67 |
| | Hill | 9.67 | 8.11 |
| | DPSB 19 | 8.67 | 8.44 |
| 50 | Gazelle | 8.50 | 6.44 |
| | Nyala | 7.17 | 7.11 |
| | EAI 3600 | 9.17 | 7.00 |
| | DPSB 8 | 8.83 | 7.00 |
| | Hill | 7.50 | 7.11 |
| | DPSB 19 | 7.50 | 6.67 |
| 25 | Gazelle | 7.00 | 5.44 |
| | Nyala | 7.33 | 6.45 |
| | EAI 3600 | 7.33 | 6.44 |
| | DPSB 8 | 8.33 | 6.11 |
| | Hill | 6.67 | 5.45 |
| | DPSB 19 | 7.50 | 7.00 |
| Mean | | 8.67 | 7.83 |
| *p*-value | | 0.002 | |
| SED | | 0.530 | |
| CV (%) | | 8.0 | |

CWR = crop water requirement; SED = ± Standard error of difference of means; CV = Coefficient of variation.

***Leaf area***

Leaf area changed with interaction of soil moisture regimes and seasons ($p < 0.01$) and of cultivars and seasons ($p < 0.001$). Highest leaf area was attained at 100% CWR during 2018 season (Figure 4.5). Soil moisture limitation reduced leaf area regardless of seasons. Cultivars DPSB 8, EAI 3600 and Hill had highest leaf area during both seasons. Larger leaf area was attained during 2018 season which was 14.19% more than leaf area registered during 2019 season.

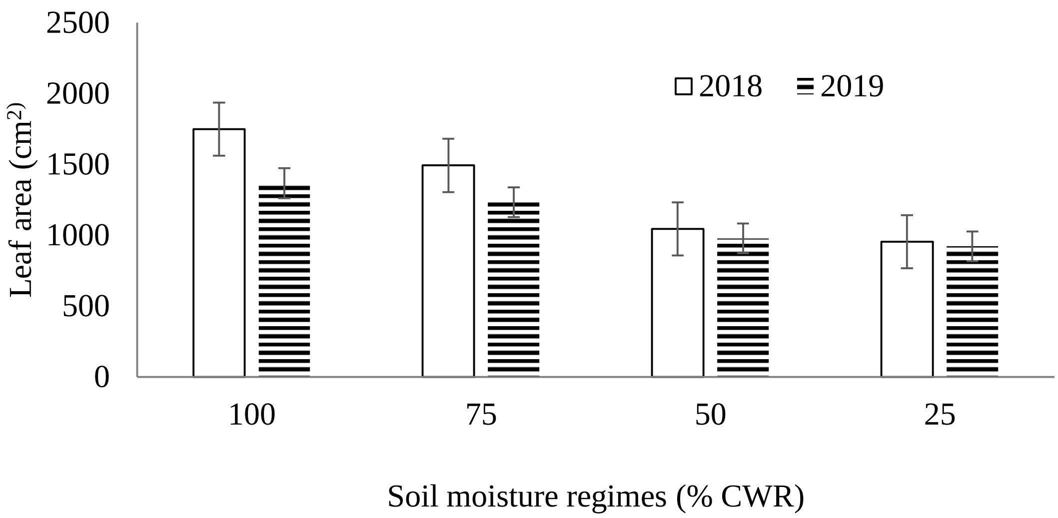


Figure 4.5 Effect of soil moisture regimes and seasons on leaf area at 50% podding stage. Error bars represent ± standard error. Values significantly different at $p < 0.01$. CWR = Crop water requirement.

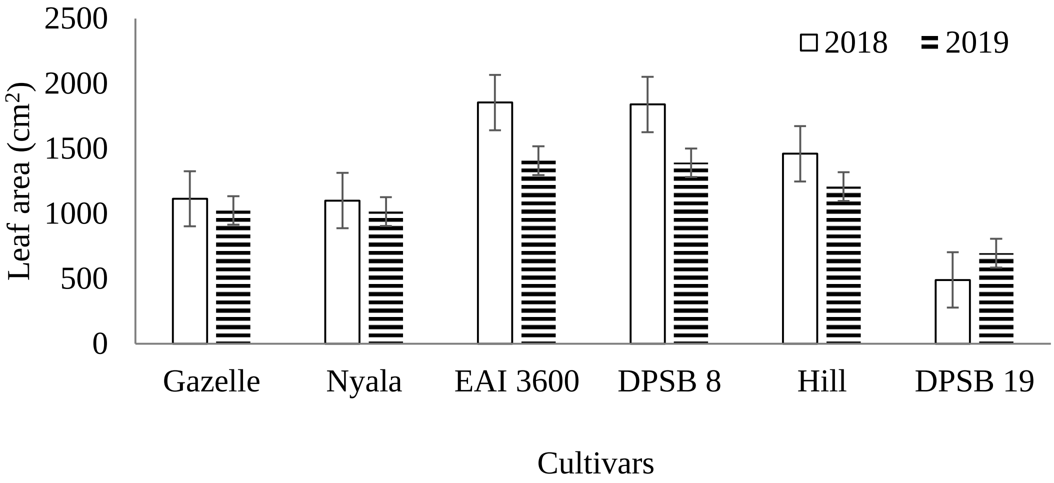


Figure 4.6 Effect of varieties and seasons on leaf area at 50% podding stage. Error bars represent ± standard error. Values significantly different at $p < 0.001$.

***Leaf area index***

Leaf area index (LAI) was significantly ($p < 0.01$) responsive to interaction effects of soil moisture regimes and seasons and of cultivars and seasons. Highest LAI was attained at 100% CWR during both seasons which was, nonetheless, at par with LAI attained at 75% CWR (Figure 4.7). Cultivar and season interaction led to cultivars DPSB 8, EAI 3600 and Hill having highest LAI during 2018 season. The same cultivars also registered highest LAI during 2019 season (Figure 4.8).

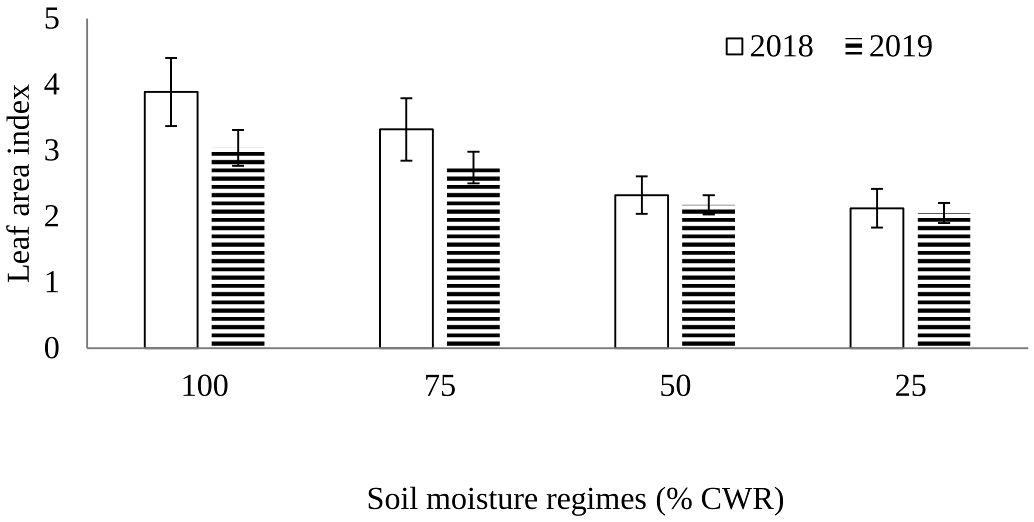


Figure 4.7 Effect of soil moisture regimes and seasons on leaf area index at 50% podding stage. Error bars represent ± standard error. Values significantly different at $p < 0.01$. CWR = Crop water requirement.

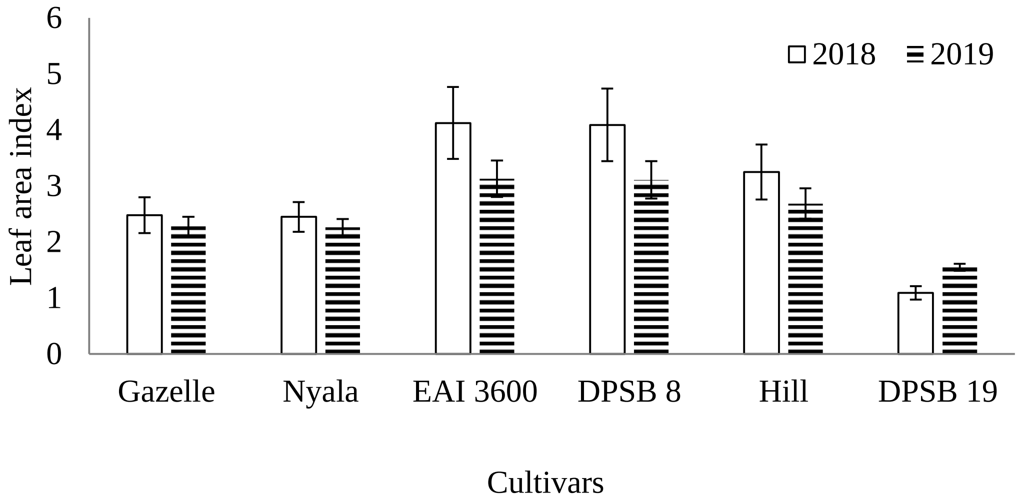


Figure 4.8 Effect of cultivars and seasons on leaf area index at 50% flowering stage. Error bars represent ± standard error. Values significantly different at $p < 0.01$.

### 4.4.2 Effect of soil moisture regimes, cultivars and seasons on physiological characteristics

***Intercepted photosynthetically active radiation***

Interception of photosynthetically active radiation (IPAR) was significantly dependent on interactions of soil moisture regimes and cultivars ($p < 0.01$), soil moisture regimes and seasons ($p < 0.01$) and of cultivars and seasons ($p < 0.05$). Soybean cultivars had highest IPAR at 100% CWR after which IPAR decreased with increased soil moisture limitation (Figure 4.9). Interception of photosynthetically active radiation was higher during 2018 season for all soil moisture regimes though plants grown at 100% CWR had highest IPAR compared to other soil moisture regime treatments (Figure 4.10). All soybean cultivars had higher IPAR during 2018 season. Overall, cultivar DPSB 8 had highest IPAR of 73.67 % while DPSB 19 had lowest IPAR of 63.99 %.

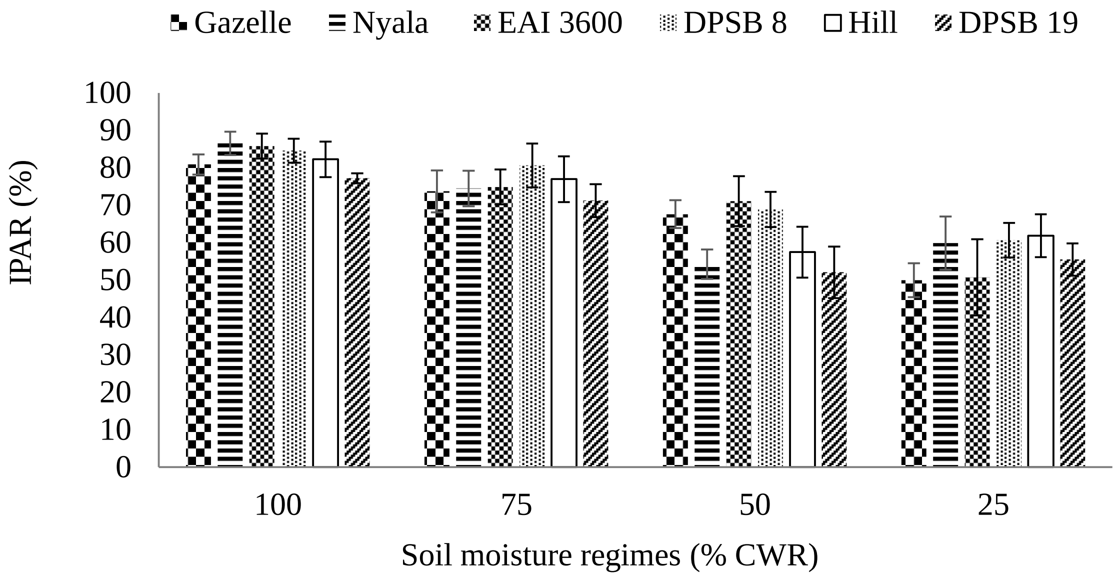


Figure 4.9 Effect of soil moisture regimes and cultivars on interception of photosynthetically active radiation (IPAR) at 50% flowering stage. Error bars represent ± standard error. Values significantly different at $p < 0.01$. CWR = Crop water requirement.

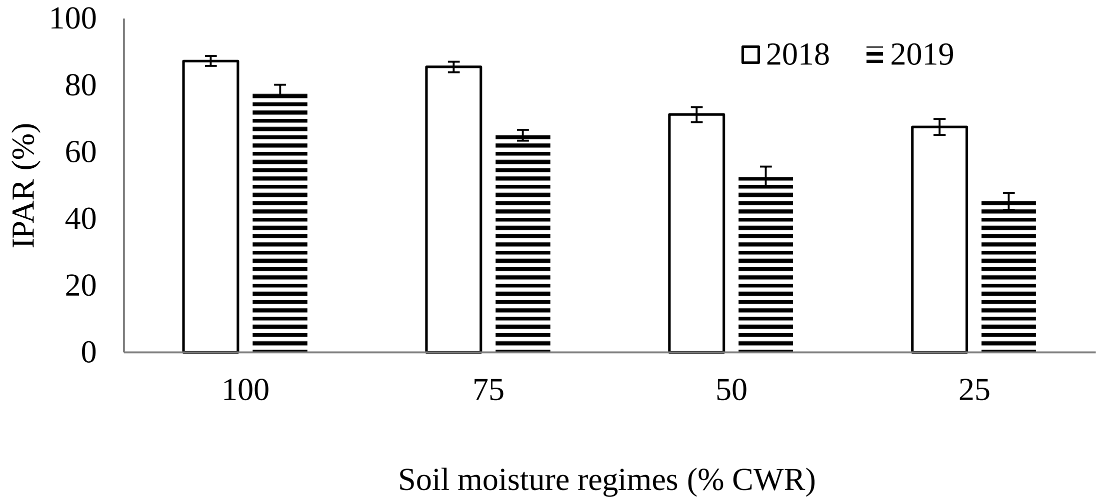


Figure 4.10 Effect of soil moisture regimes and seasons on interception of photosynthetically active radiation (IPAR) at 50% flowering stage. Error bars represent ± standard error. Values significantly different at $p < 0.01$. CWR = Crop water requirement.

***Chlorophyll content***

Chlorophyll 'a' and total chlorophyll contents of soybean leaves were significantly responsive to main effects of soil moisture regimes ($p < 0.001$) and seasons ($p < 0.01$) while soil moisture regimes did not have significant influence on chlorophyll 'b' concentration. Nonetheless, chlorophyll 'b' concentration varied with seasons ($p < 0.001$). Concentrations of total chlorophyll 'a' and total chlorophyll decreased with increased soil moisture stress (Table 4.6). Plants grown at 100% CWR had 33.44% more total chlorophyll concentration than those grown at 25% CWR. Concentration of chlorophyll 'a', chlorophyll 'b' and total chlorophyll were higher during 2018 season than during 2019 season.

Table 4.6 Effect soil moisture regimes and seasons on chlorophyll content (mg $g^{-1}$ fresh weight) at 50% flowering stage

| | Chlorophyll content (mg $g^{-1}$ fresh weight) | | |
|---|---|---|---|
| Soil moisture regime (% CWR) | Chlorophyll 'a' | Chlorophyll 'b' | Total chlorophyll |
| 100 | 2.35 | 0.64 | 2.99 |
| 75 | 1.87 | 0.64 | 2.51 |
| 50 | 1.52 | 0.69 | 2.21 |
| 25 | 1.34 | 0.65 | 1.99 |
| *p*-value | <0.001 | 0.481 | <0.001 |
| SED | 0.201 | 0.038 | 0.235 |
| CV (%) | 4.0 | 7.1 | 4.5 |
| Seasons | | | |
| 2018 | 1.90 | 0.72 | 2.62 |
| 2019 | 1.64 | 0.59 | 2.23 |
| *p*-value | 0.004 | < 0.001 | 0.001 |
| SED | 0.235 | 0.035 | 0.268 |
| CV (%) | 4.1 | 7.1 | 4.5 |

CWR = crop water requirement; SED = ± Standard error of difference of means; CV = Coefficient of variation.

***Leaf relative water content***

Leaf relative water content (LRWC) was significantly dependent on interactions of soil moisture regimes and cultivars ($p < 0.05$) and of cultivars and seasons ($p < 0.001$). All soybean cultivars registered higher LRWC at soil moisture regime of 100% CWR. Indeterminate cultivar DPSB 8 had highest LRWC at the highest and lowest soil moisture regimes of 100 and 25% respectively. Cultivar EAI 3600 had lowest reduction (2.9%) in LRWC between the highest and lowest soil moisture regimes. Soybean cultivar had relatively higher LRWC during 2018 season than during 2019 season (Table 4.7).

Table 4.7 Effect of soil moisture regimes, cultivar and season on leaf relative water content (%) at 50% flowering stage

| Leaf relative water content (%) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Cultivar | | | | | | |
| Soil Moisture Regimes (% CWR) | Gazelle | Nyala | EAI 3600 | DPSB 8 | Hill | DPSB 19 | Mean |
| 100 | 83.01 | 84.76 | 82.32 | 86.38 | 84.56 | 80.30 | 83.56 |
| 75 | 81.69 | 82.95 | 81.85 | 79.81 | 82.66 | 78.35 | 81.22 |
| 50 | 81.15 | 82.11 | 77.12 | 84.57 | 79.58 | 72.31 | 79.48 |
| 25 | 79.72 | 78.53 | 79.93 | 78.92 | 75.34 | 64.13 | 76.10 |
| Mean | 81.39 | 82.09 | 80.31 | 82.42 | 80.54 | 73.77 | |
| *p*-value | 0.019 | | | | | | |
| SED | 3.519 | | | | | | |
| CV (%) | 4.7 | | | | | | |
| **Seasons** | | | | | | | |
| 2018 | 82.63 | 83.14 | 83.92 | 81.96 | 84.41 | 73.72 | 81.63 |
| 2019 | 80.16 | 81.04 | 76.70 | 82.69 | 76.66 | 73.82 | 78.54 |
| *p*-value | <0.001 | | | | | | |
| SED | 1.891 | | | | | | |
| CV (%) | 4.8 | | | | | | |

CWR = crop water requirement; SED = ± Standard error of difference of means; CV = Coefficient of variation.

***Stomata conductance***

Interaction of soil moisture regimes, cultivar and seasons significantly influenced stomata conductance at vegetative ($p < 0.001$) and at 50% flowering ($p < 0.01$) stages. Soybean cultivars had increased stomata conductance rates at the highest soil moisture regime of 100% CWR during both seasons. Stomata conductance was higher during 2018 season than 2019 season (Table 4.8).

Table 4.8 Effect of soil moisture regimes, cultivar and season on stomata conductance (mmol $m^{-2}$ $s^{-1}$) at vegetative and 50% flowering stages

| | | Stomata conductance (mmol $m^{-2}$ $s^{-1}$) | | | |
|---|---|---|---|---|---|
| Soil Moisture | | Vegetative stage | | 50% flowering stage | |
| regimes (% CWR) | Cultivar | 2018 | 2019 | 2018 | 2019 |
| 100 | Gazelle | 76.37 | 44.62 | 61.55 | 35.67 |
| | Nyala | 76.77 | 61.52 | 62.33 | 27.60 |
| | EAI 3600 | 51.07 | 46.57 | 59.60 | 27.23 |
| | DPSB 8 | 69.73 | 42.88 | 49.80 | 27.63 |
| | Hill | 53.67 | 57.08 | 60.87 | 28.82 |
| | DPSB 19 | 54.20 | 76.10 | 72.87 | 22.63 |
| 75 | Gazelle | 34.63 | 26.38 | 57.57 | 21.10 |
| | Nyala | 63.17 | 65.47 | 54.63 | 22.08 |
| | EAI 3600 | 38.70 | 38.93 | 53.77 | 22.12 |
| | DPSB 8 | 25.20 | 32.17 | 53.33 | 23.56 |
| | Hill | 44.83 | 38.75 | 41.30 | 20.17 |
| | DPSB 19 | 44.83 | 66.65 | 68.05 | 14.43 |
| 50 | Gazelle | 27.03 | 25.52 | 43.90 | 18.33 |
| | Nyala | 30.10 | 66.82 | 59.60 | 16.10 |
| | EAI 3600 | 25.80 | 45.40 | 53.43 | 12.77 |
| | DPSB 8 | 37.50 | 35.85 | 49.53 | 17.33 |
| | Hill | 43.10 | 19.03 | 39.03 | 17.17 |
| | DPSB 19 | 31.03 | 52.38 | 61.33 | 13.63 |
| 25 | Gazelle | 14.20 | 22.87 | 57.90 | 14.47 |
| | Nyala | 30.17 | 48.68 | 50.13 | 14.13 |
| | EAI 3600 | 27.13 | 29.13 | 39.47 | 11.20 |
| | DPSB 8 | 12.47 | 18.08 | 46.57 | 11.13 |
| | Hill | 21.50 | 31.90 | 49.20 | 14.37 |
| | DPSB 19 | 27.60 | 41.47 | 60.17 | 17.40 |
| *p*-value | | <0.001 | | 0.009 | |
| SED | | 7.959 | | 4.095 | |
| CV (%) | | 23.10 | | 13.70 | |

CWR = crop water requirement; SED = ± Standard error of difference of means; CV = Coefficient of variation.

***Sub-stomatal carbon dioxide concentration***

Sub-stomatal carbon dioxide concentration was significantly responsive to main effects of soil moisture regimes ($p < 0.05$) and seasons ($p < 0.001$) at both vegetative and 50% flowering stages. Highest sub-stomatal carbon dioxide concentration was attained at 100% CWR which corresponded to 56.88 and 47.99% increase over the lowest soil moisture regime of 25% CWR at vegetative and 50% flowering stages, respectively (Figure 4.11). Highest sub-stomatal carbon dioxide concentration of 104.65 µmol $mol^{-1}$ was attained during 2019 season which was 8.75% more than sub-stomatal carbon dioxide concentration registered during 2018 season.

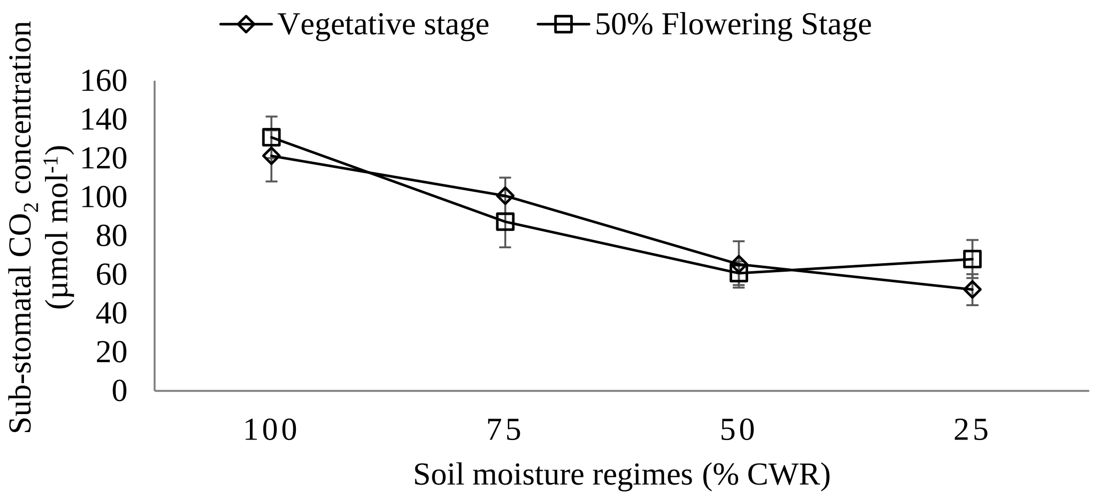


Figure 4.11 Effect of soil moisture regimes on sub-stomata $CO_2$ concentration at vegetative and 50% flowering stages. Error bars represent ± standard error. Values significantly different at $p < 0.05$. CWR = Crop water requirement.

***Photosynthetic rate***

Photosynthetic rate significantly varied with main effects of soil moisture regimes ($p < 0.05$), cultivars ($p < 0.01$) and seasons ($p < 0.001$) at vegetative stage. At 50% flowering stage, photosynthetic rate varied with soil moisture regimes. Soil moisture limitation reduced photosynthetic rate of soybean plants (Figure 4.12) and there was 76.53 and 77.29% reduction in photosynthetic rate at the lowest soil moisture regime of 25% CWR relative to highest soil moisture regime of 100% CWR at vegetative and 50% flowering stages, respectively. Cultivar DPSB 19 and EAI 3600 had highest and lowest photosynthetic rates, respectively (Figure 4.13). Photosynthetic rate was higher (11.09 µmol $m^{-2}$ $s^{-1}$) during 2019 season which corresponded to 35.84% increase over photosynthetic rate registered during 2018 season.

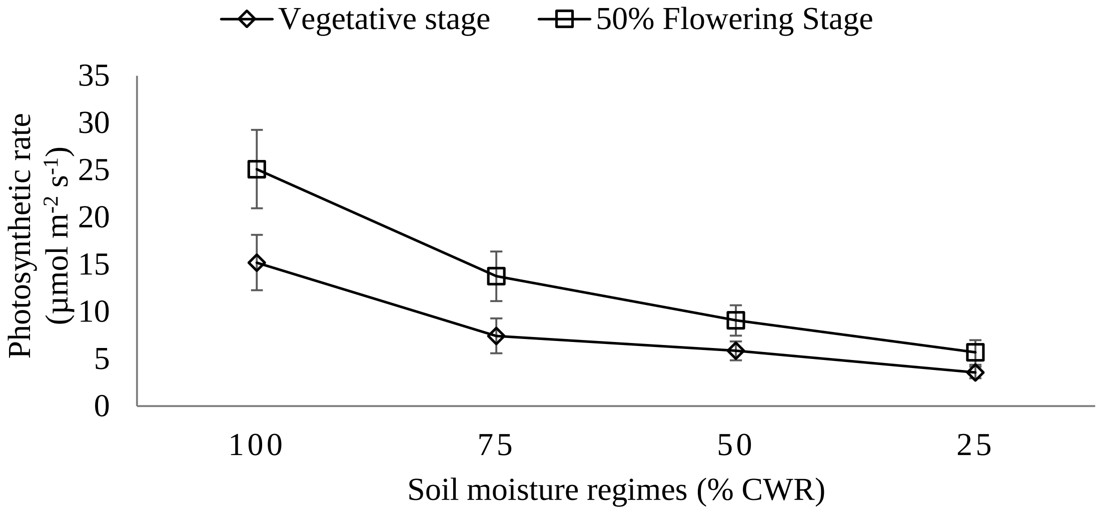


Figure 4.12 Effect of soil moisture regimes on photosynthetic rate at vegetative and 50% flowering stages. Error bars represent ± standard error. Values significantly different at $p < 0.05$. CWR = Crop water requirement.

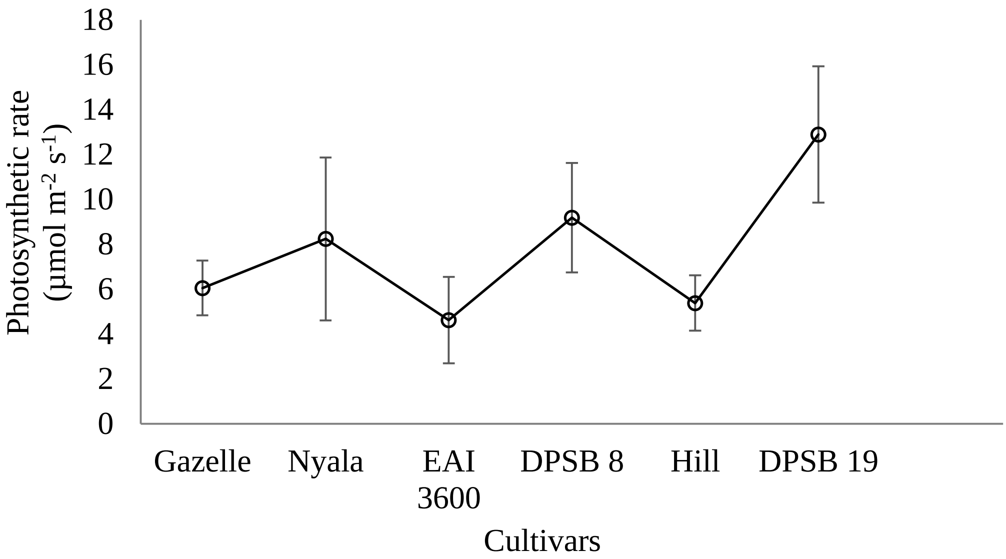


Figure 4.13 Effect of soybean cultivars on photosynthetic rate at vegetative stage. Error bars represent ± standard error. Values significantly different at $p < 0.01$.

***Transpiration rate***

Transpiration rate at vegetative stage was significantly ($p < 0.01$) responsive to interaction of soil moisture regimes, cultivars and seasons while at 50% flowering stage, transpiration rate was significantly dependent on interactions of soil moisture regimes and cultivars ($p < 0.001$) and of cultivars and seasons ($p < 0.05$). All soybean cultivars had higher transpiration rates at 100% CWR during vegetative stage of 2019 season (Figures 4.14 and 4.15). At 50% flowering stage, all soybean cultivars had lowest transpiration rates at the lowest soil moisture regime of 25% CWR (Figure 4.16). Interaction of cultivars and seasons resulted into increased transpiration rate during 2019 season where cultivars Nyala and EAI 3600 had highest (19.69 mmol $m^{-2}$ $s^{-1}$) and lowest (17.56 mmol $m^{-2}$ $s^{-1}$) transpiration rates, respectively.

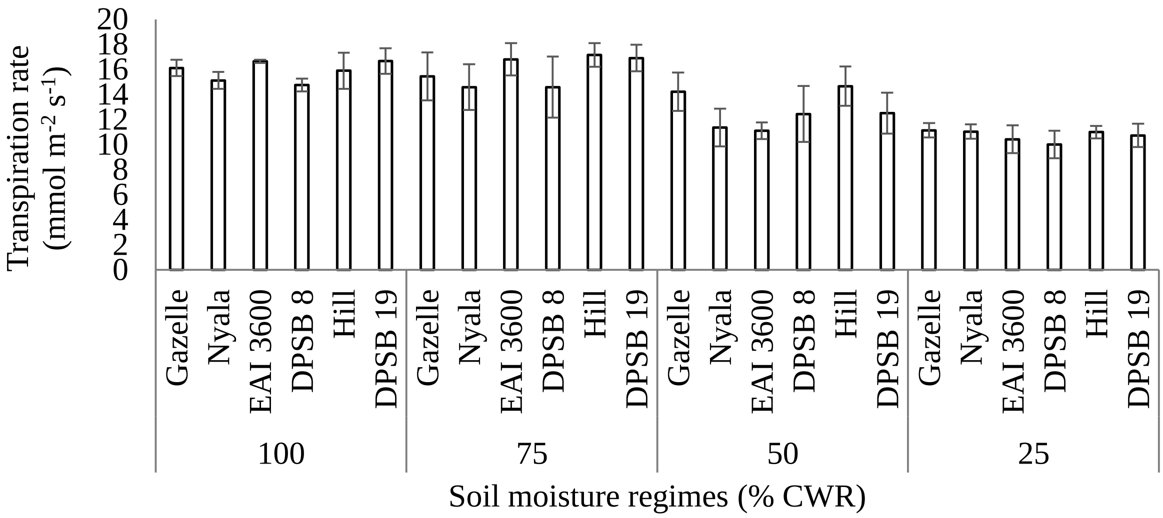


Figure 4.14 Effect of soil moisture regimes and cultivars on transpiration rate at vegetative stage during 2018 season Error bars represent ± standard error. Values significantly different at $p < 0.01$. CWR = Crop water requirement.

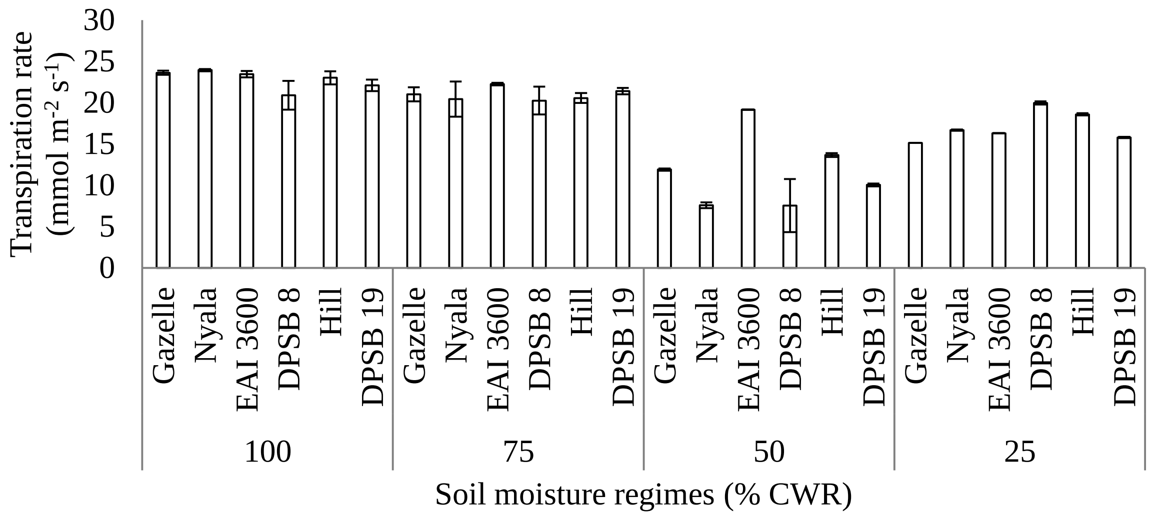


Figure 4.15 Effect of soil moisture regimes and cultivars on transpiration rate at vegetative stage during 2019 season. Error bars represent ± standard error. Values significantly different at $p < 0.01$. CWR = Crop water requirement.

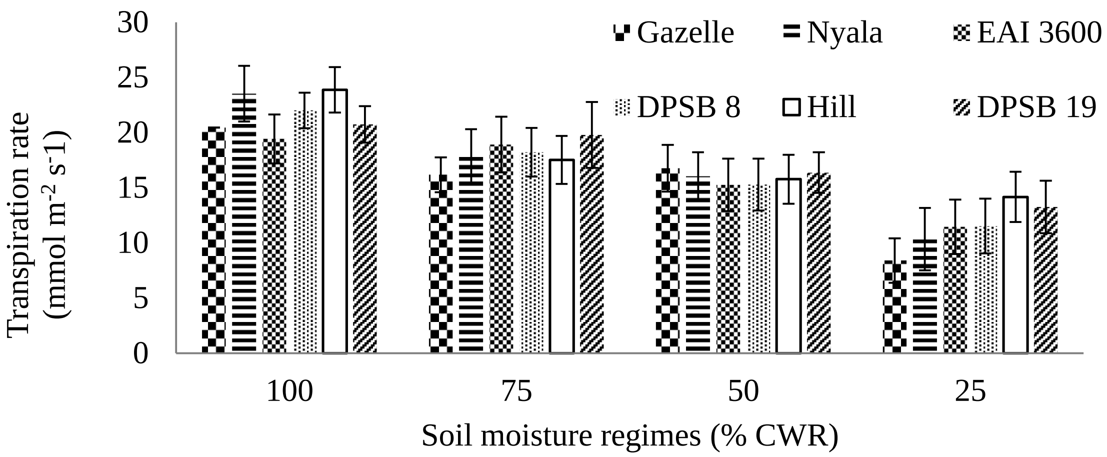


Figure 4.16 Effect of soil moisture regimes and cultivars on transpiration rate at 50% flowering stage. Error bars represent ± standard error. Values significantly different at $p < 0.001$. CWR = Crop water requirement.

***Leaf temperature***

Interactions of soil moisture regimes and cultivars and of soil moisture regimes and seasons significantly ($p < 0.001$) influenced soybean leaf temperature during vegetative stage (Figures 4.17 and 4.18). At 50% flowering stage, leaf temperature significantly ($p < 0.001$) varied with interaction of soil moisture regimes and cultivars (Figure 4.19). Soybean cultivars had increased leaf temperature at the lowest soil moisture regime of 25% CWR at both vegetative and 50% flowering stages. Overall, 2018 season registered higher leaf temperature than 2019 season.

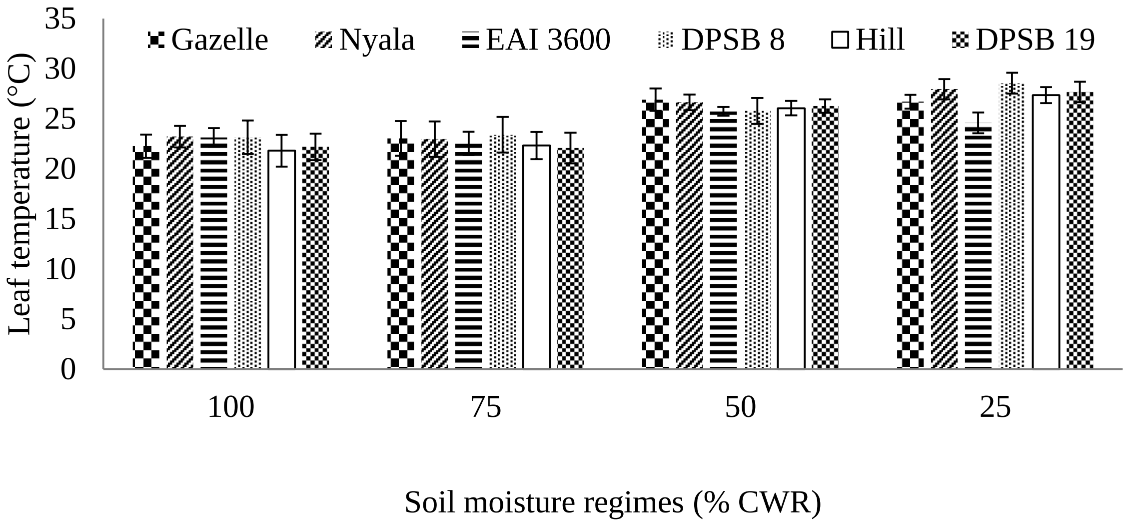


Figure 4.17 Effect of soil moisture regimes and cultivars on leaf temperature at vegetative stage. Error bars represent ± standard error. Values significantly different at $p < 0.001$. CWR = Crop water requirement.

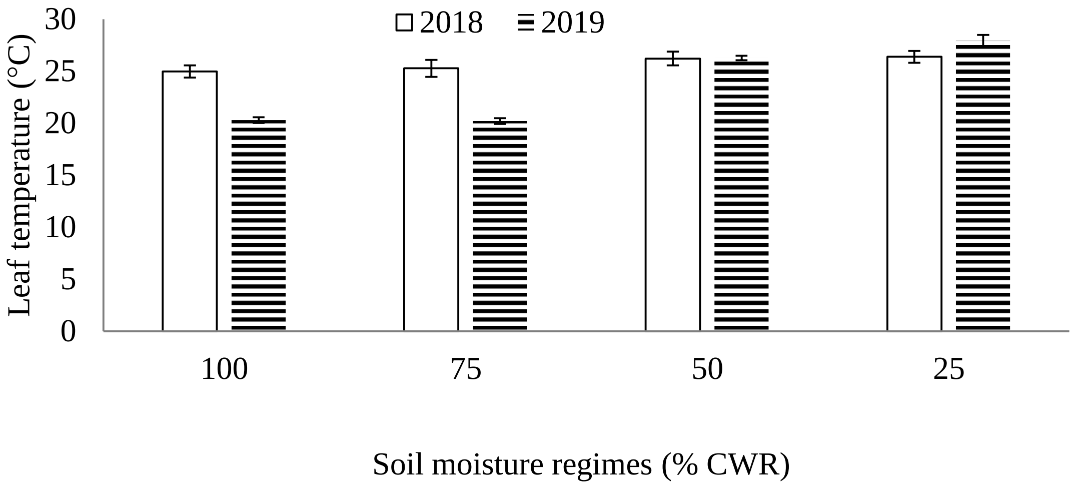


Figure 4.18 Effect of soil moisture regimes and seasons on leaf temperature at vegetative stage. Error bars represent ± standard error. Values significantly different at $p < 0.001$. CWR = Crop water requirement.

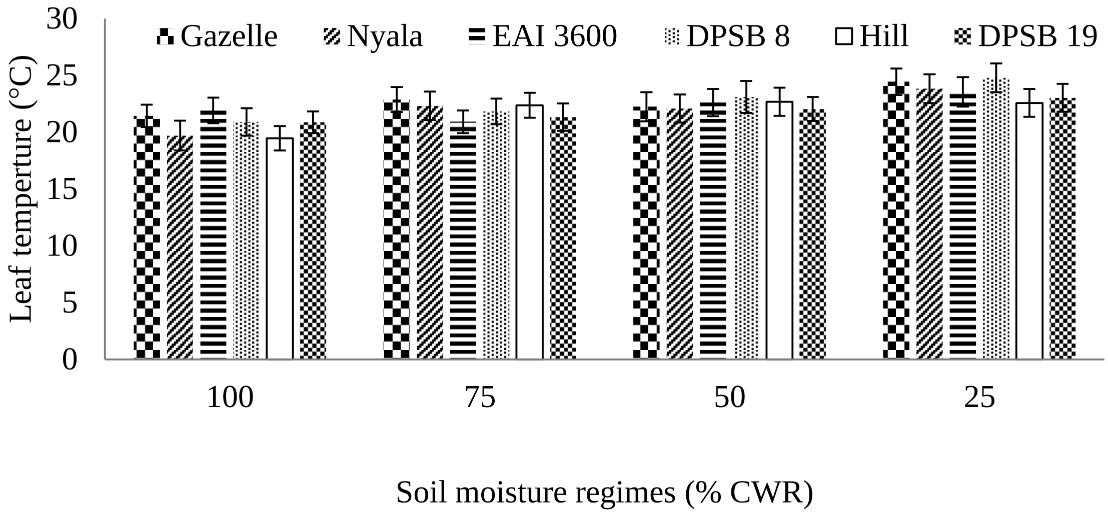


Figure 4.19 Effect of soil moisture regimes and varieties on leaf temperature at 50% flowering stage. Error bars represent ± standard error. Values significantly different at $p < 0.001$. CWR = Crop water requirement.

***Correlations of soybean grain yield with selected leaf gas exchange traits***

Increases in stomata conductance, photosynthesis rate, interception of photosynthetically active radiation, leaf relative water content and sub-stomatal carbon dioxide concentration positively correlated with soybean grain yield. Stomata conductance had positive and significant effect on concentration of sub-stomatal carbon dioxide concentration and photosynthetic rate (Table 4.9).

Table 4.9 Correlation of soybean grain yield with selected leaf gas exchange traits

| | Yield | PN rate | IPAR | LRWC | $g_s$ | $C_i$ |
|---|---|---|---|---|---|---|
| Yield | - | - | - | - | - | - |
| PN rate | $0.2584^{**}$ (0.0668) | - | - | - | - | - |
| IPAR | $0.6777^{***}$ (0.4593) | $0.2166^{**}$ (0.0469) | - | - | - | - |
| LRWC | $0.4193^{***}$ (0.1758) | $0.1314^{ns}$ (0.0173) | $0.3982^{***}$ (0.1586) | - | - | - |
| $g_s$ | $0.4760^{***}$ (0.2266) | $0.2534^{**}$ (0.0642) | $0.5943^{***}$ (0.3532) | $0.1629^{ns}$ (0.0265) | - | - |
| $C_i$ | $0.1142^{ns}$ (0.0130) | $0.2513^{**}$ (0.0632) | $0.0554^{ns}$ (0.0031) | $0.1015^{ns}$ (0.0103) | $0.3187^{***}$ 0.1016) | - |

PN, IPAR, LRWC, $g_s$, $C_i$ = net photosynthesis, intercepted photosynthetically active radiation, leaf relative water content, stomata conductance and sub-stomatal carbon dioxide concentration respectively. ***, ** represent significance at $p < 0.001$ and $p < 0.01$ respectively; ns = not significant; figures in parentheses represent coefficient of determination.

### 4.4.3. Effect of soil moisture regimes and cultivars on reproductive growth

***Days to flowering***

Number of days of to 50% flowering by soybean plants significantly ($p < 0.001$) varied with main effects of soil moisture regimes and cultivars. Soybean plants grown at soil moisture regime of 25% CWR flowered 82 days after planting which was 5 days earlier than plants grown at 100% CWR. Cultivar DPSB 19 took 71.46 days to flower which was the earliest compared to other test cultivars.

***Days to maturity***

Number of days to 50% pod maturity significantly varied with main effects of soil moisture regimes, ($p < 0.05$) and cultivars ($p < 0.001$). Soil moisture stress hastened pod maturity with soybean plants grown at 25% CWR maturing after 132.72 days after planting which was 7.54 days earlier than plants grown at higher soil moisture levels. Cultivar DPSB 19 was the earliest to mature after 115.6 days after planting while cultivar DPSB 8 matured late after 146.3 days after planting.

### 4.4.4. Effect of soil moisture regimes, cultivars and seasons on yield, yield components and grain quality

***Pods per plant***

Interaction of soil moisture regimes, cultivar and seasons significantly ($p < 0.05$) influenced number of pods per plant (Table 4.10). Overall, all soybean cultivars had highest number of pods per plant at 100% CWR in both seasons though higher number of pods were registered during 2018 season compared to 2019 season. While cultivar DPSB 19 had highest number of pods per plant at 100% CWR, cultivar Nyala had, on average, the lowest number of pods per plant at the lowest soil moisture regime of 25% CWR.

Table 4. 10 Effect of soil moisture regimes, cultivar and seasons on number of pods per plant

| | | Number of pods plant$^{-1}$ | |
|---|---|---|---|
| Soil moisture Regime (% CWR) | Cultivar | 2018 | 2019 |
| 100 | Gazelle | 57.00 | 48.28 |
| | Nyala | 61.00 | 52.07 |
| | EAI 3600 | 88.67 | 47.13 |
| | DPSB 8 | 71.67 | 61.23 |
| | Hill | 45.00 | 47.53 |
| | DPSB 19 | 94.67 | 69.87 |
| 75 | Gazelle | 40.33 | 39.80 |
| | Nyala | 57.67 | 38.33 |
| | EAI 3600 | 79.00 | 47.13 |
| | DPSB 8 | 60.33 | 51.33 |
| | Hill | 43.33 | 39.93 |
| | DPSB 19 | 90.67 | 46.27 |
| 50 | Gazelle | 28.00 | 25.27 |
| | Nyala | 36.33 | 24.07 |
| | EAI 3600 | 51.33 | 28.87 |
| | DPSB 8 | 26.33 | 24.13 |
| | Hill | 30.00 | 23.53 |
| | DPSB 19 | 52.67 | 24.47 |
| 25 | Gazelle | 20.67 | 26.33 |
| | Nyala | 19.67 | 23.40 |
| | EAI 3600 | 39.67 | 24.80 |
| | DPSB 8 | 49.67 | 22.53 |
| | Hill | 30.33 | 23.00 |
| | DPSB 19 | 34.35 | 21.93 |
| Mean | | 50.35 | 36.72 |
| *p*-value | | 0.046 | |
| SED | | 7.641 | |
| CV (%) | | 22.40 | |

CWR = crop water requirement; SED = ± Standard error of difference of means; CV = Coefficient of variation.

***Pods per node***

Number of pods per node was significantly dependent on interaction of soil moisture regimes and cultivars ($p < 0.05$) and interaction of cultivars and seasons ($p < 0.01$). Highest number of pods per node was attained at 100% CWR during 2018 season while the lowest number of pods per node was achieved at 25% CWR during 2019 season (Table 4.11). Cultivar and season interaction led to higher number of pods per plant being realized during 2018 season by cultivar EAI 3600 while cultivar Gazelle had the lowest number of pods per node during 2019 season.

Table 4.11 Effect of soil moisture regimes, cultivar and seasons on number of pods per node

| | Number of pods node$^{-1}$ | | |
|---|---|---|---|
| | Season | | |
| Soil moisture regimes (% CWR) | 2018 | 2019 | Mean |
| 100 | 3.34 | 2.67 | 3.01 |
| 75 | 3.01 | 2.40 | 2.71 |
| 50 | 2.60 | 1.78 | 2.19 |
| 25 | 2.37 | 1.60 | 1.99 |
| Mean | 2.83 | 2.11 | |
| *p*-value | 0.015 | | |
| SED | 0.031 | | |
| CV% | 5.1 | | |
| Cultivars | | | |
| Gazelle | 2.26 | 1.91 | 2.09 |
| Nyala | 2.60 | 1.92 | 2.26 |
| EAI 3600 | 3.40 | 2.31 | 2.86 |
| DPSB 8 | 3.32 | 1.95 | 2.64 |
| Hill | 2.80 | 2.00 | 2.40 |
| DPSB 19 | 2.59 | 2.48 | 2.54 |
| Mean | 2.83 | 2.10 | |
| *p*-value | <0.001 | | |
| SED | 0.033 | | |
| CV (%) | 5.1 | | |

CWR = crop water requirement; SED = ± Standard error of difference of means; CV = Coefficient of variation.

***Pod length***

Lengths of soybean pods were significantly responsive ($p < 0.05$) to interaction effects of soil moisture regimes, cultivars and seasons (Table 4.12). Variety EAI 3600 had longest pods at 100% CWR during 2018 season while shortest pods were attained at 25% CWR by cultivar DPSB 19 during 2019 season (Table 4.12).

Table 4.12 Effect of soil moisture regimes, cultivar and seasons on pod length

| | | Pod length (cm) | |
|---|---|---|---|
| Soil moisture Regime (% CWR) | Cultivar | 2018 | 2019 |
| 100 | Gazelle | 4.16 | 3.90 |
| | Nyala | 4.63 | 3.96 |
| | EAI 3600 | 4.66 | 4.09 |
| | DPSB 8 | 3.91 | 3.59 |
| | Hill | 4.57 | 3.90 |
| | DPSB 19 | 4.15 | 3.96 |
| 75 | Gazelle | 4.19 | 3.73 |
| | Nyala | 4.49 | 3.93 |
| | EAI 3600 | 4.51 | 3.99 |
| | DPSB 8 | 3.88 | 3.51 |
| | Hill | 4.35 | 3.66 |
| | DPSB 19 | 3.87 | 3.50 |
| 50 | Gazelle | 3.97 | 3.65 |
| | Nyala | 3.94 | 3.69 |
| | EAI 3600 | 4.28 | 3.63 |
| | DPSB 8 | 3.60 | 3.39 |
| | Hill | 3.99 | 3.70 |
| | DPSB 19 | 3.74 | 3.23 |
| 25 | Gazelle | 3.67 | 3.43 |
| | Nyala | 3.83 | 3.48 |
| | EAI 3600 | 4.09 | 3.68 |
| | DPSB 8 | 3.35 | 3.30 |
| | Hill | 3.63 | 3.55 |
| | DPSB 19 | 3.78 | 3.21 |
| Mean | | 4.05 | 3.65 |
| *p*-value | | 0.017 | |
| SED | | 1.103 | |
| CV (%) | | 3.6 | |

CWR = crop water requirement; SED = ± Standard error of difference of means; CV = Coefficient of variation.

***Seeds per pod***

Number of seeds per pod was significantly ($p < 0.001$) responsive to main effects of soil moisture regimes, cultivars and seasons. Highest number of seeds per pod was attained at 100% CWR which corresponded to 18.19% increase over the lowest number of seeds per pod obtained at 25% CWR (Figure 4.20). Cultivar EAI 3600 had highest number of seeds per pod (2.66), followed by cultivar DPSB 19 (2.56). Cultivar Gazelle had the lowest number of seeds per pod (2.29) compared to all other cultivars. Seasonal differences led to more seeds per pod being attained during 2019 season (2.53) than 2018 season (2.39).

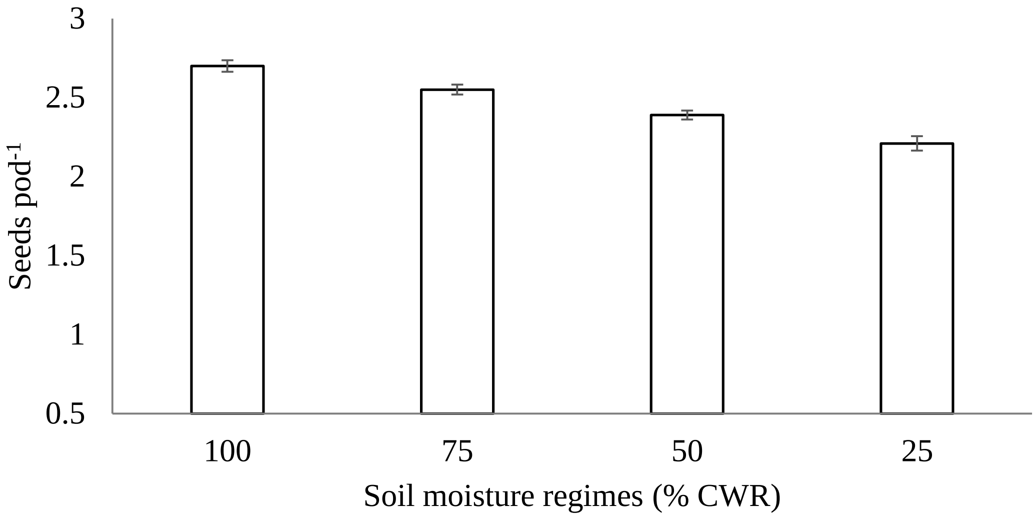


Figure 4.20 Effect of soil moisture regimes on number of soybean seeds per pod. Error bars represent ± standard error. Values significantly different at $p < 0.001$. CWR = Crop water requirement.

***Seed size***

Seed size as indicated from 100 seed weight was significantly ($p < 0.01$) dependent on interaction of soil moisture regimes and seasons and of cultivars and seasons. Highest 100 seed weight was attained at 100% CWR during 2018 season (Figure 4.21). Cultivars Nyala and DPSB 19 had highest and lowest seed sizes during both seasons, respectively (Figure 4.22).

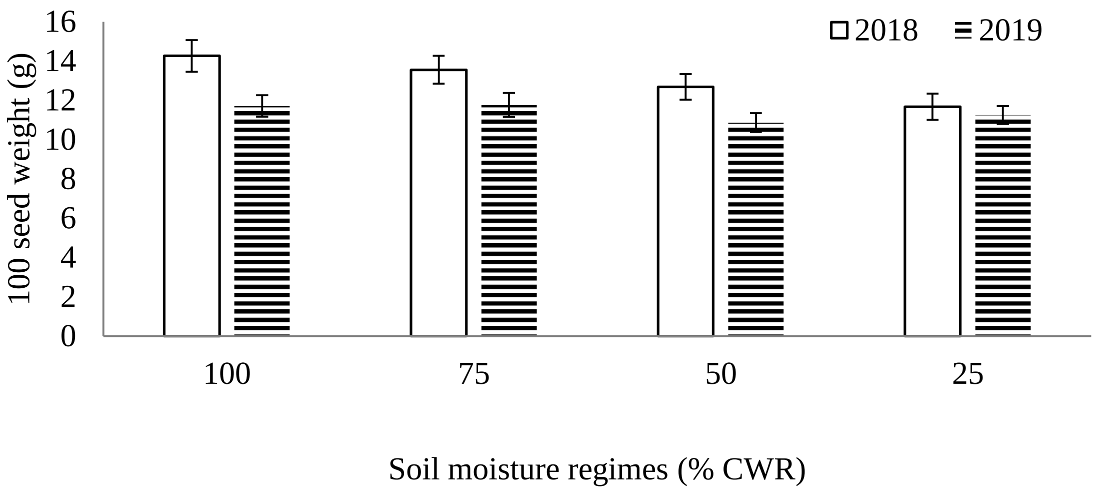


Figure 4.21. Effect of soil moisture regimes and seasons on soybean seed size. Error bars represent ± standard error. Values significantly different at $p < 0.01$. CWR = Crop water requirement.

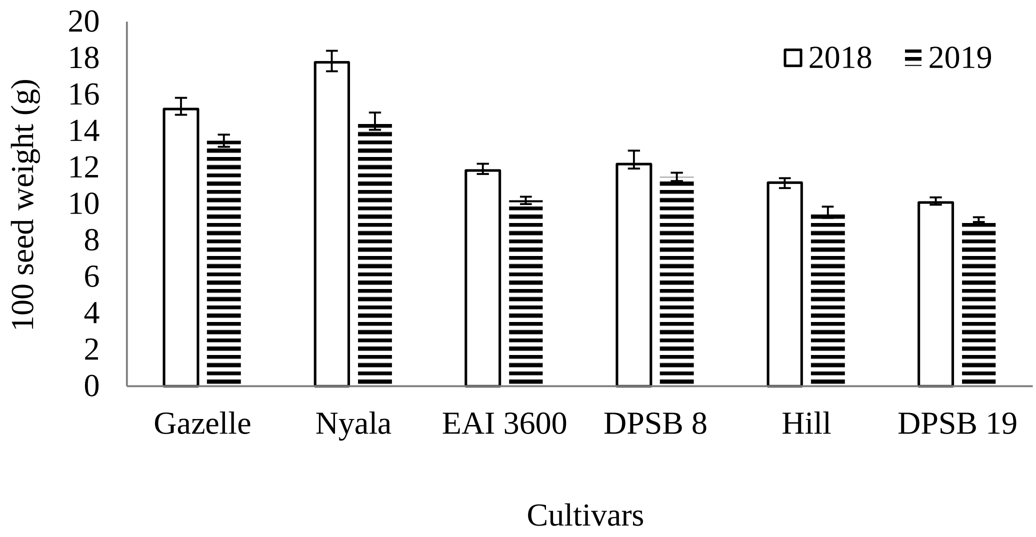


Figure 4.22 Effect of varieties and seasons on soybean grain yield. Error bars represent ± standard error. Values significantly different at $p < 0.01$. CWR = Crop water requirement.

***Grain yield***

Grain yield significantly varied with interactions of soil moisture regimes and seasons ($p < 0.01$) and of cultivars and seasons ($p < 0.001$). Highest and lowest grain yields were attained at 100 and 25% CWR respectively, in both seasons (Figure 4.23). Soybean yield was higher during 2018 season than 2019 season at each soil moisture regime but only significantly higher at 50% and 25% CWR. Interaction of cultivars and seasons led to highest grain yields being attained by cultivars Nyala and DPSB 19 during 2018 and 2019 seasons respectively (Figure 4.24). Cultivars Gazelle and EAI 3600 had lowest and highest yield reduction at 25% CWR relative to grain yield obtained at 100% CWR, respectively.

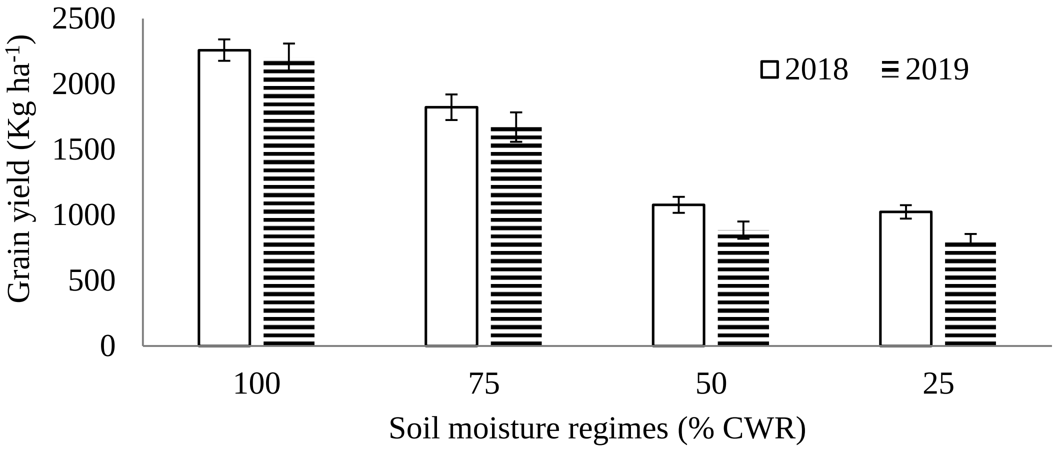


Figure 4.23 Effect of soil moisture regimes and seasons on soybean grain yield. Error bars represent ± standard error. Values significantly different at $p < 0.01$. CWR = Crop water requirement.

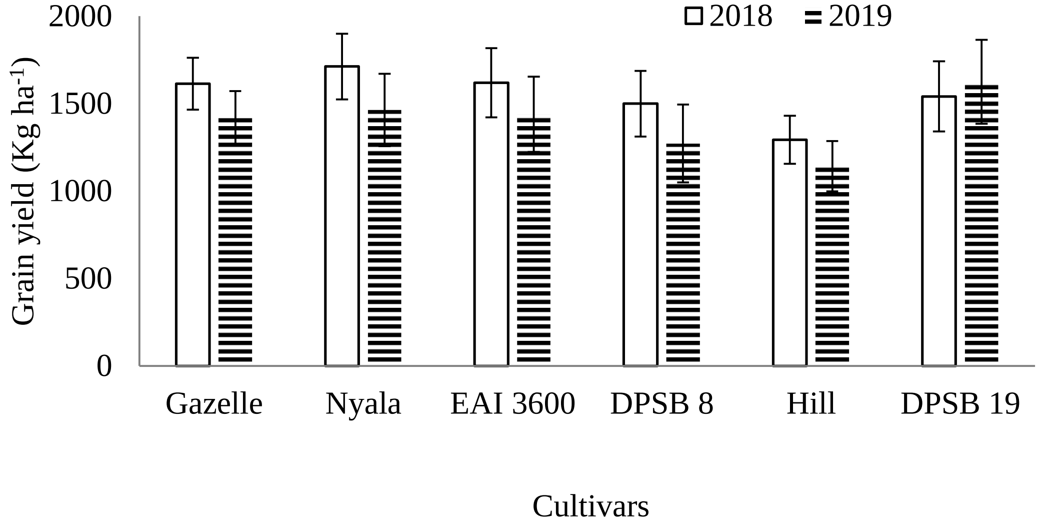


Figure 4.24 Effect of cultivars and seasons on soybean grain yield. Error bars represent ± standard error. Values significantly different at $p < 0.001$.

***Protein***

Grain protein content significantly varied with main effects of soil moisture regimes ($p < 0.05$) and seasons ($p < 0.001$). Highest protein content was attained at the highest soil moisture regime of 100% CWR which corresponded to 5.69% increase over the lowest protein content obtained at 25% CWR (Figure 4.25). Seasonal variations led to higher protein content being attained during 2018 season (29.58%) compared to 2019 season protein content of 28.19%.

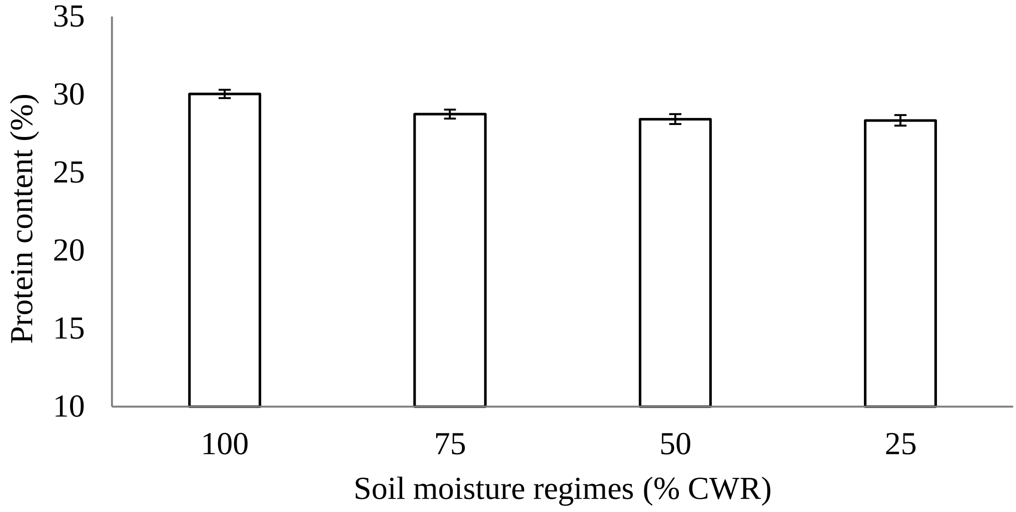


Figure 4.25 Effect of soil moisture regimes on soybean grain protein content. Error bars represent ± standard error. Values significantly different at $p < 0.05$.

***Grain yield and yield components correlations***

Correlations of grain yield and some quantitative traits show that increases in leaf area, number of pods per plant, pod length and seed size positively contributed to grain yield (Table 4.13). Coefficients of determination ($r^2$) show that 10.27, 43.24, 31.92 and 6.1% variations in grain yield amongst soil moisture regimes may attributed to differences in leaf area, number of pods per plant, pod length and seed size, respectively.

Table 4.13 Correlation of soybean grain yield with selected quantitative yield components traits

| | Leaf area | Pods plant$^{-1}$ | Pod length | Seed size | Yield |
|---|---|---|---|---|---|
| Leaf area | - | - | - | - | - |
| Pods plant$^{-1}$ | 0.5371 $^{***}$ (0.2885) | - | - | - | - |
| Pod length | 0.3525$^{***}$ (0.1243) | 0.5331$^{***}$ (0.2842) | - | - | - |
| Seed size | 0.1399$^{ns}$ (0.0195) | 0.1379$^{ns}$ (0.019) | 0.3579$^{***}$ (0.1281) | - | - |
| Yield | 0.3204$^{***}$ (0.1027) | 0.6576$^{***}$ (0.4324) | 0.5650*** (0.3192) | 0.2471$^{**}$ (0.061) | - |

***, ** represent significance at $p < 0.001$ and $p < 0.01$ respectively; ns = not significant; figures in parentheses represent coefficient of determination.

### 4.5 Discussion

**Effect of soil moisture stress on shoot growth**

Soil moisture stress suppressed soybean shoot growth by reducing plant height, internode length, canopy development, stem thickness, number of branches, number of leaves and leaf area. At the most limiting soil moisture regime of 25% CWR, plant height, canopy spread, stem thickness and leaf area were reduced by 31.54, 34.71, 8.0 and 39.77%, respectively relative to plants grown at 100% CWR. These findings concur with observations by Karam *et al.* (2005), Kirnak *et al*. (2010), Maleki *et al*. (2013), Candogan and Yazgan (2015) and Iqbal *et al*. (2018) who reported reduced soybean plant growth due to soil moisture limitation.

Plant growth is anchored by photosynthesis through synthesis of photoassimilates for plant cell division, multiplication, elongation and general plant growth (Kirnak *et al.,* 2010). Findings of this study have shown that soil moisture stress reduced stomata conductance, sub-stomatal carbon dioxide concentration which led to reduced photosynthetic rate. Reduced photosynthetic rate means that plants grown at lower than optimal soil moisture levels had limited cell division and elongation leading to retarded plant growth (Rehem *et al*., 2012). Cell turgidity, which is a function of plant water status, helps water uptake, maintenance of plant metabolic activities leading to plant growth (Gunasekera and Berkowitz, 1992; Zlatev and Lidon, 2005). Leaf relative water content, as an indicator of plant water status, was lower at higher soil moisture limitation which could have contributed to reduced plant cellular and metabolic activities translating into retarded soybean plant growth. Under soil moisture stress, there is limited uptake of mineral nutrients to support plant growth. Limited mineral nutrient acquisition may arise from suppressed root growth, limited root penetration in the soil profile and limited uptake of less mobile nutrients like phosphorous due to absence of water as solvent and medium through which nutrients are acquired (Fahad *et al*., 2017). Reduced leaf area and LAI at lower soil moisture levels may be a result of suppressed leaf production in addition to increased leaf senescence. Shoot growth varied with type of cultivars used though it was generally observed that indeterminate cultivars were taller and determinate cultivars bushier (wider canopy) which are typical characteristics of the two growth habits of soybean (Mangena, 2018). Early cessation of flowering and vegetative growth in determinate soybean cultivars suppresses increase in plant height which leads to increased stem thickness (Szareski *et al.,* 2018).

**Effect of soil moisture stress on leaf gaseous exchange**

Results have shown that soil moisture stress reduced IPAR, leaf relative water content (LRWC), chlorophyll 'a' and total chlorophyll contents, stomata conductance, sub-stomatal carbon dioxide concentration, transpiration and photosynthetic rates. Soil moisture limitation increased leaf temperature while chlorophyll 'b' concentration was not significantly responsive to soil moisture variations. Reductions in IPAR, leaf relative water content, chlorophyll 'a' and total chlorophyll contents, stomata conductance, sub-stomatal carbon dioxide concentration, transpiration and photosynthetic rate due to soil moisture stress effects were reported by Kirnak *et al*. (2010), Krivodska and Filova (2013) and Jha *et al*. (2018) which is in agreement with findings of this study. Results however contradict findings of Zhang *et al*. (2016) who reported increased sub-stomatal carbon dioxide concentrations and chlorophyll contents at reduced soil moisture levels. Silvente *et al.* (2012) indicated that soil moisture limitation did not have a significant effect on leaf chlorophyll concentration which is also at variance with results of this study. Variations in results between previous studies and current results can be attributed to differences in soil moisture levels and durations of stress considering that most previous studies imposed water limitation either at flowering or pod filling stages. In this study soil moisture stress was imposed from 30 days after seed germination up to physiological maturity of the crop.

Soil moisture stress suppressed production of branches and leaves which might have contributed to reduction in plant canopy development and leaf area. This led to reduced IPAR at lower soil moisture regimes. Reduced canopy development at lower soil moisture regimes increases exposure of plants to excessive heat which may lead to photo-oxidation. Photo-oxidation enhances production of reactive oxygen species (ROS) which have deleterious effects on photosynthesis (Li *et al*., 2009). Production of ROS reduce tissue concentration of chlorophyll which possibly explains lower concentrations of chlorophylls at lower soil moisture regimes (Kiani *et al*., 2008). Soil moisture stress increases production of endogenous abscisic acid which leads to closure of stomata to avoid desiccation of plants through tissue water loss through transpiration (Osakabe *et al*., 2014). Stomata closure at lower soil moisture levels could also have emanated from reduction in leaf water potential as evidenced from lower LRWC (Yan *et al.,* 2016). Stomata closure under soil moisture tress limited transpiration rate, uptake and diffusion of carbon dioxide into intercellular spaces of plant leaves (Dalal *et al*., 2012). Decrease in stomata conductance under soil moisture stress increases leaf temperature due to reduced transpiration rate which helps with evaporative cooling of plants (Monteiro *et* *al.*, 2016). Reduced uptake and diffusion of carbon dioxide suppresses photosynthetic rate (Jaleel *et al*., 2009). Results of the study have shown that soil moisture limitation reduced leaf production which could have therefore led to lower photosynthesis in plants under soil moisture stress. Considering that chlorophyll has a significant role in light harvesting for photosynthesis, reduced metabolism of chlorophyll due to soil moisture stress could have also contributed to reduction in photosynthetic rates under soil moisture limiting conditions (Jaleel, *et al.*, 2009). Soil moisture reduces activity of photosynthetic enzymes such as Rubisco and phosphoenolpyruvate carboxylase which can lead to a reduction in photosynthesis (Zlatev and Lidon, 2012). This may have led to the observed reduction in photosynthesis.

Day time temperatures were higher and relative humidity lower during 2019 season compared to 2018 season which could have triggered increased stomata resistance to water loss. Higher photosynthetic rate during 2019 season could have emanated from increased sub-stomatal carbon dioxide concentration relative to 2018 season. Even under drier conditions, plants will open stomata to allow more carbon dioxide to enter for photosynthesis to take place (Araújo *et al*., 2011). Higher leaf temperature during 2018 season could have resulted from reduction in transpiration rate which helps with cooling of plants (Monteiro, *et al.*, 2016). Lower LRWC during a hotter and drier season of 2019 concurs with findings of Jeon *et al*. (2006) who indicated that plants will generally have reduced LRWC when temperatures are higher. Jeon *et al.* (2006) also indicated that photo-oxidative damage to chlorophyll is lower at higher relative humidity and lower daytime temperatures. This possibly explains higher chlorophyll content during 2018 season when relative humidity was higher and temperatures lower than 2019 season. All soybean cultivars had more leaves and higher leaf area during 2018 season which translated into increased IPAR during the season compared to 2019 season.

Stomata conductance and photosynthetic rate were generally higher for soybean cultivars with indeterminate growth habit (DPSB 19 and DPSB 8) compared to cultivars with determinate growth habit. Soybean cultivars with indeterminate growth habit exhibit greater stomata density, higher number of epidermal cells and are able to recover from soil moisture stress much faster than determinate cultivars (Villalobos-Rodriquez and Shibles, 1985). This explains why indeterminate soybean cultivars had relatively higher photosynthetic rate compared to determinate ones.

### Effect of soil moisture stress on reproductive growth

Reduction in number of days to flowering and pod maturity by soybean plants grown under soil moisture limitation as found in the study is in line with findings of Jha *et al*. (2018). Similar results with common beans were reported by Rezene *et al*. (2013) and Ntukamazina *et al*. (2017). Early flowering and pod maturity under soil moisture stress is considered as a drought escape mechanism that allows plants to complete their life cycle within a short period of favourable conditions and in the process minimize exposure of plants to drought stress effects (Franks, 2011). Drought escape allows rapid transition from vegetative to reproductive development due to accelerated flower differentiation (Su *et al*., 2013; Shavrukov *et al*., 2017). Soil moisture stress also contributes to over-expression of flowering time genes and transcription factors (GmFDL19) which lead to early flowering of soybean plants (Li *et al*., 2017). Soybean plants flowered and matured earlier during 2019 season which could have been a result of higher temperatures. High temperatures accelerate floral bud formation which may also lead to early maturity of soybean plants (Zheng *et al.*, 2002).

### Effect of soil moisture stress on soybean yield and yield components

Soil moisture stress reduced number of pods per plant, number of pods per node, pod length, number of seeds per pod, seed weight, protein content and grain yield. These results correspond to findings by Demirtas *et al.* (2010), Ghassemi-Golezani and Lofti (2012) and Chafi and Gohari (2013). Karam *et al*. (2005) who reported that soil moisture stress did not have a significant effect on number of seeds per pod which contradicts results of this study. Equally, Iqbal *et al*. (2018) reported an increase in protein content of soybean grains due to soil moisture limitation which also differs with findings of this study.

Soil moisture stress during flowering, podding and grain filling stages increases flower and pod abortions and thus result into reduced number of pods per plant, number of pods per node and number of seeds per pod (Pushpavalli *et al*., 2014). Reduction in pod formation under soil moisture stress may also arise from pollen sterility which leads to poor pollen germination (Al-Ghzawi *et al.*, 2009). Photosynthesis is a source of photo-assimilates for pod and seed development (Farooq *et al*., 2014). Results of this study have however shown that soil moisture stress reduced photosynthetic rate which could have limited supply of photosynthates to reproductive sinks (Gusmao *et al*., 2012). Effective nodulation and biological nitrogen fixation are key to realization of optimal soybean grain yield. It is however reported that under soil moisture stress, rhizobia undergo morphological changes that cause reduction in infection and nodulation of soybean roots leading to low grain yield (Busse and Bottomley, 1989; Farooq *et al*., 2017). Lower number of pods per plant, pod length, 100 seed weight and grain yield during 2019 season may be due to higher day temperature experienced during 2019 season relative to 2018 season. High day temperatures increase flower and pod abortions and reduces grain filling in soybean resulting into reduced grain yield (Gibson and Mullen, 1996; Pushpavalli *et al*., 2014). Despite higher photosynthetic rates during 2019 than 2018 season, soybean yields were lower during 2019 season which can be attributed to effects of soybean bacterial blight (*Pseudomona savastonoi* pv. *glycinea*) which affected soybean plants during pod filling stage. Reduction in protein content under soil moisture limitation could have arisen from reduced partitioning and fixation of nitrogen which led to lower protein accumulation in soybean grains (Singh, 2007).

Results of the study have shown that soil moisture stress reduced soybean plant growth through suppression of plant height, branching and leaf production. Soil moisture limitation resulted into reduced stomata conductance and sub-stomata carbon dioxide concentration which led to reduced rates of photosynthesis. Lower rates of photosynthesis due to soil moisture stress meant a reduction in the synthesis of photoassimilates to support pod development and grain filling which reduced grain yield. Soybean grain yield were generally higher during 2018 season compared to 2019 season. Cultivar DPSB 19 had highest photosynthetic rate which meant synthesis of adequate photoassimilates that supported retention of high number of pods per plant which ultimately led to increased grain yield by the cultivar.

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# CHAPTER FIVE

# EFFECT OF PLANTING DENSITY ON YIELD AND YIELD COMPONENTS OF SOYBEAN

**Abstract**

Planting density affects plant structural characteristics and may influence competition for mineral nutrients and light interception for plant growth and photosynthesis amongst plants. An experiment was conducted to determine the effect of planting density on yield and yield components of soybean (*Glycine max* (L) Merrill) cultivars. The experiment was laid out as a randomized complete block design (RCBD) in a 5 by 2 factorial treatment arrangement and was replicated three times. Planting density (10, 12, 20, 40 and 80 plants $m^{-2}$) and soybean cultivars (EAI 3600 and DPSB 19) were first and second factors, respectively. Collected data were subjected to analysis of variance (ANOVA) using Linear Mixed Model in GENSTAT. Higher planting density significantly ($p < 0.001$) increased soybean plant height, internode length, interception of photosynthetically active radiation and grain yield. Increasing number of plants per unit area significantly ($p < 0.001$) reduced soybean canopy diameter, stem thickness, number of branches per plant, leaf area, stomata conductance, sub-stomatal carbon dioxide concentration and photosynthetic rate. Highest number of nodules per plant were attained at 10 plants $m^{-2}$ which was 34.76% more than number of nodules obtained at 80 plants $m^{-2}$. Soil moisture depletion at 80 plants $m^{-2}$ was 15.22% higher than at the lowest plant population of 10 plants $m^{-2}$. Highest soybean yields of 2246 kg $ha^{-1}$were obtained at the highest plant density of 80 plants $m^{-2}$. However due to high incidences of lodging at 80 plants $m^{-2}$, planting soybean at 20 plants $m^{-2}$ is recommended for use by farmers when planting soybean.

## 5.1 Introduction

Planting density in crop production affects plant structural characteristics and may help improve disease avoidance, lodging resistance, adaptation to mechanical harvesting and seed yield (Rahman *et al*., 2011). A higher plant density has the potential to increase competition for nutrients, light and space while lower plant density may lead to inefficient use of natural resources and inputs (Lone *et al*., 2010; Deressegn and Telele, 2017). Total dry weight of leaves, leaf area index (LAI) and nodulation are all dependent on plant density (Lone *et al*., 2010). In soybeans, grain quality such as protein, oil and mineral contents depend on field production conditions with planting population playing a significant role (Shamsi and Kobraee, 2011).

Previous plant density studies have recommended different plant populations for optimization of soybean yields. In United States of America, optimum plant populations for soybean vary from 30 to 50 plants $m^{-2}$ (Grichar, 2007) while in Iran and India, soybean yields were optimized at 60 plants $m^{-2}$ (Daroish *et al*., 2005; Singh, 2010). In Turkey, Mehmet (2008) found highest soybean yields at plant density of 12.5 plants $m^{-2}$ while Rahman *et al*. (2011) recommended a planting density of 80-100 plants $m^{-2}$ in Bangladesh. In Ethiopia, the recommended plant population for soybean is about 40 plants $m^{-2}$ (Deressegn and Telele, 2017). Plant populations also varied with soybean growth habits and seasons. The reported results confirm the thinking that plant density may vary with type of cultivar used and that some areas, depending on geographical location, have capacity to support higher planting densities than others due to differences in soil and other environmental conditions (Bilal Ahmad *et al*., 2009). This, therefore, shows the need of subjecting new soybean cultivars to plant population studies in time and space so that variety and area specific recommendations are made to optimize soybean yields. The advent of climate change due to global warming in recent years has also brought with it various biotic and abiotic stresses which makes it prudent to adjust agronomic practices in line with prevailing climatic conditions. It was for this reason that a study was undertaken to determine the effect of plant density on yield components and yield of determinate and indeterminate soybean cultivars in Kenya.

### 5.1.1 Effect of planting density on shoot growth and root nodulation

Soybean shoot growth response to different seeding rates by Cox *et al*. (2011) showed a 20% increase in number of branches per plant at higher seeding rates than at lower seeding rates. Plant height, leaf area and leaf area index (LAI) were not significantly affected by differences in seeding rates at reproductive stage of soybean growth. Chauhan and Opeňa (2013) reported a non-significant effect of plant spacing variations on plant height. Wider row spacing however reduced leaf area and leaf biomass but increased number of leaves per plant. Soybean morphophysiological and yield responses to seeding systems and plant population study by Souza *et al.* (2016) reported an increased plant height and faster canopy closure at higher sowing density relative to lower plant density. Neither leaf area nor leaf area index was affected by different sowing densities. Growth habit of soybean cultivars significantly influenced leaf area and leaf area index with determinate growth habit having 19.83% and 15.7% increase in leaf area and leaf area index over semi-determinate growth habit. Worku and

Astatkie (2011) reported an increase on number of branches per plant at lower plant density than at higher plant density.

Plant density and nodulation studies by Khubele (2015) and Luca and Hungria (2014) indicated that lower plant density increased both number of nodules per plant and nodule biomass compared to treatments with higher plant population. Bejandi *et al.* (2012) and Kena (2018) indicated a non-significant effect of plant density on total number of nodules and number of effective nodules per plant. Total number of nodules per plant and nodule efficiency also varied with type of cultivar.

### 5.1.2 Effect of planting density on chlorophyll content and leaf gas exchange

A study by Moreira *et al*. (2015) reported that higher plant density reduced soybean stomata conductance, transpiration rate and chlorophyll content. Photosynthesis rate and intercellular carbon dioxide concentration were not significantly influenced by differences in plant populations. Koesmaryono *et al*. (1997) studied effects of plant density on photosynthetic rate, dry matter production and $^{13}C$ labelled distribution in soybean. Results of this study indicated that the lower the planting density, the higher the photosynthetic rate per plant. However, net photosynthesis rate per unit area was greater at higher plant density than at lower plant density. Reductions in intercepted photosynthetically active radiation (IPAR) and radiation use efficiency (RUE) at lower plant density were reported by Zhou *et al.* (2011).

Plant population studies with pigeon peas (*Cajanus cajan*) by Wilson *et al*. (2012) showed that varying plant population did not have a significant effect on photosynthetic rate, stomata conductance and transpiration rate. Nonetheless, photosynthetic rate, stomata conductance and transpiration rate varied with type of pigeon pea cultivar used. Plant population studies on groundnuts (*Arachis hypogaea*) by Suprapto *et al*. (2012) showed an increased interception of solar radiation at higher than at lower plant population and radiation efficiency varied with interception varying with cultivar used. Studies with sorghum (*Sorghum bicolor*) by Li *et al*. (2014) concluded that high plant population per unit area reduced light interception which also translated into reductions in stomata density, stomatal conductance and photosynthetic rate.  Non-significant effect of plant density on chlorophyll content on chickpea (*Cicer arietinum* L.) were reported by Bejandi *et al*. (2012).

### 5.1.3 Effect of plant density on soil moisture status

It is generally expected that a higher plant population will lead to increased depletion of soil moisture which may also vary with stage of crop growth, type of row arrangement, soil type and amount of rainfall received (Shaxson and Barber, 2003). While this is the case, studies with various crops have generated wide range of results on how soil moisture is impacted by variations in plant density. Zhou *et al.* (2015) reported that soybean plant density did not have a significant effect on soil moisture content. Soil moisture content however varied with crop growth stage. Results on plant density studies with maize (*Zea mays*) by Okbagabir *et al*. (2017) showed that variations in plant density did not significantly influence soil moisture content during early stage of crop development which was attributed to minimal differences in canopy formation. At later stages of crop development (40-60 days after planting), higher plant density significantly decreased soil moisture content. Maize varieties did not however have a significant effect on soil moisture depletion. Studies with barley (*Hordeum vulgare)* by Kumar *et al*. (2017) indicated a significant increase in soil moisture depletion at higher plant density compared to lower plant density. Soil moisture depletion also significantly varied with type of cultivar used which was attributed to increased evapotranspiration demand for genotypes with more vigorous growth characteristics.

### 5.1.4 Effect of planting density on reproductive growth

Kena (2018) indicated that number of days for soybean to flower and attain physiological maturity were not significantly responsive to differences in plant population. This observation however contradicted results by Akond *et al*. (2013) which indicated a delayed flowering of soybean at lower plant density. Number of days to flowering and pod maturity varied with type of cultivar. Studies with faba beans (*Phaseolus vugaris* L) by Mekonnen (2012) showed that high plant density hastened flowering unlike at lower plant density. Determinate faba bean cultivars flowered earlier than indeterminate ones. Number of days to maturity of faba beans were not significantly responsive to variations in planting density. While this was the case, accelerated physiological maturity of beans at higher plant density was reported by Masa *et al*. (2017). Studies with chickpea indicated a hastened maturity of the crop at higher plant density (Bejandi *et al*., 2012). Plant density studies with mung bean (*Vigna radiata*) in Ethiopia by Birhanu *et al.* (2018) reported that high plant density reduced both number of days to 50% flowering and 90% pod maturity.

### 5.1.5 Effect of planting density on yield components and yield

Effects of plant density on growth, yield and yield components of soybean under equidistant planting arrangement were studied by Rahman and Hossain (2011). Findings of the study showed an increase in soybean grain yield at higher plant density of up to 80-100 plants $m^{-2}$ which also varied with types of cultivar and seasons. Increase in plant density reduced number of pods per plant, number of seeds per pod and 100 seed weight. In a related study by Rahman *et al*. (2013), protein content of soybean grain showed a quadratic relationship with plant density. Seed protein content decreased with increase in plant density up to between 80-100 plants $m^{-2}$ and then increased with further increase in plant density. A decrease in protein content for soybean planted at lower plant density was reported by Luca and Hungria (2014).

Soybean plant density study in Japan by Matsuo *et al*. (2018) reported a 13% increase in soybean grain yield at higher plant density compared to grain yield obtained at lower plant density. Number of pods per $m^{-2}$ was greater at higher plant density than at lower plant density. Higher plant density also led to higher incidences of plant lodging which also varied with type of cultivar. Results by Gulluoglu *et al*. (2017) indicated that varying soybean plant population led to higher soybean grain yield at higher plant density. Number of pods per plant and 100 seed weight were significantly reduced with an increase in plant density. Number of seeds per pod was not responsive to variations in plant density. Similarly, Ibrahim and Kandil (2007) and Madanzi *et al*. (2012) reported reductions in soybean grain yield at low plant density with number of pods per plant, number of seeds per pod and seed weight decreasing with increase in plant density. Concentration of nitrogen, phosphorous, potassium and iron in soybean grain increased with reduction in plant density.

The foregone review has shown contradictory responses on the effect of plant density on soybean plant growth and yield. Results reported were in some instances influenced by supplementary management practices including irrigation, use of nitrogenous fertilizers and limitation in use of soybean cultivars with different growth habits. The current study incorporated soybean genotypes with determinate and indeterminate growth habits which is expected to give more insights on how soybean cultivars with different growth habits would respond when plant populations are varied. It has also been shown from the review that results also varied with geographical location suggesting a possible effect of soil types and environmental conditions in plant population studies. This points to the importance of using locally generated results to improve crop production and productivity. Results of the study will therefore help narrow information gap in time and space on effect of plant density on soybean growth and yield under Kenyan conditions.

## 5.2 Materials and methods

### 5.2.1 Site description

The experiment was conducted at Egerton University agronomy teaching and research farm in Njoro, Nakuru County over two seasons. The first season was during long rains of March to July 2018 while the second season was during short rains of September to November 2018. Egerton University teaching and research farm ($0^{o}$ 22'S; $35^{o}$ 56'E) is at an altitude of 2267 m.a.s.l. Soil sampling and analysis of physical and chemical properties of the soil from the site was done prior to planting as described under section 3.3.1 of experiment 1. Monthly rainfall amounts, minimum and maximum temperature and relative humidity of the site were monitored from Egerton University metrological station.

### 5.2.2 Experimental design and treatments

The experiment was conducted in a randomized complete block design (RCBD) with a 5 x 2 factorial treatment arrangement and replicated 3 times. Treatments consisted of two factors: factor 1 being planting density and factor 2 being cultivars. Treatment combinations are presented in Table 5.1

Table 5.1 Description of experimental treatments

| NO. | Treatment combinations | Row spacing |
|---|---|---|
| 1 | 10 plants per $m^2$ × cultivar EAI 3600 | 45 cm between rows, 20 cm within row |
| 2 | 12 plants per $m^2$ × cultivar EAI 3600 | 45 cm between rows, 15 cm within row |
| 3 | 20 plants per $m^2$ × cultivar EAI 3600 | 45 cm between rows, 10 cm within row |
| 4 | 40 plants per $m^2$ × cultivar EAI 3600 | 45 cm between rows, 5 cm within row |
| 5 | 80 plants per $m^2$ ×cultivar EAI 3600 | 25 cm between rows, 5 cm within row |
| 6 | 10 plants per $m^2$ × cultivar DPSB 19 | 45 cm between rows, 20 cm within row |
| 7 | 12 plants per $m^2$ × cultivar DPSB 19 | 45 cm between rows, 15 cm within row |
| 8 | 20 plants per $m^2$ × cultivar DPSB 19 | 45 cm between rows, 10 cm within row |
| 9 | 40 plants per $m^2$ × cultivar DPSB 19 | 45 cm between rows, 5 cm within row |
| 10 | 80 plants per $m^2$ × cultivar DPSB 19 | 25 cm between rows, 5 cm within row |

### 5.2.3 Planting and crop management

Based on results of experiments 1 and 2, cultivars EAI 3600 (determinate) and DPSB 19 (indeterminate) were used in the experiment based on moisture stress tolerance and early maturing attributes. First season experiment was planted on 29th March 2018 while a second season experiment was planted on 12th July 2018. Gross plot sizes were 4.5 m long and 4 m wide (18 $m^2$) while net plot size were 2.25 m by 3 m (6.75 $m^2$). Two soybean seeds were planted per hill and where both emerged it was thinned to one plant 7 days after emergence. Soybean seeds were inoculated with BIOFIX *(Bradyrhizobium japonicum)* inoculant strain USD 110 from Mea Limited–Kenya at the rate of 10 g $kg^{-1}$ of seed prior to planting. Triple Super Phosphate and Muriate of Potash were applied at 30 kg $P_2O_5$ $ha^{-1}$and 30 kg $K_2O$ $ha^{-1}$ respectively as basal dressing fertilizers. Weeding was done using hand hoe as weeds appeared.

### 5.2.4 Data collection

Data were collected on plant height, internode length, number of branches per plant, stem diameter, number of leaves per plant, canopy diameter, leaf area, leaf biomass, soil moisture content, root nodulation, intercepted photosynthetically active radiation (IPAR), stomata conductance, photosynthesis rate, transpiration rate, chlorophyll content, leaf carbon dioxide concentration, leaf temperature, number of days to flowering and pod maturity, harvest lodging, number of pods per plant, number of seeds per pod, pod length, 100 seed weight, grain yield and grain protein content. Details of data collection on the above parameters are as described under sections 3.3.5 and 4.3.5 of experiments1 and 2, respectively.

**Soybean lodging assessment**

Soybean lodging was assessed using a scale of 1 to 5 (Table 5.2) as described by Lommel (2016).

Table 5.2 Scoring scale of soybean lodging

| Score | Description |
|---|---|
| 1 | Almost all plants erect |
| 2 | Less than 25% of plants lodged, or plants lean > 60° from ground |
| 3 | 25-50% of plants lodged, or all plants lean approximately 45° from ground |
| 4 | 50-80% of plants are lodged, or all plants lean < 45° from the ground |
| 5 | Almost all plants are lodged |

**5.3 Statistical model and data analysis**

Data were checked for fulfilment of analysis of variance (ANOVA) assumption of normality by using Shapiro-Wilk normality test in Genstat release 18.1. Data were considered normally distributed when *p*-value for Shapiro-Wilk statistic was greater than the threshold *p*-value of 0.05. Data that did not meet the aforesaid ANOVA assumption were subjected to log base 10 [log 10(x+c] transformation before analysis. Data were then subjected to analysis of variance (ANOVA) using linear mixed model for factorial experiment in GENSTAT (REML). The following statistical model was used in the analysis of experimental results.

$Y_{ijkm} = \mu + V_i + ß_j + (Vß)_{ij} + R_k + S_m + (VS)_{im} + (ßS)_{jm} + (VßS)_{ijm} + \varepsilon_{ijk},$

Where:

$Y_{ijk}$ = $k^{th}$ observation on $i^{th}$ treatment in $j^{th}$ block; µ = overall mean; $V_i$ = effect of density at $i^{th}$ level; $ß_j$ = effect of cultivar at $j^{th}$ level; $(Vß)_{ij}$ = interaction effect of density at $i^{th}$ level and cultivar at $j^{th}$ level; $R_k$ = effects of block; $S_m$ = effect of season; $(VS)_{im}$ = interaction effect of density and season; $ßS)_{jm}$ = interaction effect of cultivar and season; $(VßS)_{ijm}$ = interaction effect of density, cultivar and season; $\varepsilon_{ijkm}$ = random error normally distributed with mean zero.

Correlation analyses were done on individual treatment means using Genstat release 18.1 to determine inter-character association amongst some selected yield components and quantitative traits.

### 5.4. Results

### 5.4.1. Effect of plant density on shoot growth

***Plant height***

Plant height significantly ($p < 0.001$) varied with plant density (Figure 5.1), cultivars and seasons. Tallest plants were obtained at the highest plant density of 80 plants $m^{-2}$ which corresponded to 16.64% increase over the shortest plants attained at plant density of 12 plants $m^{-2}$. Cultivar EAI 3600 had tallest plants (78.49 cm) compared to cultivar DPSB 19 (58.29 cm. Soybean plants were taller during short rainy season (74.46 cm) compared to long rainy season (62.32 cm).

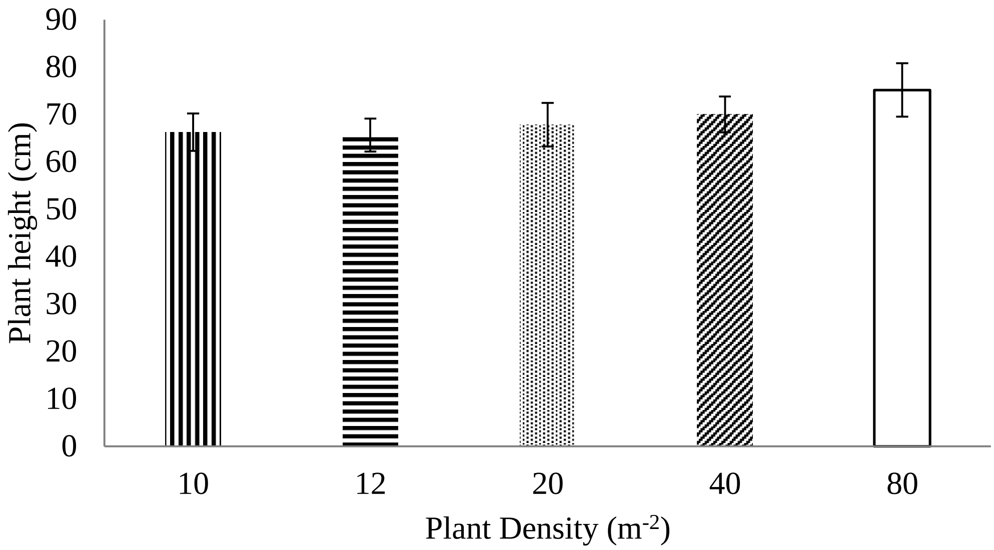


Figure 5.1 Effect of plant density on soybean plant height at 50% podding stage. Error bars represent ± standard error. Values significantly different at $p < 0.001$.

***Internode length***

Internode length was significantly influenced by interaction of density and cultivars ($p < 0.001$) and interaction of density and seasons ($p < 0.01$). Longest internode length was attained at 80 plants $m^{-2}$ by cultivar EAI 3600 (Table 5.3).

Table 5.3 Effect of planting density, cultivar and season on internode length (cm) at 50% podding stage

| Internode length (cm) | | | |
|---|---|---|---|
| | Cultivars | | |
| Plant density ($m^{-2}$) | EAI 3600 | DPSB 19 | Mean |
| 10 | 5.56 | 4.62 | 5.09 |
| 12 | 5.07 | 5.24 | 5.15 |
| 20 | 5.91 | 4.98 | 5.45 |
| 40 | 7.58 | 5.85 | 6.71 |
| 80 | 8.00 | 6.68 | 7.34 |
| Mean | 6.42 | 5.47 | |
| *p*-value | < 0.001 | | |
| SED | 0.189 | | |
| | Seasons | | |
| Plant density ($m^{-2}$) | Long rains 2018 | Short rains 2018 | |
| 10 | 4.72 | 5.46 | |
| 12 | 4.74 | 5.56 | |
| 20 | 5.04 | 5.85 | |
| 40 | 6.77 | 6.66 | |
| 80 | 7.03 | 7.65 | |
| Mean | 5.66 | 6.24 | |
| *p*-value | 0.006 | | |
| SED | 0.189 | | |
| Cultivar × Season | 0.947 | | |
| Density × Cultivar × Season | 0.211 | | |

SED = ± Standard error of difference of means

***Canopy diameter***

Plant canopy development was significantly ($p < 0.001$) responsive to plant density and type of cultivar used (Figure 5.2). Widest plant canopy diameter was attained at the lowest plant population of 10 plants $m^{-2}$ corresponding to 28.38% increase over canopy diameter obtained at the highest plant population of 80 plants $m^{-2}$. A determinate cultivar EAI 3600 had widest canopy diameter (47.55 cm) compared to indeterminate cultivar DPSB 19 (40.88 cm).

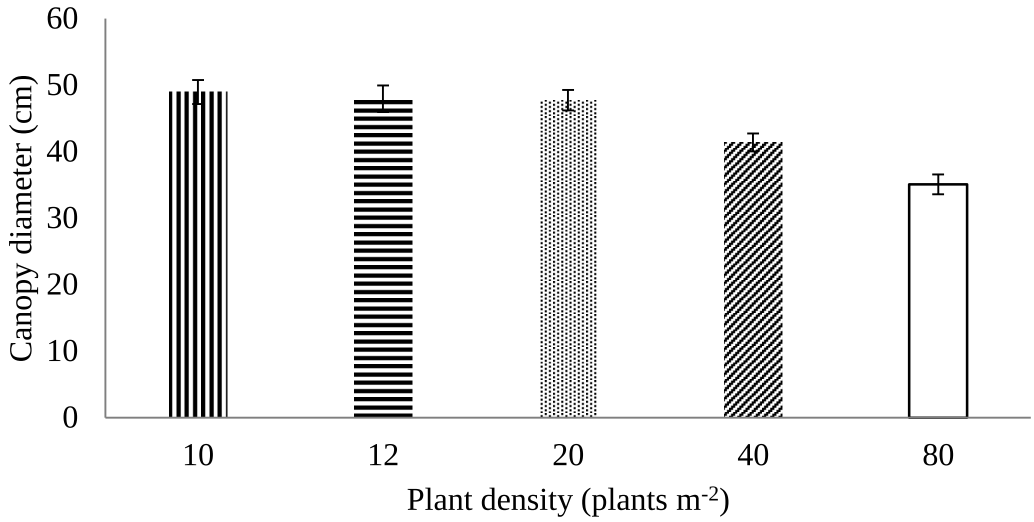


Figure 5.2 Effect of plant density on soybean canopy diameter at 50% podding stage Error bars represent ± standard error. Values significantly different at $p < 0.001$.

***Stem diameter***

The interaction of plant density, cultivars and seasons significantly ($p < 0.001$) influenced stem diameter (Table 5.4). Cultivar EAI 3600 had thickest stems at the lowest plant density of 10 plants $m^{-2}$ during long rainy season. On the other hand, cultivar DPSB 19 had thinnest stems at 80 plants $m^{-2}$ during short rainy season.

Table 5.4 Effect of planting density, cultivar and season on stem diameter (mm) at 50% podding stage

| | Stem diameter (mm) | | | | |
|---|---|---|---|---|---|
| | EAI 3600 | | DPSB 19 | | |
| Density (Plants $m^{-2}$) | Long rains 2018 | Short rains 2018 | Long rains 2018 | Short rains 2018 | Mean |
| 10 | 6.87 | 6.63 | 6.13 | 5.56 | 6.30 |
| 12 | 6.50 | 5.63 | 5.53 | 5.21 | 5.71 |
| 20 | 5.56 | 5.84 | 5.83 | 5.10 | 5.58 |
| 40 | 4.29 | 4.53 | 4.42 | 4.28 | 4.38 |
| 80 | 4.48 | 4.68 | 4.33 | 3.99 | 4.37 |
| Mean (cultivar) | 5.50 | | 5.04 | | |
| *p*-value | < 0.001 | | | | |
| SED | 0.106 | | | | |
| CV (%) | 3.5 | | | | |

SED = ± Standard error of difference of means; CV = Coefficient of variation.

***Number of branches***

Number of braches borne from primary stem significantly ($p < 0.001$) changed with main effects of plant density, cultivars and seasons. Planting at 40 and 80 plants m$^{-2}$ reduced branches per plant compared to having 10, 12 and 20 plants m$^{-2}$ (Figure 5.3). Cultivar EAI 3600 had highest number of branches (6.74) compared to DPSB 19 (5.84). Highest number of branches were attained during short rainy season (7.42) than during long rainy season (5.16).

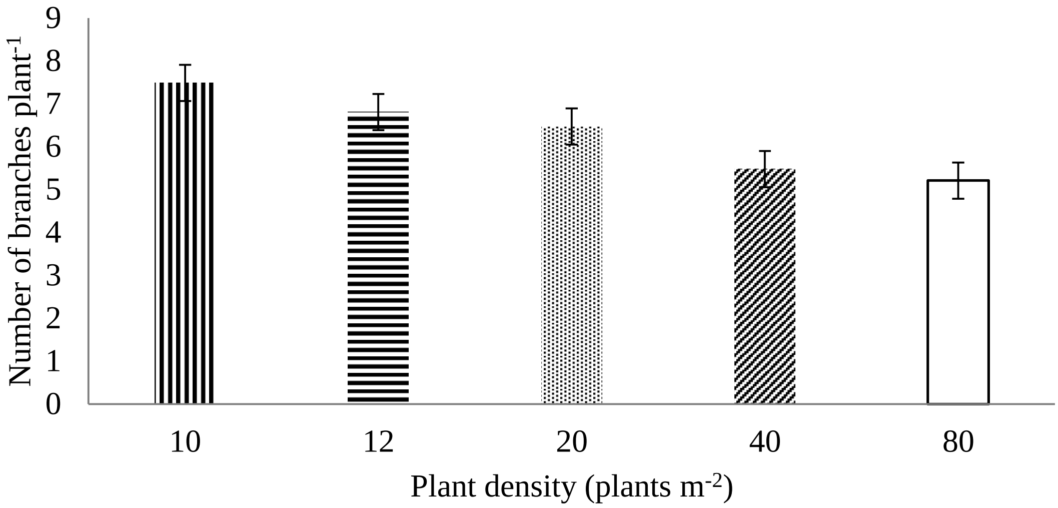


Figure 5.3 Effect of plant density on number of soybean branches per plant at 50% podding stage. Error bars represent ± standard error. Values significantly different at $p < 0.001$.

***Number of leaves***

Interaction effects of plant density and cultivars ($p < 0.05$) and that of cultivars and seasons ($p < 0.001$) significantly influenced number of leaves borne from primary stem (Table 5.5). Highest number of leaves were attained by cultivar EAI 3600 at the lowest plant density of 10 plants m$^{-2}$. Cultivar EAI 3600 had highest number of leaves during short rains.

Table 5.5 Effect of plant density, cultivar and season on number of leaves at 50% podding stage

| Number of leaves on primary stem | | | |
|---|---|---|---|
| | Cultivar | | |
| Plant density (plants $m^{-2}$) | EAI 3600 | DPSB 19 | Mean |
| 10 | 10.93 | 9.47 | 10.20 |
| 12 | 10.90 | 9.28 | 10.09 |
| 20 | 10.92 | 8.48 | 9.70 |
| 40 | 10.40 | 7.67 | 9.03 |
| 80 | 8.70 | 8.23 | 8.47 |
| Mean | 10.37 | 8.63 | |
| *p*-value | 0.033 | | |
| SED) | 0.52 | | |
| CV (%) | 9.5 | | |
| **Seasons** | | | |
| Long rains 2018 | 10.11 | 9.44 | 9.78 |
| Short rains 2018 | 10.63 | 7.81 | 9.22 |
| Mean | 10.37 | 8.63 | |
| *p*-value | < 0.001 | | |
| SED | 0.329 | | |
| CV (%) | 9.5 | | |
| | *p*-value | | |
| Density × Season | 0.083 | | |
| Density × Season × Cultivar | 0.114 | | |

SED = ± Standard error of difference of means; CV = Coefficient of variation.

***Measure of leaf area***

Results from Table 5.6 indicate that leaf area significantly varied with interaction of plant density and cultivars ($p < 0.01$) and with interaction of cultivars and seasons. Highest leaf area per plant was attained by determinate cultivar EAI 3600 at the lowest plant population of 10 plants $m^{-2}$. Cultivar and season interaction led to increased leaf area during short rains by cultivar EAI 3600.

Table 5.6 Effect of plant density, cultivar and season on leaf area ($cm^2$) at 50% podding stage

| | Total leaf area ($cm^2$) | | |
|---|---|---|---|
| | Cultivar | | |
| Plant density (plants $m^{-2}$) | EAI 3600 | DPSB 19 | Mean |
| 10 | 3259 | 1897 | 2578 |
| 12 | 3231 | 1579 | 2405 |
| 20 | 2657 | 1169 | 1913 |
| 40 | 1368 | 831 | 1100 |
| 80 | 1058 | 669 | 863 |
| Mean | 2315 | 1229 | |
| *p*-value | 0.009 | | |
| SED | 291.2 | | |
| CV (%) | 28.5 | | |
| **Season** | | | |
| Long rains 2018 | 1849 | 1524 | 1687 |
| Short rains 2018 | 2781 | 934 | 1858 |
| Mean | 2315 | 1229 | |
| *p*-value | < 0.001 | | |
| SED | 184.1 | | |
| CV (%) | 28.5 | | |
| | *p*-value | | |
| Density × Season | 0.297 | | |
| Density × Season × Cultivar | 0.055 | | |

SED = ± Standard error of difference of means; CV = Coefficient of variation

***Leaf area index***

Leaf area index was determined as a ratio of total leaf area to ground area. Results in Table 5.7 indicate that leaf area index was significantly responsive to interaction of plant density and seasons ($p < 0.05$) and that of cultivars and seasons ($p < 0.001$). Leaf area index was highest at the highest plant density of 80 plants $m^{-2}$ during short rainy season. Cultivar EAI 3600 had highest leaf area index during short rains.

Table 5.7 Effect of density, cultivar and season on leaf area index at 50% poding stage

| | Leaf area index | | |
|---|---|---|---|
| | Seasons | | |
| Plant density (plants $m^{-2}$) | Long rains 2018 | Short rains 2018 | Mean |
| 10 | 2.76 | 2.80 | 2.78 |
| 12 | 3.57 | 3.07 | 3.32 |
| 20 | 3.59 | 4.25 | 3.92 |
| 40 | 5.04 | 4.40 | 4.72 |
| 80 | 4.86 | 5.86 | 5.69 |
| Mean | 3.96 | 4.08 | |
| *p*-value | 0.048 | | |
| SED | 0.951 | | |
| CV (%) | 17.2 | | |
| Cultivar | | | |
| EAI 3600 | 4.30 | 6.84 | 5.57 |
| DPSB 19 | 3.55 | 2.43 | 2.99 |
| Mean | 3.93 | 4.64 | |
| *p*-value | < 0.001 | | |
| SED | 0.601 | | |
| CV (%) | 17.2 | | |
| | *p*-value | | |
| Density × Cultivar | 0.781 | | |
| Density × Season × Cultivar | 0.481 | | |

SED = ± Standard error of difference of means; CV = Coefficient of variation.

### 5.4.2 Effect of plant density on leaf chlorophyll content and leaf gas exchange

***Chlorophyll content***

Total leaf chlorophyll and chlorophyll 'b' contents were not responsive to variations in plant density, cultivars and seasons. However, chlorophyll 'a' content significantly ($p < 0.01$) changed with plant density (Figure 5.4). Planting soybean at the lowest plant density of 10 plants $m^{-2}$ led to increased concentration of chlorophyll 'a' which was 25.38% more than the lowest chlorophyll 'a' levels obtained at plant density of 20 plants $m^{-2}$.

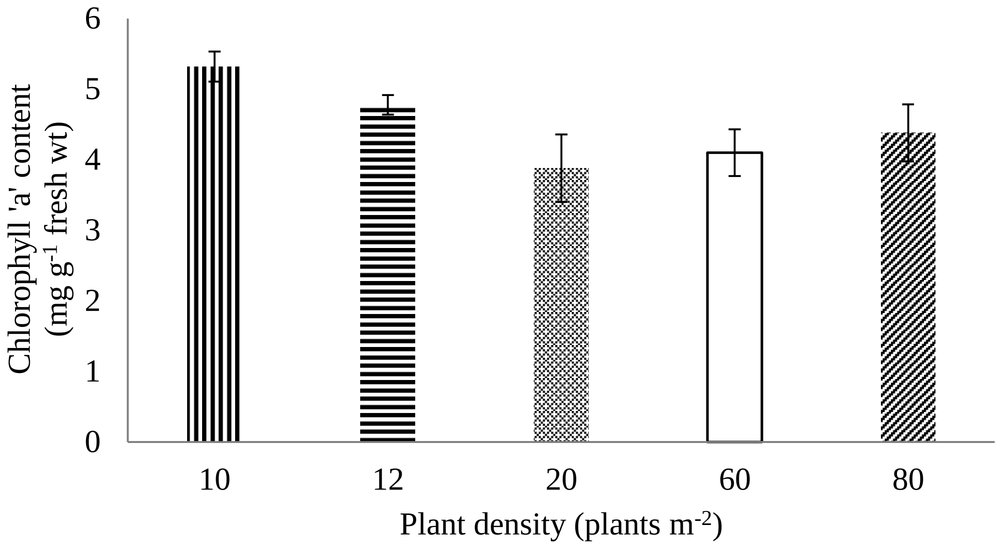


Figure 5.4 Effect of plant density on chlorophyll ‘a’ content of soybean leaves. Error bars represent ± standard error. Values significantly different at $p < 0.01$.

***Intercepted photosynthetically active radiation (IPAR)***

Interception of photosynthetically active radiation significantly ($p < 0.001$) changed with interaction of plant density and cultivars (Table 5.8). Both cultivars had increased interception of photosynthetically active radiation at the highest plant density of 80 plants $m^{-2}$. There was an increased interception of photosynthetically active radiation by the determinate cultivar EAI 3600 compared to indeterminate cultivar DPSB 19.

Table 5.8 Effect of plant density and cultivar on intercepted photosynthetically active radiation (IPAR) at 50% flowering stage

| | Intercepted photosynthetically active radiation (% of total in-coming) | | |
|---|---|---|---|
| | Cultivars | | |
| Plant density (plants $m^{-2}$) | EAI 3600 | DPSB 19 | Mean |
| 10 | 86.5 | 60.0 | 73.2 |
| 12 | 83.1 | 73.8 | 78.5 |
| 20 | 87.1 | 67.8 | 77.4 |
| 40 | 88.7 | 83.1 | 85.9 |
| 80 | 92.7 | 90.5 | 91.6 |
| Mean | 87.6 | 75.1 | |
| *p*-value | 0.034 | | |
| SED | 5.93 | | |
| CV (%) | 12.6 | | |
| | *p*-value | | |
| Density × Season | 0.557 | | |
| Variety × Season | 0.989 | | |
| Density × Season × Cultivar | 0.970 | | |

SED = ± Standard error of difference of means; CV = Coefficient of variation

***Stomata conductance***

Results in Table 5.9 indicate that stomata conductance was significantly ($p < 0.01$) responsive to interaction of plant density and cultivar; and also plant density and season at vegetative stage. At 50% flowering stage, stomata conductance varied with interaction of plant density and cultivar ($p < 0.001$), plant density and season ($p < 0.01$) and also cultivar and season ($p < 0.01$). At vegetative stage, stomata conductance was highest at the lowest plant density of 10 plants $m^{-2}$ by cultivar DPSB 19 while cultivar EAI 3600 had highest stomata conductance at the same plant density at 50% flowering stage. Plant density by season interaction led to increased stomata conductance at the lowest plant density during long rainy season regardless of plant growth stage. Interaction of cultivar and season resulted in cultivar DPSB 19 having highest stomata conductance level during long rainy season.

Table 5.9 Effect of plant density and cultivar on stomata conductance (mmol $m^{-2}$ $s^{-1}$) at vegetative and 50% flowering stages

| | Stomata conductance (mmol $m^{-2}$ $s^{-1}$) | |
|---|---|---|
| | Vegetative stage | 50% Flowering stage |
| Density (plants $m^{-2}$) x Cultivar | | |
| 10 × EAI 3600 | 60.9 | 38.44 |
| 10 × DPSB 19 | 69.6 | 29.33 |
| 12 × EAI 3600 | 61.8 | 33.87 |
| 12 × DPSB 19 | 50.0 | 33.08 |
| 20 × EAI 3600 | 50.7 | 30.38 |
| 20 × DPSB 19 | 68.7 | 24.09 |
| 40 × EAI 3600 | 46.2 | 16.28 |
| 40 × DPSB 19 | 60.4 | 26.45 |
| 80 × EAI 3600 | 49.1 | 15.95 |
| 80 × DPSB 19 | 53.1 | 24.12 |
| *p*-value | 0.009 | < 0.001 |
| SED | 5.83 | 7.24 |
| Density (plants $m^{-2}$) x Season | | |
| 10 × long rains | 72.7 | 45.11 |
| 10 × short rains | 57.8 | 22.67 |
| 12 × long rains | 64.2 | 39.52 |
| 12 × short rains | 47.6 | 27.43 |
| 20 × long rains | 54.3 | 36.36 |
| 20 × short rains | 65.1 | 18.12 |
| 40 × long rains | 52.6 | 23.96 |
| 40 × short rains | 54.0 | 18.77 |
| 80 × long rains | 48.6 | 25.30 |
| 80 × short rains | 53.6 | 14.77 |
| *p*-value | 0.005 | 0.002 |
| SED | 5.83 | 7.24 |
| Cultivar x Season | | |
| EAI 3600 × Long rains | 54.7 | 31.58 |
| EAI 3600 × Short rains | 52.8 | 22.39 |
| DPSB 19 × Long rains | 62.3 | 36.51 |
| DPSB 19 × Short rains | 58.5 | 18.32 |
| p-value | 0.719 | 0.002 |
| SED | 3.69 | 4.58 |
| Density ×Cultivar × Season | ns | ns |

SED = ± Standard error of difference of means; ns = not significant.

***Photosynthetic rate***

Photosynthetic rate at 50% flowering stage was significantly ($p < 0.001$) dependent on interaction of density and cultivar (Figure 5.5). Highest photosynthetic rate was attained at plant density of 20 plants $m^{-2}$ by cultivar DPSB 19 while the lowest photosynthetic rate was achieved at the highest plant population of 80 plants $m^{-2}$ by the same cultivar.

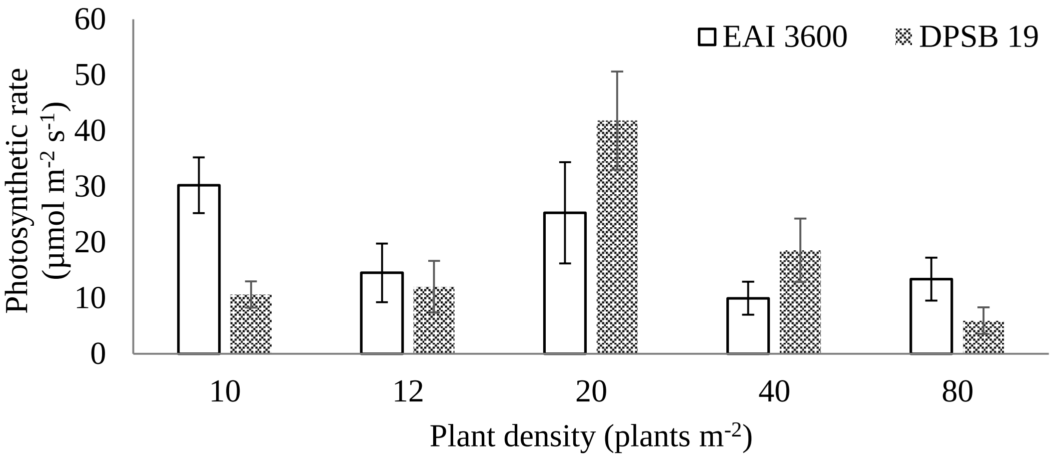


Figure 5.5 Effect of plant density and cultivar on photosynthetic rate at 50% flowering stage. Error bars represent ± standard error. Values significantly different at $p < 0.001$.

***Sub-stomatal carbon dioxide concentration***

Interaction of plant density, cultivar and season had a significant ($p < 0.001$) effect on sub-stomata carbon dioxide concentration (Table 5.10). Highest concentration of carbon dioxide was achieved at the lowest plant density of 10 plants $m^{-2}$ by cultivar DPSB 19 during long rains. On the other hand, the lowest level of carbon dioxide concentration was at the highest plant population of 80 plants $m^{-2}$ by the same cultivar.

Table 5.10 Effect of plant density, cultivar and season on Sub-stomatal carbon dioxide concentration (µmol $mol^{-1}$) at 50% flowering stage

| | Sub-stomatal carbon dioxide concentration (µmol $mol^{-1}$) | | | | |
|---|---|---|---|---|---|
| | EAI 3600 | | DPSB 19 | | |
| Plant Density (plants $m^{-2}$) | Long rains 2018 | Short rains 2018 | Long rains 2018 | Short rains 2018 | Mean |
| 10 | 93.12 | 61.78 | 207.65 | 81.90 | 104.86 |
| 12 | 154.75 | 79.56 | 58.37 | 107.54 | 96.83 |
| 20 | 65.57 | 103.43 | 149.57 | 97.42 | 102.41 |
| 40 | 107.95 | 40.70 | 27.04 | 70.06 | 57.61 |
| 80 | 46.92 | 38.93 | 109.41 | 48.16 | 58.06 |
| Mean (cultivar) | 75.86 | | 89.30 | | |
| *p*-value | < 0.001 | | | | |
| SED | 1.48 | | | | |
| CV (%) | 20.0 | | | | |

SED = ± Standard error of difference of means; CV = Coefficient of variation.

***Transpiration rate***

Transpiration rate was significantly ($p < 0.05$) responsive to interaction of plant density and seasons (Figure 5.6). Soybean plants had increased rate of transpiration at plant density of 20 plants $m^{-2}$ during long rainy season while the lowest transpiration rate was achieved at the highest plant density of 80 plants $m^{-2}$ during short rains.

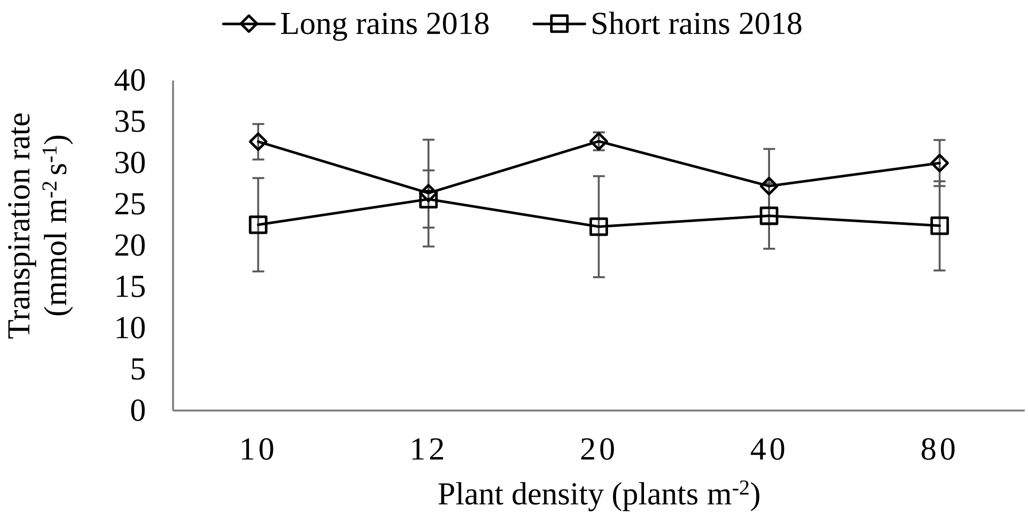


Figure 5.6 Effect of density and season on soybean transpiration rate at 50% flowering stage. Error bars represent ± standard error. Values significantly different at $p < 0.05$.

***Leaf temperature***

Leaf temperature significantly ($p < 0.05$) varied with interaction of plant density and seasons (Figure 5.7). Lower leaf temperatures were attained during long rainy seasons across all plant densities though having 10 plants $m^{-2}$ led to a relatively lower leaf temperature compared to other treatments.

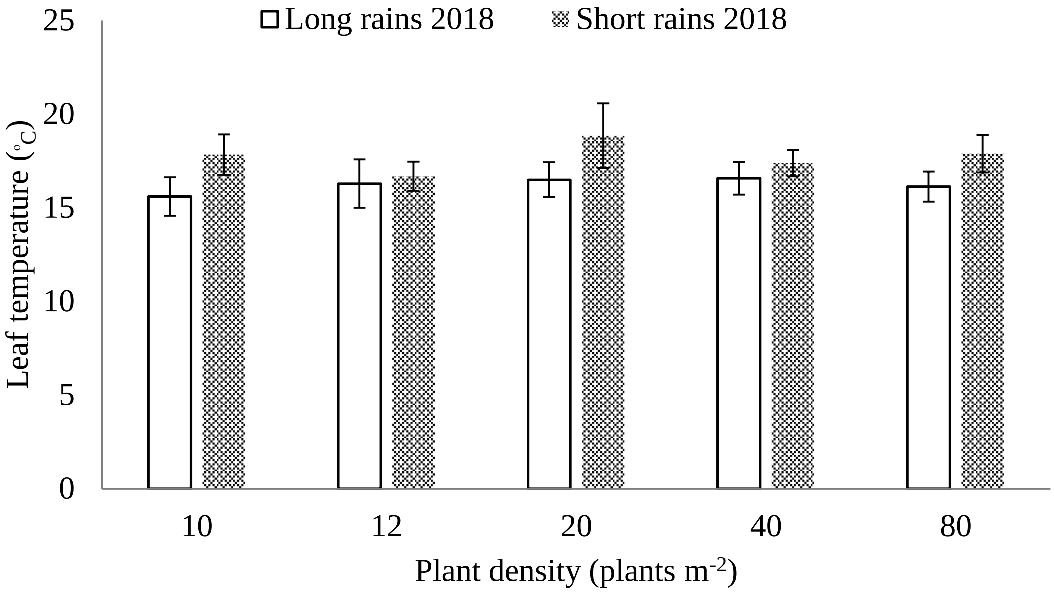


Figure 5.7 Effect of plant density on soybean leaf temperature (°C) at 50% flowering stage. Error bars represent ± standard error. Values significantly different at $p < 0.05$.

### 5.4.3 Effect of plant density on soil moisture content

Soil moisture content (Table 5.11) was responsive to interaction of plant density and cultivars ($p < 0.05$), density and season ($p < 0.05$) and then cultivars and seasons ($p < 0.001$). Lowest soil moisture level was attained at the highest plant density of 80 plants $m^{-2}$ by cultivar DPSB 19. Plant density and season interaction led to reduced soil moisture content during short rainy season across all plant densities. Season by cultivar interaction resulted into an increased soil moisture during long rains by a determinate cultivar EAI 3600.

Table 5.11 Effect of plant density, cultivar and season on soil moisture content (% v/v) at 50% flowering stage

| | Soil moisture content (% v/v) | | |
|---|---|---|---|
| | Cultivars | | |
| Plant density (plants $m^{-2}$) | EAI 3600 | DPSB 19 | Mean |
| 10 | 24.93 | 23.95 | 24.44 |
| 12 | 24.98 | 27.41 | 26.19 |
| 20 | 26.51 | 23.65 | 25.08 |
| 40 | 23.92 | 23.75 | 23.84 |
| 80 | 21.54 | 19.90 | 20.72 |
| Mean | 24.38 | 23.73 | |
| *p*-value | 0.043 | | |
| SED | 1.196 | | |
| CV (%) | 8.6 | | |
| | Season | | |
| Plant density (Plants $m^{-2}$) | Long rains 2018 | Short rains 2018 | |
| 10 | 33.31 | 8.13 | |
| 12 | 37.27 | 10.41 | |
| 20 | 36.29 | 13.87 | |
| 40 | 39.97 | 12.42 | |
| 80 | 37.92 | 10.96 | |
| Mean | 36.95 | 11.16 | |
| *p*-value | 0.029 | | |
| SED | 1.196 | | |
| CV (%) | 8.6 | | |
| Cultivar | | | |
| EAI 3600 | 38.14 | 10.62 | 24.38 |
| DPSB 19 | 35.77 | 11.70 | 23.73 |
| *p*-value | 0.003 | | |
| SED | 0.757 | | |
| CV (%) | 8.6 | | |
| | *p*-value | | |
| Density × Season × Cultivar | 0.091 | | |

SED = ± Standard error of difference of means; CV = Coefficient of variation.

### 5.4.4 Effect of plant density on root nodulation

Number of nodules per plant significantly ($p < 0.05$) varied in response to interaction of plant density and seasons (Figure 5.8). Overall, highest number of nodules were found during short rains at all plant densities though the lowest plant density of 10 plants $m^{-2}$ recorded the highest number of nodules per plant.

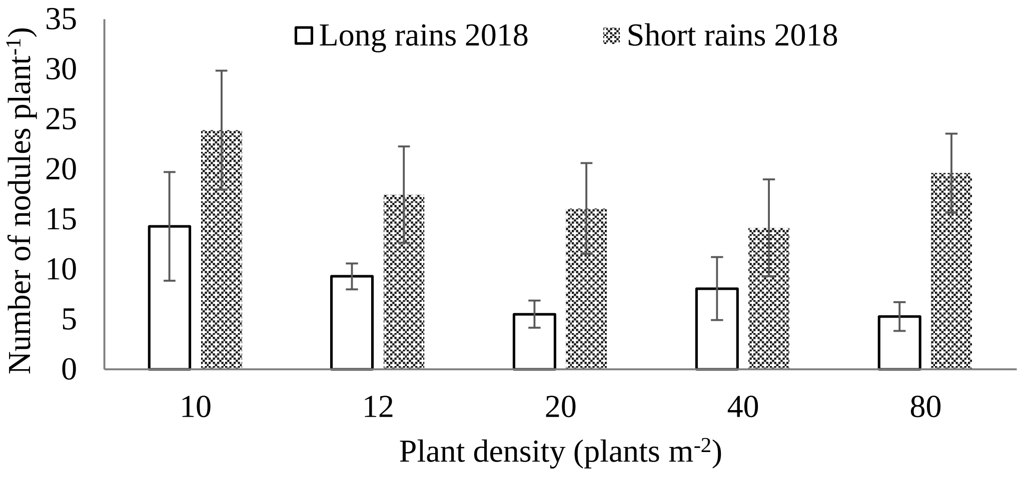


Figure 5.8 Effect of plant density and season on soybean root nodulation at 50% flowering. Error bars represent ± standard error. Values significantly different at $p$ < 0.05. stage.

### 5.4.5. Effect of plant density on reproductive growth

***Days to flowering***

Number of days to 50% flowering were affected ($p$ < 0.001) by interaction of plant density and season (Figure 5.9). Soybean plants flowered earlier at the highest plant density of 80 $m^{-2}$ during long rains while the lowest plant density of 10 plants $m^{-2}$ during short rains took relatively more days to flower than other treatments.

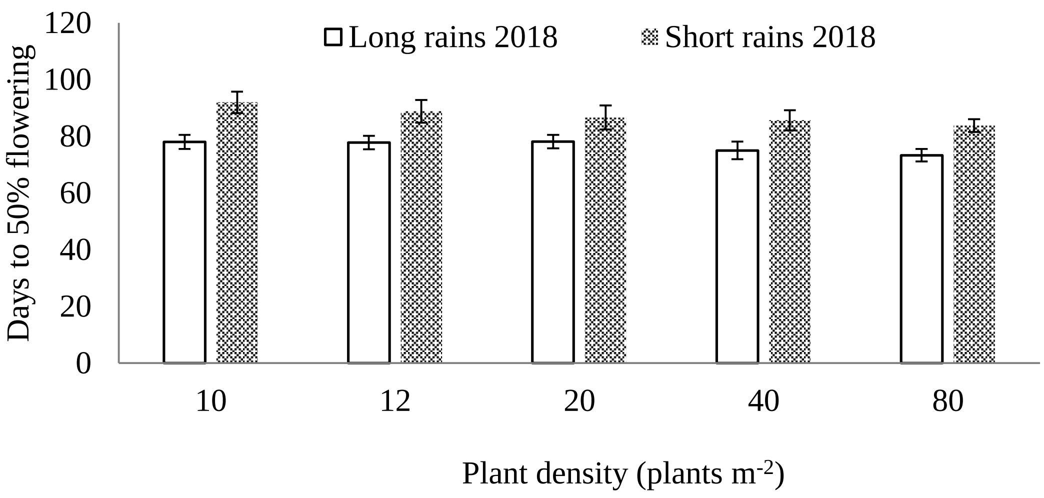


Figure 5.9 Effect of plant density and season on number of days to 50% flowering. Error bars represent ± standard error. Values significantly different at $p$ < 0.001.

***Days to maturity***

Number of days for soybean to attain 75% physiological maturity were significantly ($p < 0.001$) dependent on interaction of cultivar and season (Figure 5.10). There was delayed maturity of soybean during short rains by the determinate cultivar EAI 3600.

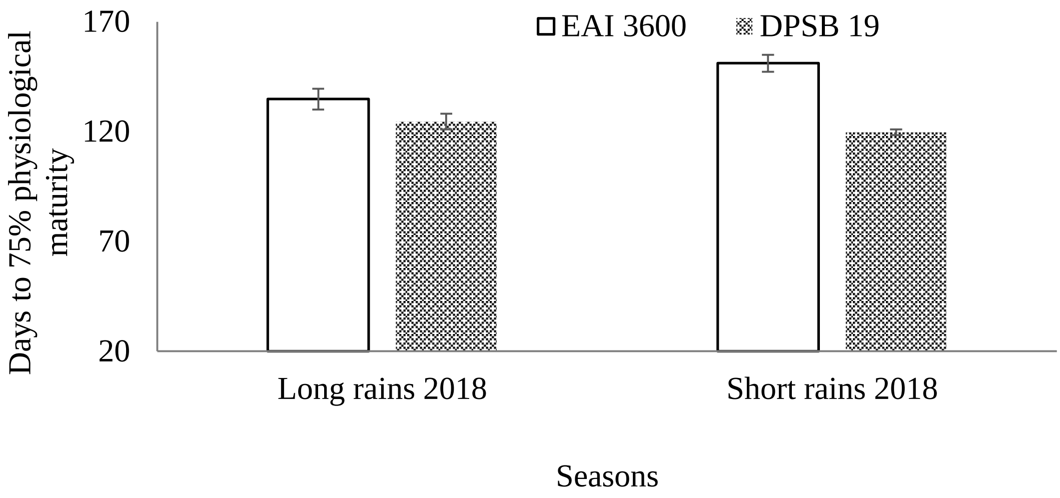


Figure 5.10 Effect of cultivars and seasons on number of days to 50% physiological maturity Error bars represent ± standard error. Values significantly different at $p < 0.001$.

### 5.4.6 Effect of plant density on soybean lodging

Lodging of soybean was significantly ($p < 0.05$) dependent on the interaction of plant density and seasons (Figure 5.11). Lodging was highest at 80 plants $m^{-2}$ during short rains.

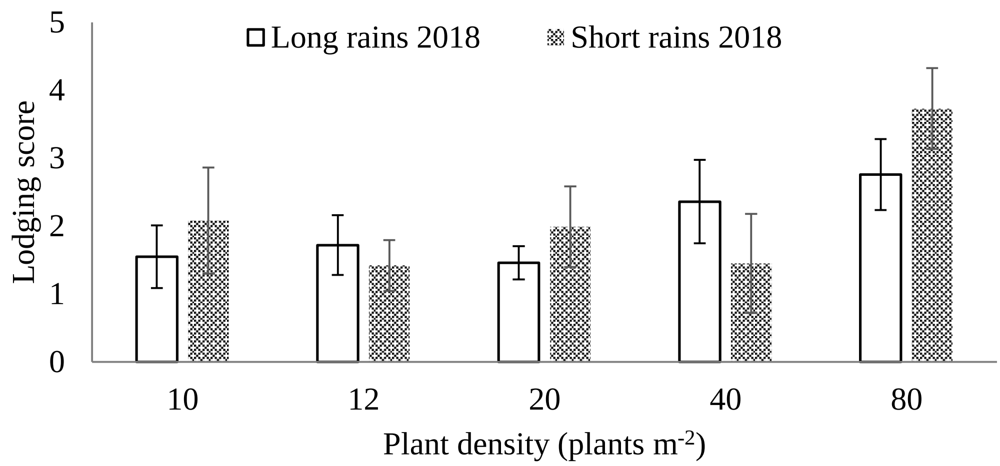


Figure 5.11 Effect of plant density and season on lodging of soybean. Error bars represent ± standard error. Values significantly different at $p < 0.05$.

### 5.4.7 Effect of plant density and cultivars on yield, yield components and grain quality

***Number of pods per plant***

Number of pods per plant (Table 5.12) significantly varied with interaction effects of plant density and season ($p < 0.001$) and interaction of cultivars and seasons ($p < 0.05$). Highest number of pods per plant were obtained at the lowest plant density during short rainy season. All cultivars had highest number of pods per plant during short rains.

Table 5.12 Effect of plant density, cultivar and season on number of pods per plant

| Number of pods per plant | | | |
|---|---|---|---|
| | Seasons | | |
| Plant density (plants m$^{-2}$) | Long rains 2018 | Short rains 2018 | Mean |
| 10 | 60.8 | 87.3 | 74.0 |
| 12 | 58.9 | 66.9 | 62.9 |
| 20 | 47.5 | 51.9 | 49.7 |
| 40 | 32.2 | 32.1 | 32.1 |
| 80 | 25.8 | 24.2 | 25.0 |
| Mean | 45.0 | 52.6 | |
| *p*-value | < 0.001 | | |
| SED | 4.56 | | |
| CV (%) | 16.2 | | |
| Cultivar | | | |
| EAI 3600 | 40.9 | 52.9 | 46.9 |
| DPSB 19 | 49.2 | 52.1 | 50.7 |
| *p*-value | 0.032 | | |
| SED | 2.89 | | |
| Density ×Cultivar | 0.521 | | |
| Density × Cultivar × Season | 0.770 | | |

SED = ± Standard error of difference of means; CV = Coefficient of variation

***Pod length***

Pod length was significantly dependent on main effects of plant density ($p < 0.001$), type of cultivar ($p < 0.001$) and seasons ($p < 0.01$). Increasing plant population to 80 plants m$^{-2}$ led to a 10.43% reduction in pod length relative to the lowest plant density of 10 plants m$^{-2}$. The determinate cultivar EAI 3600 had longer pods (4.27 cm) compared to indeterminate cultivar DPSB 19 (3.97 cm). Longer pods were attained during short rains (4.16 cm) compared to long rainy season (4.07).

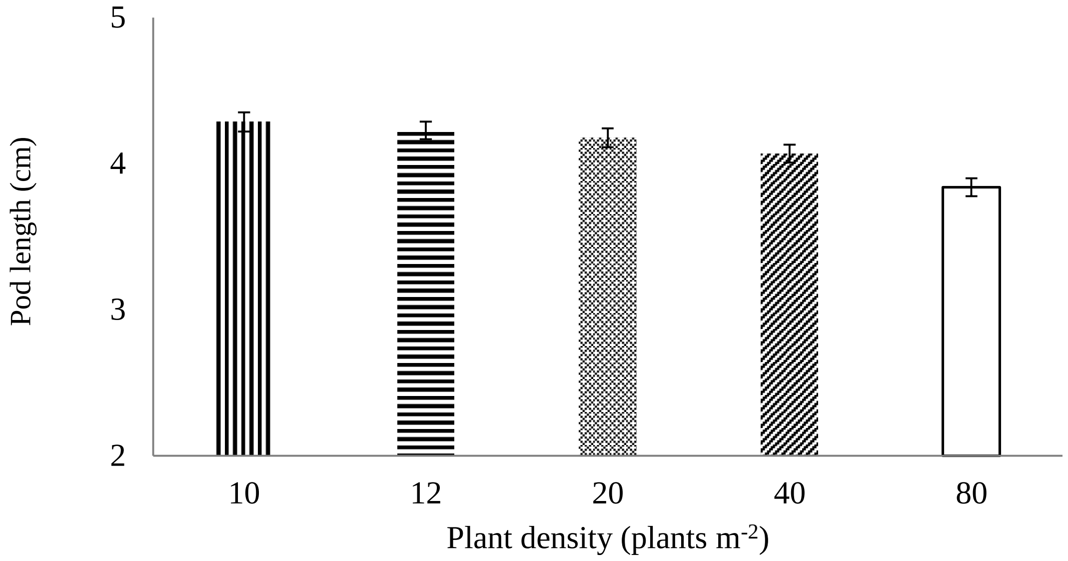


Figure 5.12 Effect of plant density on soybean pod length. Error bars represent ± standard error. Values significantly different at $p < 0.001$.

***Seeds per pod***

Number of seeds per pod was significantly ($p < 0.001$) affected by main effects of plant density and seasons (Figure 5.13). Planting soybean at 40 and 80 plants $m^{-2}$ reduced number of seeds per pod compared to lower plant density of 10, 12 and 20 plants $m^{-2}$. Highest number of seeds per pod were obtained during short rains (2.6) than during long rainy season (2.4).

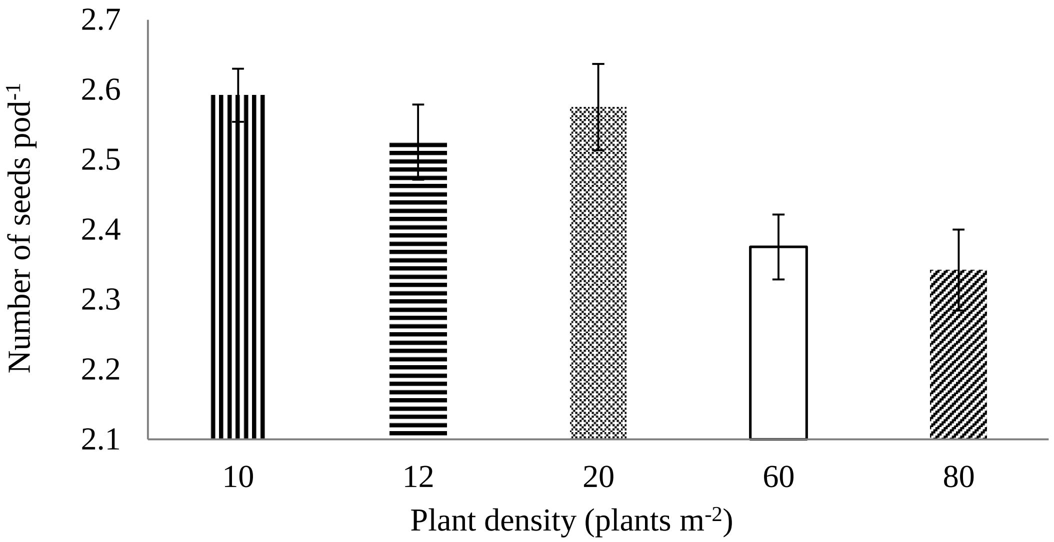


Figure 5.13 Effect of plant density on number of soybean seeds per pod. Error bars represent ± standard error. Values significantly different at $p < 0.001$.

***Seed weight***

Seed weight significantly ($p < 0.001$) varied with interaction of cultivar and season with the highest seed weight attained by cultivar EAI 3600 during long rains (Figure 5.14).

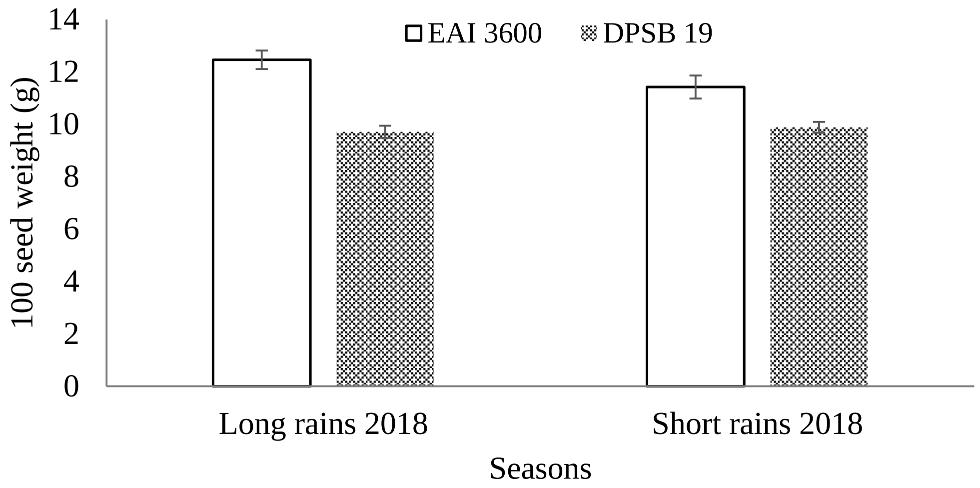


Figure 5.14 Effect of plant density on soybean 100 seed weight. Error bars represent ± standard error. Values significantly different at $p < 0.001$.

***Grain yield and grain protein content***

Grain yield was significantly ($p < 0.001$) responsive to plant density and season (Figure 5.15). Highest grain yield was achieved at the highest plant density of 80 plants $m^{-2}$ which corresponded to a 41.0% increase over the lowest grain yield obtained at 12 plants $m^{-2}$. Seasonal differences led to highest grain yield of 2246 kg $ha^{-1}$ being obtained during short rains representing a 35.75% increase over long rainy season yield. Plant density, cultivars and seasons did not have a significant influence on protein content of soybean grain.

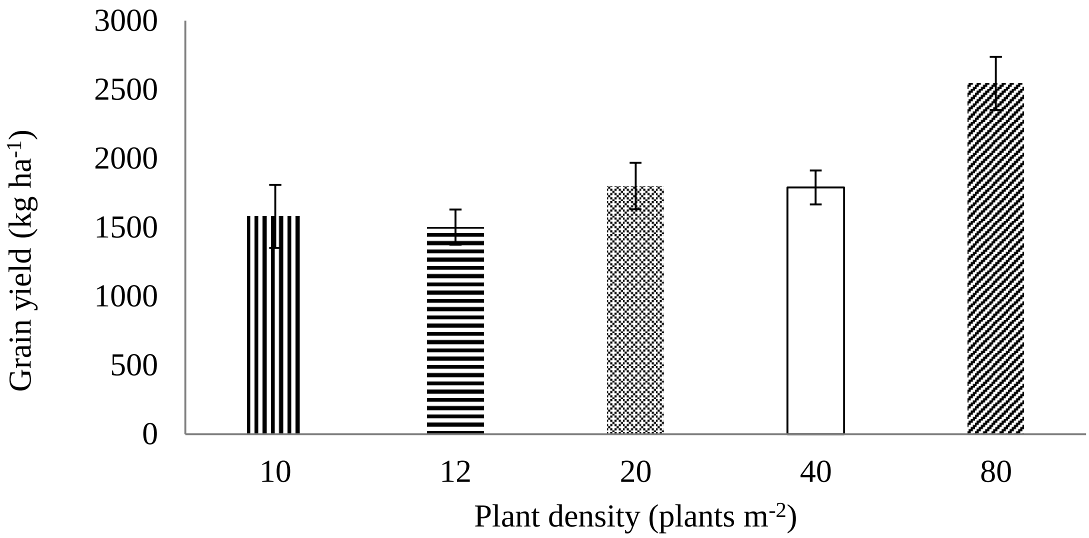


Figure 5.15 Effect of plant density on soybean grain yield. Error bars represent ± standard error. Values significantly different at $p < 0.001$.

### *Yield correlations*

There were positive correlations between grain yield and number of pods per plant, number of seeds per pod and 100 seed weight. Pod length and grain yield had a negative relationship. Number of seeds per pod had a negative and non-significant correlation with 100 seed weight (Table 5.13).

Table 5. 13 Grain yield and yield components correlations

| | Pods plant $^{-1}$ | Seeds pod $^{-1}$ | Pod length | Seed weight | Grain yield |
|---|---|---|---|---|---|
| Pods plant$^{-1}$ | - | - | - | - | - |
| Seeds pod$^{-1}$ | 0.4841$^{***}$ | - | - | - | - |
| Pod length | 0.4675*** | 0.4484$^{***}$ | - | - | - |
| Seeds weight | 0.0544$^{ns}$ | -0.1185$^{ns}$ | 0.4788$^{***}$ | - | - |
| Grain yield | 0.1906$^{ns}$ | 0.0777$^{ns}$ | -0.3102$^{ns}$ | 0.0316$^{ns}$ | - |

*** Represents significance at $p < 0.001$; ns = not significant

## 5.5 Discussion

### Effect of plant density on shoot growth and root nodulation

Higher number of plants per unit area reduced soybean plant growth by suppressing canopy development, stem thickness, development of branches, leaf production and nodulation. Plant height, internode length and leaf area index (LAI) increased with an increase in plant population. Shoot growth also varied with seasons and growth habit of cultivars with determinate growth habit registering highest number of branches, more leaves per plant, thicker stems and wider plant canopies. These results concur with observations by Worku and Astatkie (2011), Cox *et al*. (2011), Luca and Hungria (2014), Khubele (2015) and Souza *et al*. (2016). Results however contradict observations by Bejandi *et al*. (2012), Chauhan and Opeňa (2013) and Kena (2018) who reported non-significant responses of soybean plant height and number of nodules per plant to variations in plant density.

Higher plant density causes mutual shading of plants which triggers competition for light leading to stem elongation and ultimately increased plant height (Pendersen and Lauer, 2003). Higher number of plants per unit area results in competition for resources which includes space, mineral nutrients and soil moisture. This competition not only restricts root growth and nodulation, but also retards plant growth and development through suppression of branching and leaf production. Suppressed branching and leaf production leads to reduced leaf area which also translates into reduction in production of photoassimilates to support plant growth and nodulation. Higher number of branches at lower plant density may be a result of compensatory growth. The principle of compensatory growth alludes that growth of plants occurs in areas free of neighbours to compensate for loss of resources in the zone of interaction (Brisson and Reynolds, 1997). Relative leaf expansion rate in soybean has been reported to be greater at lower plant populations (Wells, 1993) which explains higher leaf area at lower plant density relative to higher plant density. Differences in number of branches per plant between high and low plant density may also be due to differences in red/far red light ratio within plant canopies. Increased ratio of red/far red light in plant canopies at lower plant density results in greater branch development in soybean (Kasperbauer, 1987).

Determinate growth habit is defined by bushier canopy compared to indeterminate growth habit (Kato *et al*., 2015) which explains wider canopy diameter, higher numbers of branches and leaves and increased leaf area by a determinate cultivar EAI 3600 relative to indeterminate cultivar DPSB 19. Overall, soybean shoot growth and nodulation were optimized during short rains relative to long rains. Long rainy season was characterized by lower temperatures (mean of 18.9°C) and higher amount of rainfall (total 847.9 mm) compared to short rains mean temperature of 22.03°C and total rainfall of 234.7 mm. This meant that higher soil moisture levels and reduced temperatures during long rains relative to short rains suppressed soybean shoot growth and nodulation.

**Effect of plant density on chlorophyll content, leaf gaseous exchange and soil moisture status**

Highest levels of stomatal conductance, leaf carbon dioxide concentration and chlorophyll 'a' content were attained at the lowest plant population while increased photosynthetic rate was registered at 20 plants $m^{-2}$. Highest rate of transpiration was obtained at 20 plants $m^{-2}$ during long rains. Determinate growth habit led to increased IPAR while higher rates stomata conductance, sub-stomatal carbon dioxide concentration and transpiration rate were registered with the indeterminate cultivar DPSB 19. These results are in agreement with reports by Koesmaryono *et al*. (1997), Zhou *et al.* (2011) and Moreira *et al*. (2015) whose studies indicated reductions in stomata conductance, photosynthetic and transpiration rates at higher plant populations of soybean. Similarly, studies with sorghum by Li *et al.* (2014) also indicated reductions in stomata conductance and photosynthetic rate at higher planting populations relative to lower planting density. On the other hand, a study with pigeon peas by Wilson *et al*. (2012) showed that varying planting density did not have a significant effect on stomata conductance, photosynthetic and transpiration rates which is at variance with findings of this study. Variations in results could be attributed to differences in crop species used and also due the fact that a study by Wilson *et al.* (2012) varied planting dates which was not the case with this study.

Studies have shown a positive relationship between soil moisture levels and stomata conductance, photosynthetic and transpiration rates (Haile and Higley, 2003; Gilbert *et al.,* 2011; Nasaruddin and Ridwan, 2018). Results of this study have shown that there was increased depletion of soil moisture at higher plant density which led to reductions in stomata conductance. Reduction in stomata conductance meant reduced diffusion of carbon dioxide and water in and out of plant tissues which could have led to lower photosynthetic and transpiration rates. Stomata conductance, carbon dioxide concentration and transpiration were higher during long rains compared to short rains. Variations in levels of stomata conductance, photosynthetic and transpiration rates between long and short rains may be associated with differences in soil moisture levels considering that soil moisture level was significantly higher during long rains compared to short rains. Soil moisture levels during long rains were 74.17% higher than during short rains. Fanourakis *et al*. (2015) indicated that indeterminate soybean cultivars have higher numbers of stomata and epidermal cells per unit area compared to determinate soybean cultivars. This, in addition to the fact that indeterminate soybean cultivars have smaller leaflets with a potential of minimizing leaf overlaps within a plant, explains the prevalence of increased levels of stomata conductance, photosynthetic and transpiration rates by indeterminate cultivar DPSB 19 compared to a determinate cultivars EAI 3600. Increased leaf temperature at higher plant population could have been a result of increased stomata resistance to water loss from plant tissues due to stomata closure as evidenced from lower stomata conductance level. Equally, lower stomata conductance and transpiration rate at higher plant populations meant that there was a reduction in evaporative cooling of plants which is synonymous with higher stomata conductance and transpiration levels (Lu *et al*., 1994). Higher soil moisture depletion by the determinate cultivar (EAI 3600) could have been due to increased evaporation demand that comes with vigorous plant growth and increased leaf area (Kumar *et al*., 2012).

**Effect of plant density on reproductive growth**

Soybean plants flowered earlier at higher plant population during long rains while pod maturity varied with interaction of seasons and cultivar. Mekonnen (2012) and Akond *et al.* (2013) reported earlier flowering of faba beans and soybeans at higher plant density while Kena (2018) indicated a non-significant effect of plant density on commencement of soybean flowering. Delayed flowering at lower plant population could be due to unlimited availability of growth resources such as moisture and mineral nutrients which supported extended period of plant growth (Birhanu *et al.,* 2018). The expectation was that soybean plants would have delayed flowering during long rains when soil moisture levels were higher and temperatures lower. Soybean is classified as a facultative short day plant (Jung *et al*., 2012) and earlier flowering during long rains could therefore be due to responsiveness of soybean to shorter day lengths during long rains which accelerated floral bud development and opening (Hu and Wiatrak, 2012). Flowering in soybean is also controlled by flowering-time genes whose expression varies with photoperiod and temperature. Longer days and higher temperatures over express flowering-time genes which delays flowering of soybean plants (Jung *et al*., 2012; Cober *et al.,* 2014). This possibly explains delayed flowering of soybean plants during short rains when day length is relatively longer and temperatures higher than during long rains.

Differences in maturity between cultivars may be linked to differences in genetic makeup of the two cultivars.

**Effect of plant density on grain yield, yield components and grain quality**

Increase in planting density reduced number of pods per plant, pod length and number of seeds per pod. High planting density increased soybean grain yield and lodging of soybean plants. Seasonal variations and type of cultivar used had proportionate effect on protein content of soybean grain. Longer pods, higher number of seeds per pod and overall grain yield were attained during short rains. Previous studies by Ibrahim and Kandil (2007) and Madanzi *et al*. (2017) reported reductions in number of pods per plant, number of seeds per pod, pod length and increased incidences of lodging at higher plant populations. Relatedly, Rahman and Hossain (2011), Gulluoglu *et al*. (2017) and Matsuo *et al.* (2018) reported reductions in soybean grain yield at lower plant populations which is in line with current findings. Increased protein content at higher plant populations were reported by Rahman *et al*. (2013) and Luca and Hungria (2014) which contradicts results of this study.

Higher grain yield at higher plant population could be associated with higher number of plants per unit area which offset the effects of reduced number of pods per plant, shorter pod length and lower number of seeds per pod (El-Gazzar and Salwa-Gaweesh, 2002). In addition, higher plant density led to early canopy closure which facilitated increased IPAR. Increased IPAR leads to accelerated growth rate, increased dry matter accumulation and higher yield per unit area (Rahman *et al*., 2004). Increased grain yield at higher plant density may also arise from optimal utilization of soil moisture and mineral nutrients (Board, 2000). High plant density increases nitrogen use efficiency due to increased nitrogen uptake capacity which leads to higher grain yield (Xu *et al*., 2017). Lower plant density led to higher number of branches per plant which could have translated into higher number of pods per plant at lower plant density. Photosynthetic rate was higher at lower plant population which indicates that there was optimal synthesis of photoassimilates to meet the demand of increased pod and seed development which contributed to both higher number of pods per plant and higher number of seeds per pod. Increased number of pods per plant and seeds per pod at lower plant density could have also emanated from reduced competition for growth resources such as light, moisture and mineral nutrients (Ibrahim and Kandil, 2007). Soybean plants at higher plant population were taller with thinner stems which led to higher incidence of lodging.

Highest soybean yields were obtained at the highest plant density of 80 plants $m^{-2}$. Stomata conductance, photosynthetic and transpiration rates were reduced with increase in plant population. Due to increased incidences of lodging at 80 plants $m^{-2}$, planting soybean at 20 plants $m^{-2}$ would be appropriate for optimum soybean yields. In addition, due to close spacing of 25 cm by 5 cm, farmers would find it difficult to implement it unless under mechanized operation.

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## CHAPTER SIX

## EFFECT OF SOYBEAN AND MAIZE INTERCROPPING ON STOMATA CONDUCTANCE, SHOOT CHARACTERISTICS AND YIELD OF SOYBEAN

### Abstract

A study to determine effect of soybean [*Glycine max* (L.) Merrill] and maize (*Zea mays*) intercropping on stomata conductance, shoot characteristics and yield of soybean was conducted in Siaya, Busia and Nakuru counties in Kenya during 2018 season. The experiment was raid out in a randomized complete block design (RCBD) and was replicated three times. It had seven treatments; sole maize, sole soybean, within row intercropping, 1M: 1S row pattern, 2M: 2S row pattern, 2M: 1S row pattern, and 1M: 2S row pattern. Kenya seed maize cultivar 513 and DPSB 19 soybean cultivar were used in the study. Data were subjected to analysis of variance (ANOVA) using Linear Mixed Model in GENSTAT. Soybean plant height was higher under intercropping with maize. Intercropping maize and soybean significantly reduced soybean stem thickness, leaf area, leaf expansion rate, interception of photosynthetically active radiation (IPAR), photosynthetic rate and number pods per plant. Soybean leaf chlorophyll content under intercropping was 21.16% more than under mono cropping while the highest stomata conductance of 70.6 mmol $m^{-2}$ $s^{-1}$ was attained under sole cropping. Intercropping reduced soybean yield by 83.85% compared to sole cropping. Intercropping soybean and maize in 1M: 1S gave relatively higher soybean yields compared to other row patterns and is recommended for use by farmers intending to intercrop the two crops. Further studies on wider row spacings for maize and soybean intercropping are necessary in order to get more insights on how soybean yields can be optimized under intercropping with maize.

### 6.1 Introduction

Intercropping is the agricultural practice of cultivating two or more crops on the same piece of land at the same time (Malèzieux *et al*., 2009). Multiple cropping systems are estimated to account for 15-20% of world food production and the amount of land devoted to intercropping varies from as low as 17% in India to as high as 94% in Malawi (Vandermeer, 1989; Altieri, 1999). Increase in human population and urbanization has reduced availability of agricultural land making intercropping a system of choice amongst farmers with small land holdings.

Intercropping allows more efficient utilization of plant growth resources such as light, water and nutrients when component crops differ in peak demand and competitive ability for the resources (Szumigalski and Van Acker, 2008). Full canopy cover from component crops in intercropping helps reduce the impact of rain drops leading to reduction in soil loss (Gebru, 2015). Deep roots of component crops break soil hardpans and use moisture and nutrients from deeper soil horizon while shallow roots bind the soil at the surface and thereby help to reduce soil erosion (Lithourgidis *et al*., 2011). Intercropping with legumes such as soybean helps to improve soil fertility through biological nitrogen fixation (BNF). In addition, after the intercrop is harvested, decaying roots and fallen leaf biomass provide nitrogen and other nutrients for subsequent crops (Gebru, 2015). Intercropping provides insurance against crop failure in areas subjected to extreme weather conditions such as drought and floods making it much less risky than monocropping (Eskandari, 2012). Intercropping provides better lodging resistance for some crops that are highly susceptible to lodging. Lodging leads to disease infections, mechanical damage and reduces efficiency of light interception by plants. Intercropping encourages crop diversification thereby reducing labour costs (Mousavi and Eskandari, 2011). For organic sector, intercropping offers an effective means of producing healthy, safe and high quality food in the context of environmentally sound production. Most important is the role intercropping plays in mitigating soil moisture through providing enough soil cover from crop canopies. Because of its biological, environmental and economic advantages, intercropping will continue to play important roles in improving production and productivity of marginal lands. While this is so, poorly planned intercropping systems have the potential of reducing yields of the intercrops through increased competition for nutrients, water and light. Reduced light intensity which may arise from shading by a taller component of an intercrop has the potential to influence morphological and physiological processes of an understory crop species.

Much as previous studies have provided some insights into morphological and yield responses of soybean under intercropping with maize, obtained results have often been contradictory. Limited attention has also been paid to understand physiological responses of soybean in intercropping with maize. This means there is a need to continuously investigate and understand functionalities of intercropping systems while reducing potential impediments that may limit intercropping as a system of choice to improve crop yields. This study, therefore, investigated the effect of soybean and maize intercropping on soybean stomata conductance, shoot characteristics and yield of soybean.

### 6.1.1 Effect of intercropping on shoot growth and root nodulation

Studying the effects of shading and light recovery on growth, leaf structure and photosynthetic performance of soybean in a maize-soybean relay-strip cropping, Fan *et al.* (2018) indicated that sole cropping significantly reduced soybean stem diameter and total above ground biomass compared to intercropped soybean. Soybean plant height was however significantly lower under monocropping compared to intercropping. The authors further indicated that soybean leaves were 39.5% and 18% thinner under 1:1 and 2:2 row arrangements respectively compared to leaf thickness obtained under sole cropping. While Rahman *et al*. (2017) and He *et al.* (2012) reported that intercropped maize had higher total leaf area and leaf area index (LAI) compared to sole maize, Peng *et al*. (2009) reported that there were no significant differences between sole and intercropped maize and soybean on plant height and leaf area of the two crops.

Studies in the Guinea Savannah by Muoneke *et al*. (2007) indicated that maize and soybean intercropping did not have a significant effect on plant height and number of leaves per plant of both crops. El-Shellif *et al*. (2015) reported a reduction in maize plant height under intercropping with soybean. On the other hand, soybean plant height was increased in intercropping than in monocropping. Non-significant differences were also reported on number of soybean root nodules and nodule sizes between sole and intercropped soybean plants. Maize ear height did not significantly differ between monocropped and intercropped maize. Meng *et al.* (2015) indicated that intercropping of maize and soybean had no significant effect on soybean shoot biomass. Nonetheless, growing of soybean in association with maize significantly increased number of soybean nodules compared to sole cropping. Reduced nodule number and nodule biomass in intercropped soybean than sole soybean were reported by Gosh *et al*. (2004). Maize and soybean intercropping study in Mozambique by Tsujimoto *et al.* (2015) indicated that under optimal moisture conditions, soybean leaf dry weight was significantly greater in sole cropping than in intercropping with maize regardless of plant growth stage. Under limited soil moisture conditions, significant leaf abscission was observed in sole soybean compared to intercropped soybean.

From the foregoing, it is evident that varied and contradictory results exist on the response of soybean when grown in association with maize. Results of this study will therefore add more insights on the merits and demerits of soybean and maize intercropping considering that unlike most previous studies where emphasis was on single intercropping arrangement, this study will look at various maize and soybean spatial arrangements and their effects on soybean and maize shoot growth.

### 6.1.2 Effect of intercropping on leaf gas exchange and chlorophyll content

Soybean and maize relay strip intercropping studies by Gong *et al.* (2015) indicated an increase in chlorophyll ‘a’ content in soybean leaves under intercropping relative to sole soybean while net photosynthesis rate was significantly reduced under intercropping. In the same study, photosynthetically active radiation reaching soybean leaves under intercropping was significantly reduced by taller maize plants unlike in monocropping. Kamara *et al.* (2017) reported a non-significant effect on intercepted photosythetically active radiation (IPAR) between sole and intercropped maize. However, intercropped maize planted on wider row spacing (65 cm) had significantly lower IPAR than intercropped maize planted at closer row spacing of 50 cm. Intercepted photosynthetically active radiation for sole soybean was significantly higher compared to intercropped soybean. In addition, soybean intercropped with maize at 65 cm had higher IPAR than soybean intercropped with maize planted at 50 cm between rows. A study by Fan *et al.* (2018) reported that chlorophyll ‘a’ content, net photosynthesis rate and stomatal conductance in soybean grown under intercropping with maize was significantly lower compared to sole soybean both at vegetative (V5) and reproductive (R1) stages of soybean plant growth. Net photosynthesis rate also significantly varied with spatial row arrangement with 2:2 row arrangement registering higher net photosynthesis rate compared to 1:1 row arrangement.

A study by Zgang *et al.* (2013) on effects of root interaction and nitrogen fertilization on the chlorophyll content, root activity and photosynthetic characteristics of intercropped soybean indicated that leaf chlorophyll content, net photosynthesis rate, stomatal conductance and transpiration in soybean intercropped with maize was higher compared to sole soybean at vegetative, flowering and pod filling stages of soybean. Intercropping study of maize and wheat by Gou *et al*. (2018) showed a significantly higher leaf chlorophyll content of sole maize relative to intercropped maize. On the contrary, net photosynthesis rate and stomatal conductance were significantly higher in intercropping than in sole maize. On the other hand, Tsujimoto *et al*. (2015) reported an average increase of between 9-42% in stomatal conductance in monocropped soybean than in soybean intercropped with maize.

Leaf gas exchange in most crops will vary with environmental factors including temperature which, in itself, varies with altitude. While previous studies have reported leaf gas exchange variations of soybean in response to intercropping, such studies were mostly limited on number of sites which means that effects of environment on soybean and maize intercropping were not adequately addressed. This study looked at and compared soybean stomata conductance responsiveness in intercropping with maize across three sites and obtained results are expected to help narrow information gap on how environmental differences may influence stomata conductance, shoot characteristics and yield of soybean intercropped with maize.

### 6.1.3 Effect of intercropping on soil moisture status

The response of soil water retention in a potato (*Solanum tuberosum*) and maize intercropping was studied by Mushagalusa *et al*. (2008). Results of the study indicated that potato and maize intercropping did not have a significant effect on soil water retention relative to sole treatments. Soybean intercropping study in a tree-based agroforestry system by Reynolds *et al*. (2007) reported that intercropping significantly reduced soil moisture compared to monocropping. Maize and cowpea (*Vigna unguiculata* L Walp.) intercropping study in Kilifi County in Kenya concluded that intercropping increased soil moisture retention regardless of crop growth stage and depth at which soil moisture content was determined (Ndiso *et al*., 2017). It was also indicated from the study that sole cowpea treatment had relatively higher soil moisture content than sole maize plots. It is evident from this review that information on the effect of maize and soybean intercropping on soil moisture depletion is scarce and results of this study will therefore contribute in providing more insights on soil moisture content dynamics in maize and soybean intercropping.

### 6.1.4 Effect of intercropping on reproductive development, grain yield and intercropping productivity

Pierre *et al*. (2017) reported that intercropping of maize and promiscuous soybean cultivars did not have a significant effect on number of days to 50% flowering and number of days to attain 75% pod maturity in soybean. Number of days to 50% flowering and 75% pod maturity however varied with the type of soybean cultivar used. A study by Muoneke *et al*. (2007) showed that intercropping of maize and soybean did not have a significant bearing on number of days to soybean flowering. Nonetheless, intercropped soybean attained pod development earlier than sole soybean. El-Shamy *et al*. (2015) reported a 3.98% increase in soybean yield per hectare under intercropping over sole soybean yields. Intercropped maize yields were 29.79% higher than sole maize yields. Intercropping significantly increased number of maize ears per plant but negated maize 100 kernel weight. From the central highlands of Kenya, Matusso *et al*. (2013) concluded that maize and soybean intercropping reduced soybean yields by between 60-81% but overall, maize and soybean intercropping was more productive than sole cropping as expressed by higher land equivalent ratio (LER) values.

Studying yield and economics of maize and soybean intercropping systems under different tillage methods in Nepal, Paudel *et al*. (2015) showed that sole cropping of maize and soybean significantly increased grain yields of both crops than corresponding yields in intercropping. It was further indicated that maize grain yields were significantly increased under 1: 1 row arrangement while soybean grain yields were highest under 2:2 row pattern. Number of soybean pods per plant were 68.08% higher in sole soybean than in intercropping. Land equivalent ratio values in intercropping were more than unity denoting a greater production efficiency of intercropping over monocropping. Intercropping of maize and castor reduced maize yields and that LER values for maize and castor intercropping were less than unity indicating a less resource use efficiency of the intercrops (Obiero *et al*., 2013). Just like other variables studied, previous studies have reported contradictory findings on soybean yield components and yield performance under intercropping with maize. Productivity of maize and soybean also varied with studies conducted. From this review, no study has reported the effect of soybean and maize intercropping on soybean grain quality. This calls for further studies to not only elucidate the effect of soybean and maize intercropping on grain yield, but also determine how the cropping system affects soybean grain quality.

## 6.2 Materials and methods

### 6.2.1 Site description

The experiment was conducted at three sites; Siaya Agriculture Training Centre (SATC) farm in Siaya County, Busia prison farm in Busia County and at Egerton University agronomy teaching and research farm in Njoro, Nakuru County. Siaya Agriculture Training Centre ($0^{o}$ 03' N; $34^{o}$ 17' E), is at an altitude of 1270 m.a.s.l with mean temperature of $21^{o}$C. Siaya has a bimodal rainfall pattern and average rainfall ranges from 800 to 1100 mm. Long rainy season occurs from March to June and short rainy season starts from September to November. Soils are mostly *ferrasols* and fertility ranges from moderate to low with most soils requiring the use of organic and inorganic fertilizers (GOK, 2016). Busia Prison farm ($0^{o}$ 45' N; $34^{o}$ 25' E) is at an altitude of 1253 m.a.s.l with mean temperature of $22^{o}$C. The county has a bimodal rainfall pattern and average rainfall ranges from 1720 to 1790 mm. Long rainy season occurs from March to June and short rainy season starts from September to October. Soils are mostly well drained, deep, dark-red *orthic ferralisols* (Jaetzold *et al*., 2006). Egerton University agronomy teaching and research farm ($0^o$ 22' S; $35^o$ 56' E) is at an altitude of 2267 m.a.s.l with mean temperature range of 17-22$^o$C. The area has a bimodal rainfall pattern with long rainy season occurs from March to June and short rainy season starts from September to November and the area falls within agro-ecological zone III (Jaetzold *et al*., 2006).

Soil sampling and analysis of physical and chemical properties of the soil from the sites was done prior to planting as described under section 3.3.1

### 6.2.2 Experimental design and treatments

The experiment was conducted using a randomized complete block design (RCBD) with three replicates. There were five soybean and maize intercropping arrangements and two sole treatments of soybean and maize making a total of 7 treatments (Table 6.1).

Table 6.1 Description of experimental treatments

| No. | Treatment |
|---|---|
| 1 | Sole soybean |
| 2 | Sole maize |
| 3 | Within row (soybean planted in-between maize stands in the same row). |
| 4 | 1M: 1S row ratio (1 row of maize followed by 1 row of soybean). |
| 5 | 2M: 2S row ratio (2 rows of maize followed by 2 rows of soybean). |
| 6 | 2M: 1S row ratio (2 rows of maize followed by 1 row of soybean). |
| 7 | 1M: 2S row ratio (1 row of maize followed by 2 rows of soybean). |

M = Maize; S = Soybean

Gross plot sizes were 4.5 m long and 4 m wide (18 $m^2$) while net plot sizes were 3 m by 3 m (9 $m^2$). Maize rows were spaced at 75 cm apart while soybean rows were spaced at 45 cm for sole treatment, 37.5 cm apart for 1:1 and 2:1 treatments and 25 cm apart for 2:2 and 1:2 treatments. In the within row intercropping treatment, soybean was planted at 10 cm apart in-between maize hills.

### 6.2.3 Planting and crop management

Based on results of experiments 1 and 2, DPSB 19 soybean cultivar was used in the intercropping experiment because of its early maturing attribute. Planting was done on 19$^{th}$

March 2018 in Siaya, 20th March 2018 in Busia and on 30th March 2018 at Egerton University. Soybean seed was inoculated with BIOFIX *(Bradyrhizobium japonicum)* inoculant strain USD 110 from Mea Limited–Kenya at the rate of 10 g $kg^{-1}$ of seed prior to planting. For soybeans, Triple Super Phosphate and Muriate of Potash fertilizers were applied at the rates of 30 kg P $ha^{-1}$ and 30 kg K $ha^{-1}$ respectively as basal dressing fertilizers. Kenya seed maize cultivar 513 was planted in all sites at a spacing of 25 cm between hills and basal dressed with 41 kg N, 60 kg P $ha^{-1}$ at the time of planting and then top dressed 4 weeks after planting with 60 kg N $ha^{-1}$. Weeding was done using hand hoe as weeds appeared.

White flies (*Bemisia tabaci*) and thrips (*Sericothrips variabilis*), which were common in soybeans were controlled using alphacypermethrin 100g per litre (Albaz 10 EC) at the rate of 6 millilitres in 20 litres of water. One spray was applied at vegetative stage to control soybean pests and spraying was done around midday when dew had evaporated. Fall armyworm (*Spodoptera frugiperda*) in maize was controlled using Lufemtron 50g per litre (Match 50 EC) at the rate of 25 millilitres in 20 litres of water. Two sprays, one at V6 stage (6-leaf stage) and the second just before tasseling were made. Spraying was done early in the morning when caterpillars are most active. At 75% cob maturity stage, Siaya and Busia plots were sprayed with chlorpyrifos 480g per litre (Gladiator 4TC) at the rate of 250 millilitres in 20 litres of water to control harvester termites (*Cryptotemes spp*.). Pesticide and the termaticide application were done using knapsack sprayer.

### 6.2.4 Data collection

**Soybean data**

***Intercepted photosythetically active radiation***

Intercepted photosynthetically active radiation (IPAR) was measured at soybean flowering and podding stages using an AccuPar Ceptometer (LP-80 PAR/LAI Decagon Devices). For intercropped treatments, IPAR measurements were done 5 cm above maize and soybean canopies and 10 cm above ground level. For sole treatments, IPAR was measured 5 cm above canopies of maize and soybean crops and 10 cm from the ground level. Calculation of percent IPAR was done as indicated under section 4.3.5. of experiment 2.

***Chlorophyll content determination***

Total leaf chlorophyll content was measured using chlorophyll meter (CCM-200-OPTI-Sciences) on a third trifoliate leaf from top of the plant at vegetative, 50% flowering and podding stages. Three plants were measured in a net plot and measurements were done between 12.00-13.00 hours.

***Soybean lodging assessment***

Soybean lodging was assessed using a scale of 1 to 5 as described under section 5.3.4 of experiment 3.

Other soybean data were collected on stomata conductance, photosynthesis and transpiration rates, plant height, canopy diameter, internode length, stem diameter, leaf area, leaf biomass, number of nodules, nodule biomass, soil moisture content, number of pods per plant, number of seeds per pod, pod length, 100 seed weight, grain yield and seed protein content as described under sections 3.3.5 and 4.3.5 of experiments 1 and 2, respectively. Net plot area for determination of yield data is as described under section 6.3.2.

**Maize data**

***Plant growth parameters***

Maize plant height and cob height were measured on 10 randomly selected maize plants in a net plot using a measuring tape from the base of maize plant to the last leaf collar and a point of cob attachment respectively. Canopy diameter was measured on 10 plants in a net plot using a measuring tape on the widest point of maize plant. Maize leaf area was determined at vegetative and at 50% silking stages using manual method developed by Norman and Campbell (1992). It involves determination of individual leaf length ($l$) and width *(w)* and multiply the product by a coefficient *(k)* which is 0.75 for maize. Leaf area index was determined by dividing mean plot leaf area by 1875 $cm^2$ which represents land area occupied by individual maize plant at an inter spacing of 75 cm and intra row spacing 25 cm

***Number of days to tasseling and silking***

Days to 50% tasseling and 50% silking were counted from date of 50% emergence up to when 50% of plants in the plot had produced male flowers (tasseling) and female flowers (silking) respectively.

***Yield and yield components***

Maize cob length was measured at harvest using a measuring tape on 10 randomly selected maize cobs from net plot. Mean number of cob length from 10 cobs was taken as cob length for a given treatment. Kernel weight was determined from weight of 100 maize grains randomly selected from net plot at harvest. Maize grain yield was determined from net plots as described under section 6.2.3. Maize grain yields was adjusted to storage moisture content of 13% (Muparangwa *et al*., 2016).

***Soil moisture determination***

Soil moisture content from respective treatments was determined using a time domain reflectometer (TDR) at two points in a net plot at 50% flowering and 50% podding stages of soybean.

***Productivity of intercropping***

Intercropping productivity was assessed using land equivalent ratio (LER) as described by Malèzieux *et al*. (2009).

$$LER = \frac{Y_{ia}}{Y_{sa}} + \frac{Y_{ib}}{Y_{sb}} \qquad \text{Equation 6.1}$$

Where $Y_{ia}$ is intercrop yield of maize, $Y_{sa}$ is yield of sole maize, $Y_{ib}$ is yield of intercrop soybean and $Y_{sb}$ is yield of sole soybean.

Competitive ratio (CR) as a measure of competition between crop species was determined using the equation below as described by Dhima *et al*. (2007).

$$CR_{maize} = \frac{LER_{maize}}{LER_{soybean}} \times \frac{Z_{lm}}{Z_{ml}} \qquad \text{Equation 6.2}$$

$$CR_{soybean} = \frac{LER_{soybean}}{LER_{maize}} \times \frac{Z_{ml}}{Z_{lm}} \qquad \text{Equation 6.3}$$

where: $CR_{maize}$= competitive ratio for maize; $CR_{soybean}$ = competitive ratio for soybean; $LER_{maize}$ = land equivalent ratio for maize; $LER_{soybean}$ = land equivalent ratio for soybean; $Z_{lm}$ and $Z_{ml}$ = proportions of soybean and maize in the mixture.

## 6.3 Statistical model and data analysis

Data obtained were checked for fulfilment of analysis of variance (ANOVA) assumption of normality by using Shapiro-Wilk normality test in Genstat release 18.1. Data were considered normally distributed when the *p*-value for Shapiro-Wilk statistic was greater than the threshold *p*-value of 0.05. Data that did not meet the aforesaid ANOVA assumption were subjected to log base 10 [log 10(x+c] transformation before analysis. Data were then subjected to ANOVA using the linear mixed model for RCBD with factorial treatment arrangement in Genstat (Restricted Maximum Likelihood-REML. The following statistical model was used in the analysis of experimental results.

$$Y_{ijk} = \mu + V_i + \beta_j + S_k + (VS)_{ik} + \varepsilon_{ijk}$$

Where,

$Y_{ijk}$ = observed response; μ = overall mean; $V_i$ = effect of intercropping pattern; $\beta_j$ = block effects; $S_k$ = effect of sites; $(VS)_{ik}$ = interaction of intercropping pattern and sites; $\varepsilon_{ijk}$ = random error normally distributed with mean zero.

Correlation analyses were done on individual treatment means using Genstat release 18.1 to determine inter-character associations amongst some selected quantitative traits.

## 6.4 Results

### 6.4.1 Effect of maize-soybean intercropping on shoot growth

***Plant height***

Soybean plant height at vegetative stage, 50% flowering and 50% pod setting stages was significantly ($p < 0.001$) influenced by independent effects of spatial row arrangement and sites (Figure 6.1). Sole soybean treatment had shortest plants at vegetative and at 50% flowering stages. At 50% pod development stage, within role intercropping had shortest plants. Sites had a significant ($p < 0.001$) influence on soybean plant height at all growth stages. At 50% pod setting, Busia had tallest plants (70.32 cm) while Siaya had shortest (59.56 cm) plants. While spatial row arrangement did not significantly influence maize plant height at 50% cob maturity stage (Figure 6.2), differences in sites significantly ($p < 0.001$) influenced height of maize with Egerton University having tallest plants (255.1 cm) followed by Siaya (199.7 cm) and then Busia (167.4 cm).

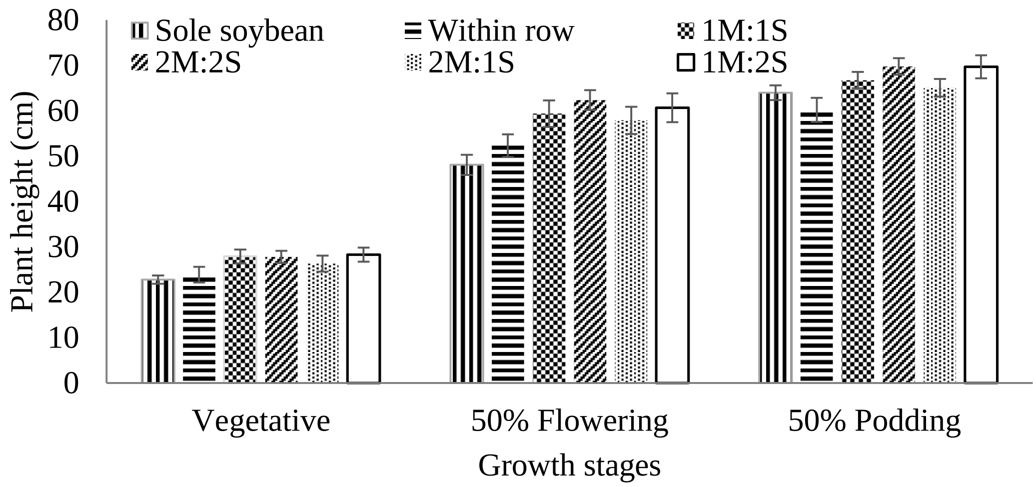


Figure 6.1 Effect of maize-soybean intercropping on soybean plant height. Error bars represent ± standard error. Values significantly different at $p < 0.001$. M = maize row, S = soybean row.

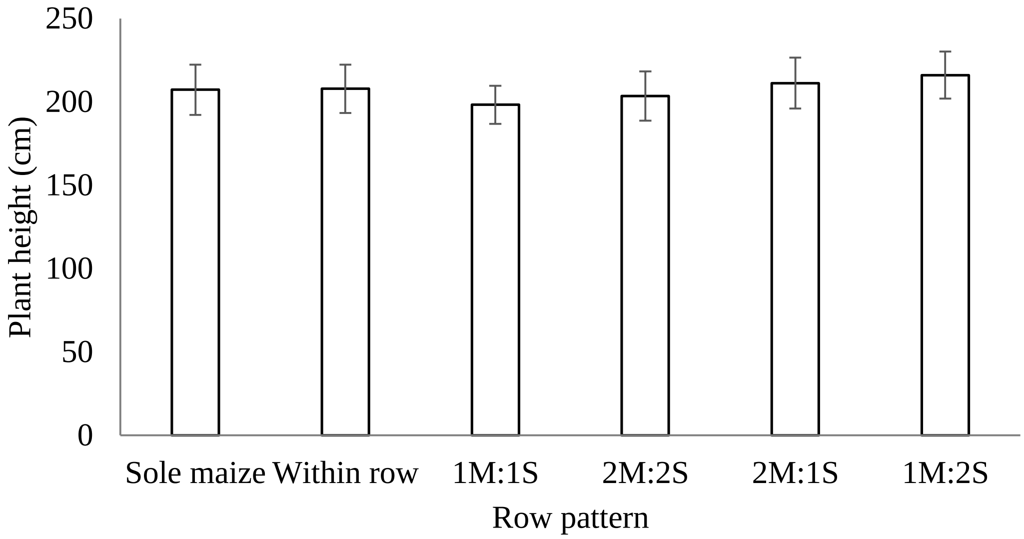


Figure 6.2 Effect of maize-soybean intercropping on maize plant height at 50% cob maturity stage. Error bars represent ± standard error. Values significantly different at $p < 0.001$. M = maize row, S = soybean row.

***Canopy diameter***

Soybean canopy diameter at vegetative, 50% flowering and 50% pod development stages was significantly ($p < 0.001$) affected by main effects of spatial row arrangement and sites. Within row intercropping of maize and soybean significantly reduced soybean canopy spread at vegetative stage. At 50% flowering and 50% pod development stages, within row intercropping and planting of two rows of soybean in between maize rows (2M:2S and 1M:2S) significantly reduced canopy diameter of soybean plants compared to sole soybean and where one row (1M:1S and 2M:1S) of soybean was planted in between maize rows (Figure 6.3). At 50% pod development stage, soybean plants in Busia had a mean canopy spread of 48.41 cm which was 14.42% and 6.16% wider than mean canopy diameters of plants at Egerton University and Siaya respectively. Maize canopy diameter at 50% cob development stage was significantly ($p < 0.001$) influenced by independent effect of sites with spatial row arrangement having a non-significant effect. Widest canopy diameter of maize was registered at Egerton University (124.48 cm), followed by Busia (107.72 cm) and Siaya (101.95 cm).

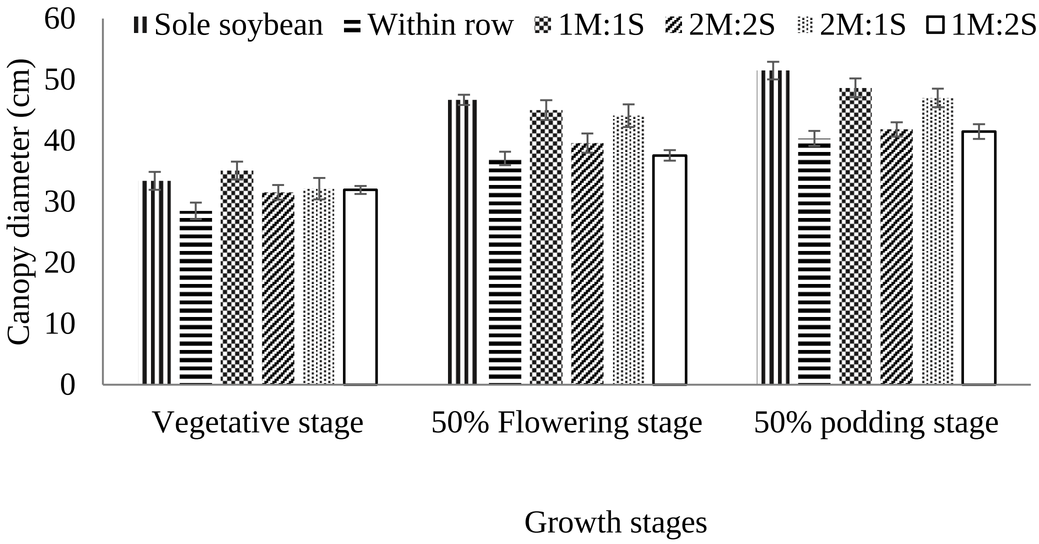


Figure 6.3 Effect of maize-soybean intercropping on soybean canopy diameter. Error bars represent ± standard error. Values significantly different at $p < 0.001$. M = maize row, S = soybean row.

***Stem diameter***

Stem diameter of soybean plants significantly ($p < 0.05$) varied with interaction effect of spatial row arrangement and sites at vegetative and 50% flowering stages. At 50% pod development stage, soybean stem diameter was significantly ($p < 0.001$) affected by spatial row arrangement with sites having a non-significant effect (Table 6.3). Sole soybean in Siaya and 2M: 1S row arrangement in Busia had largest and smallest stem diameters at vegetative stage respectively. At 50% flowering stage, sole soybean in Busia had significantly thicker stem diameter while within row intercropping in Siaya had the smallest stem diameter. At 50% pod development stage, sole soybean and within row intercropping registered largest and smallest stem diameters respectively.

Table 6. 2 Effect of maize-soybean intercropping on soybean stem diameter

| | | Soybean stem diameter (mm) | | |
|---|---|---|---|---|
| | | Vegetative stage | | |
| Treatment | Busia | Egerton | Siaya | Mean |
| Sole soybean | 3.40 | 4.93 | 5.12 | 4.48 |
| Within row | 3.24 | 3.86 | 3.66 | 3.59 |
| 1M: 1S | 2.35 | 4.71 | 4.57 | 3.88 |
| 2M: 2S | 2.72 | 4.08 | 4.08 | 3.63 |
| 2M: 1S | 2.31 | 4.55 | 4.43 | 3.77 |
| 1M 2S | 2.65 | 4.37 | 4.50 | 3.84 |
| Mean | 2.78 | 4.42 | 4.39 | |
| | *p*-value | SED | CV (%) | |
| Row pattern | <0.001 | 0.184 | | |
| Site | <0.001 | 0.130 | | |
| Interaction | 0.012 | 0.319 | 10.1 | |
| 50% Flowering stage | | | | |
| Sole soybean | 6.15 | 5.10 | 4.84 | 5.36 |
| Within row | 3.67 | 4.19 | 3.20 | 3.69 |
| 1M: 1S | 4.70 | 4.86 | 3.48 | 4.35 |
| 2M: 2S | 4.40 | 4.45 | 3.54 | 4.13 |
| 2M: 1S | 4.49 | 4.59 | 3.50 | 4.19 |
| 1M 2S | 4.78 | 4.48 | 3.34 | 4.20 |
| Mean | 4.70 | 4.61 | 3.65 | |
| | *p*-value | SED | CV (%) | |
| Row pattern | <0.001 | 0.151 | | |
| Site | <0.001 | 0.106 | | |
| Interaction | 0.014 | 0.261 | 7.4 | |
| 50% podding stage | | | | |
| Sole soybean | 5.91 | 5.70 | 5.82 | 5.81 |
| Within row | 4.20 | 4.55 | 3.92 | 4.22 |
| 1M: 1S | 5.30 | 5.00 | 4.75 | 5.01 |
| 2M: 2S | 4.447 | 4.56 | 4.73 | 4.59 |
| 2M: 1S | 4.78 | 4.93 | 4.70 | 4.80 |
| 1M 2S | 4.62 | 4.32 | 4.53 | 4.49 |
| Mean | 4.88 | 4.84 | 4.70 | |
| | *p*-value | SED | CV (%) | |
| Row pattern | <0.001 | 0.172 | | |
| Site | 0.495 | 0.247 | | |
| Interaction | 0.506 | 0.605 | 7.6 | |

SED = ± Standard error of difference of means; CV = Coefficient of variation; M = Maize row; S = Soybean row.

***Number of branches***

There were significant ($p < 0.001$) and independent effects of spatial row arrangement and sites on number of soybean primary branches at all growth stages (Figure 6.4). Sole soybean had highest number of primary branches while within row intercropping of maize and soybean reduced number of primary branches per plant. In addition, planting one row of soybean in-between maize rows (1M: 1S and 2M: 1S) gave relatively higher number of primary branches compared to planting of two soybean rows (2M: 2S and 1M: 2M) in-between maize rows. Overall, soybean plants at Egerton University had highest number of primary branches (4.71) at 50% pod development stage followed by Siaya (3.74) and Busia (3.02).

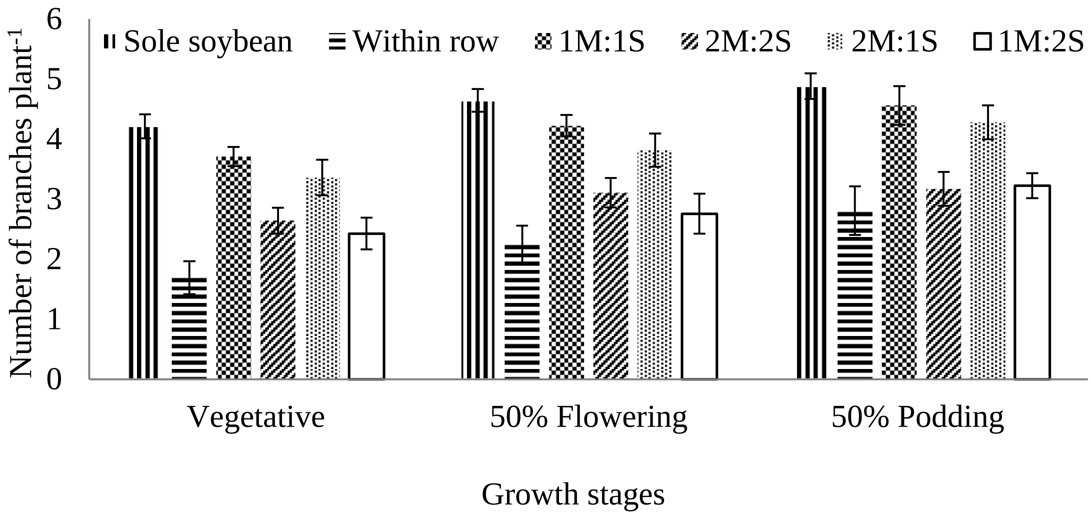


Figure 6.4 Effect of maize-soybean intercropping on number of soybean primary branches per plant. Error bars represent ± standard error. Values significantly different at $p < 0.001$. M = maize row, S = soybean row.

***Number of leaves per plant***

Number of soybean leaves arising from primary stem was significantly ($p < 0.001$) influenced by main effects of spatial row arrangement and sites at vegetative and 50% flowering stages. At 50% pod development stage, number of leaves per plant significantly ($p < 0.001$) varied with spatial row arrangement while differences in sites did not have a significant effect (Figure 6.5). Apart from within row intercropping treatment which significantly reduced number of leaves per plant at vegetative stage, all other treatments had similar number of leaves per plant. At 50% flowering and 50% pod development stages, sole soybean treatment had highest number of leaves per plant while within row intercropping had the least. Highest number of leaves per plant were registered in Busia at vegetative (6.56) and 50% flowering (8.85) stages with plants at Egerton University and Siaya having number of leaves per plant which was not significantly different.

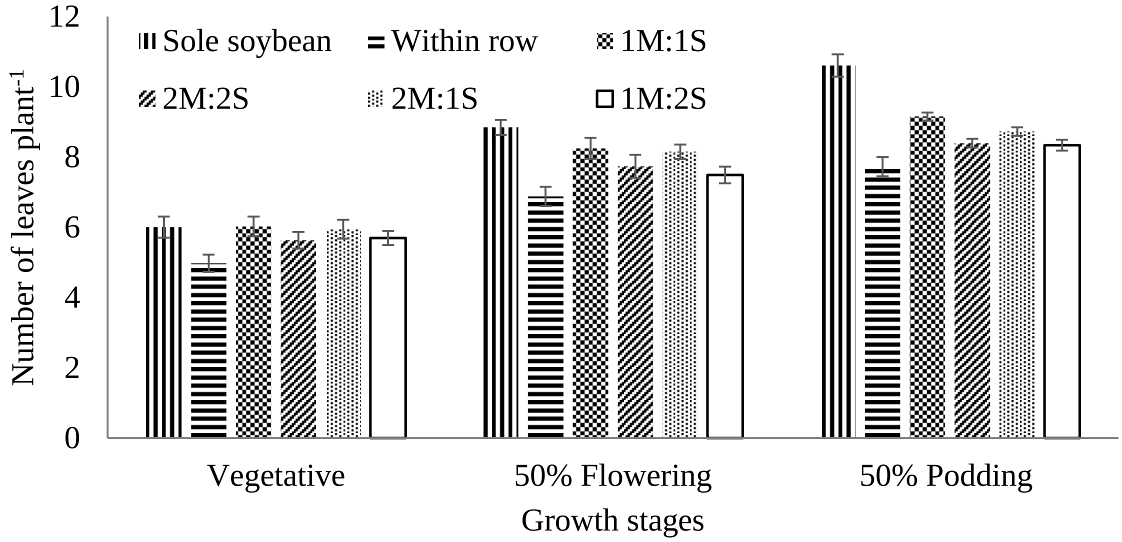


Figure 6.5 Effect of maize-soybean intercropping on number of soybean leaves per plant. Error bars represent ± standard error. Values significantly different at $p < 0.001$. M = maize row, S = soybean row.

***Leaf expansion rate***

Soybean leaf expansion rate at Egerton University was significantly ($p < 0.01$) influenced by intercropping of maize and soybean (Figure 6.6). Within row intercropping had the highest leaf expansion rate per day while sole soybean had the lowest.

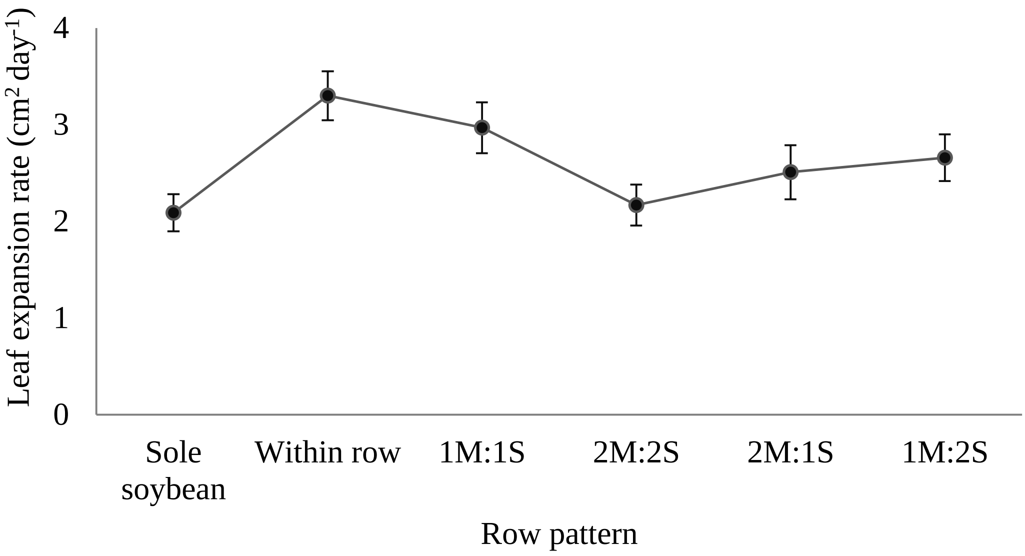


Figure 6.6 Effect of maize-soybean intercropping on soybean leaf expansion rate at Egerton University, Njoro. Error bars represent ± standard error. Values significantly different at $p < 0.01$. M = maize row, S = soybean row.

***Leaf area***

Soybean leaf area significantly responded to the interaction of spatial row arrangement and sites at 50% flowering ($p < 0.05$) and at 50% pod development ($p < 0.05$) stages (Table 6.4). At both stages, sole soybean and within row intercropping in Busia had highest and lowest total leaf area respectively. Intercropping of maize and soybean did not significantly influence maize leaf area. Maize leaf area however significantly ($p < 0.01$) varied with sites with maize plants at Egerton University having the largest leaf area, followed by Siaya and then Busia (Figure 6.7).

Table 6.3 Effect of maize-soybean intercropping of soybean leaf area

| | Soybean leaf area ($cm^2$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 50% Flowering stage | | | | 50% Podding stage | | | |
| Treatments | Busia | Egerton | Siaya | Mean | Busia | Egerton | Siaya | Mean |
| Sole soybean | 1522 | 1410 | 1327 | 1420 | 1662 | 1572 | 1399 | 1542 |
| Within row | 433 | 1054 | 441 | 643 | 460 | 1164 | 541 | 691 |
| 1M:1S | 1205 | 1027 | 700 | 977 | 1068 | 1100 | 772 | 974 |
| 2M:2S | 1120 | 703 | 857 | 893 | 1116 | 721 | 820 | 879 |
| 2M:1S | 1197 | 1024 | 594 | 938 | 1473 | 1106 | 755 | 1092 |
| 1M:2S | 1089 | 883 | 750 | 907 | 1010 | 908 | 762 | 890 |
| Mean | 1094 | 1017 | 778 | | 1107 | 1080 | 824 | |
| | *p*-value | SED | CV (%) | | *p*-value | SED | CV (%) | |
| Row pattern | <0.001 | 104.8 | | | <0.001 | 131.2 | | |
| Site | <0.001 | 74.1 | | | 0.005 | 92.70 | | |
| Interaction | 0.021 | 181.6 | 23.1 | | 0.038 | 227.2 | 13.5 | |

SED = ± Standard error of difference of means; CV = Coefficient of variation; M = Maize row; S = Soybean row.

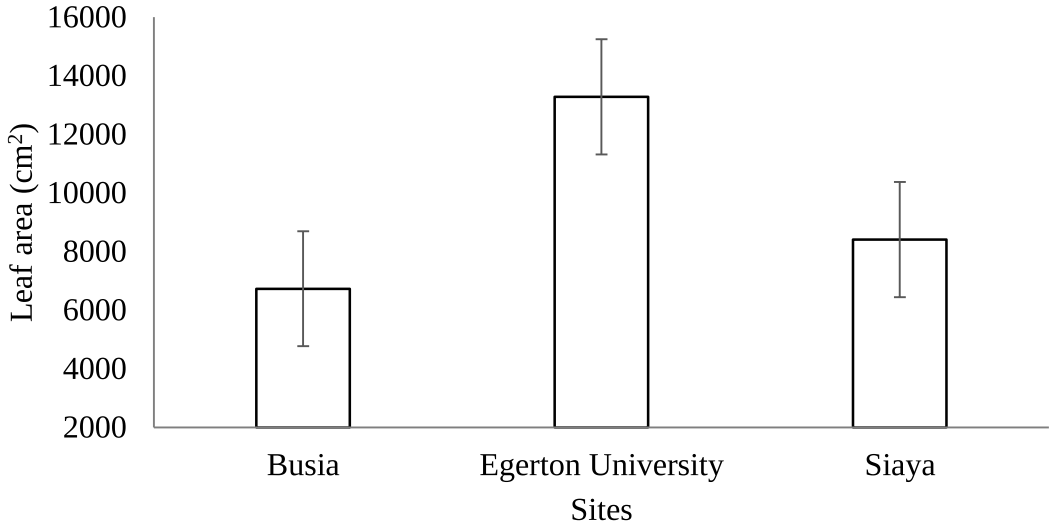


Figure 6.7 Effect of sites on maize leaf area at 50% cob development stage. Error bars represent ± standard error. Values significantly different at $p < 0.01$.

***Leaf area index (LAI)***

Soybean leaf area index was significantly ($p < 0.001$) responsive to spatial row arrangement and sites at 50% flowering and 50% pod development stages (Figure 6.8). Within row intercropping significantly reduced soybean leaf area index at both stages of plant growth. The highest leaf area index was recorded with 1M:2S planting pattern at both flowering and pod development stages which was, nonetheless, at par with leaf area indices registered with sole soybean and 2M:2S treatments. Differences in sites also significantly influenced soybean leaf area index with the highest leaf area index at 50% flowering (2.93) and at 50% pod development (3.28) stages attained at Busia while Siaya had the lowest leaf area index values of 2.03 and 2.39 at 50% flowering and 50% pod development stages respectively.

Maize leaf area index was not significantly influenced by planting patterns but significantly ($p < 0.001$) changed with sites (Figure 6.9). Maize plants at Egerton University had highest leaf area index, with maize leaf area indices at Busia and Siaya not significantly different.

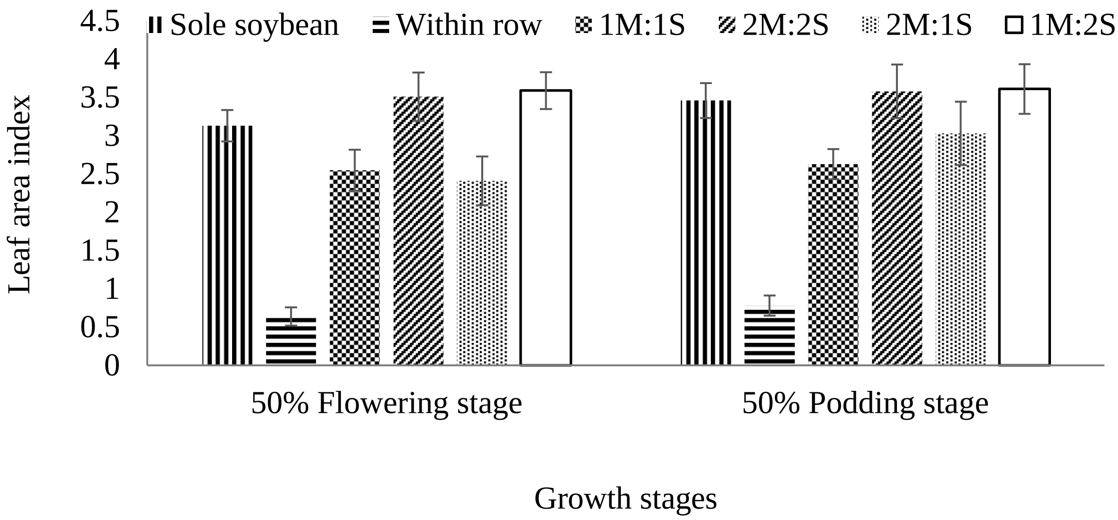


Figure 6.8 Effect of maize-soybean intercropping on soybean leaf area index. Error bars represent ± standard error. Values significantly different at $p < 0.001$. M = maize row, S = soybean row.

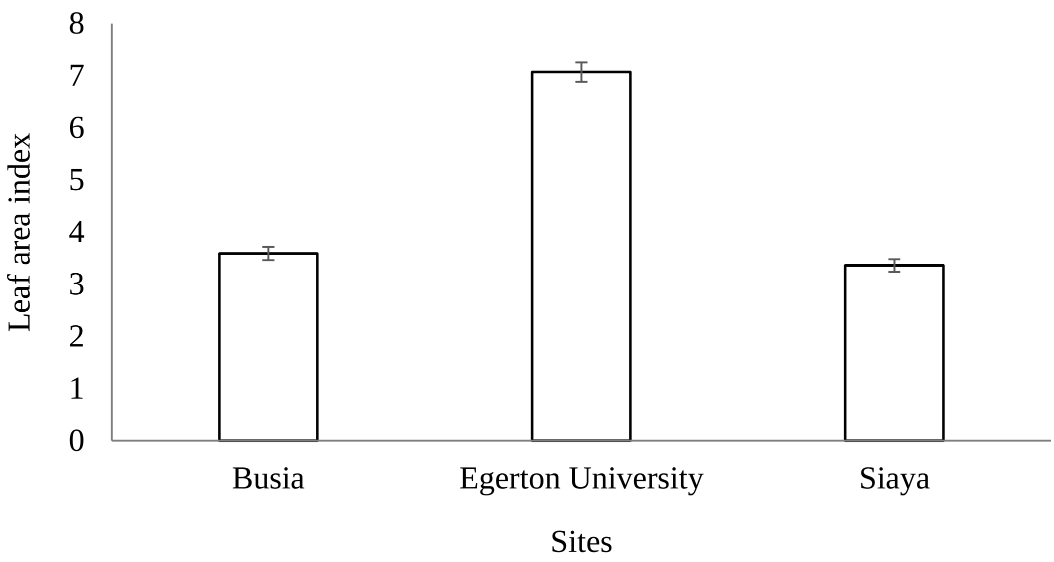


Figure 6.9 Effect of sites on maize leaf area index. Error bars represent ± standard error. Values significantly different at $p < 0.001$.

***Leaf biomass***

Soybean leaf biomass at 50% flowering stage significantly ($p < 0.001$) changed with spatial row arrangement and sites (Figure 6.10). Sole soybean had the highest leaf biomass per plant while within row intercropping had the lowest. Planting two lines of soybean in-between maize rows (2M:2S and 1M:2S) significantly reduced leaf biomass compared to when one row of soybean was planted in-between maize row in 1M:1S and 2M:1S treatments. Site differences led to a significantly ($p < 0.001$) higher leaf biomass at Egerton University (6.45 g $plant^{-1}$) which corresponded to a 44.03% and 40.31% increase over leaf biomass attained in Busia and Siaya respectively.

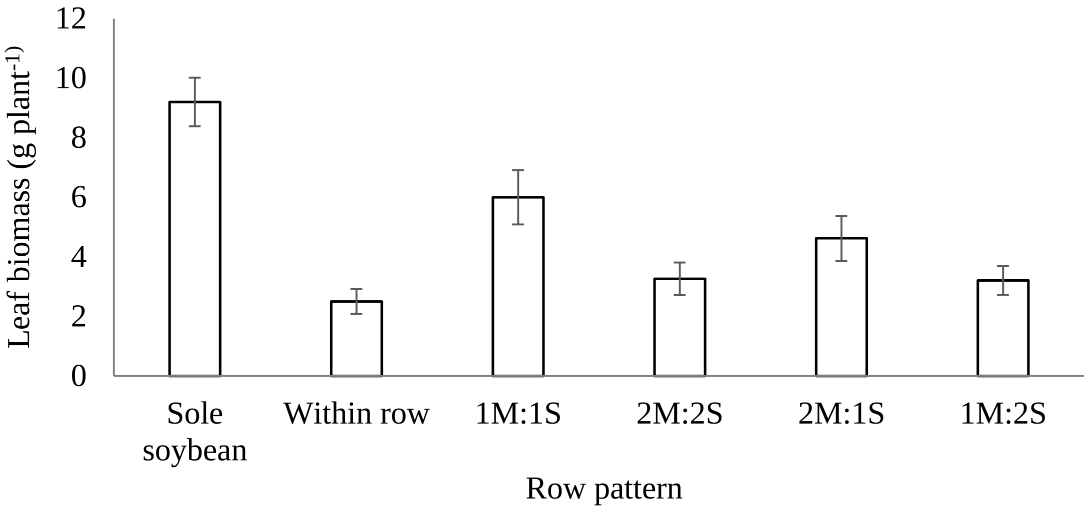


Figure 6.10 Effect of maize-soybean intercropping on soybean leaf biomass at 50% flowering stage. Error bars represent ± standard error. Values significantly different at $p < 0.001$. M = maize row, S = soybean row.

### 6.4.2 Effect of maize-soybean intercropping on intercepted photosynthetically active radiation (IPAR)

Intercepted photosynthetically active radiation (IPAR) by soybean plants at 50% flowering stage significantly ($p < 0.001$) varied with spatial row arrangement. At 50% pod development stage, intercepted photosythetically active radiation significantly ($p < 0.001$) changed with planting pattern and sites (Figure 6.11). Highest intercepted photosythetically active radiation at both growth stages was under sole soybean treatment. Within row intercropping of maize and soybean reduced interception of photosythetically active radiation at 50% flowering with all other intercropping treatments having a non-significant effect. Except for sole soybean treatment, all intercropping treatments had uniform interception of photosythetically active radiation at 50% pod development stage. Intercepted photosynthetically active radiation at 50% pod development stage was highest in Busia (34.34%) followed by Siaya (22.28%) and then Egerton University (15.37%).

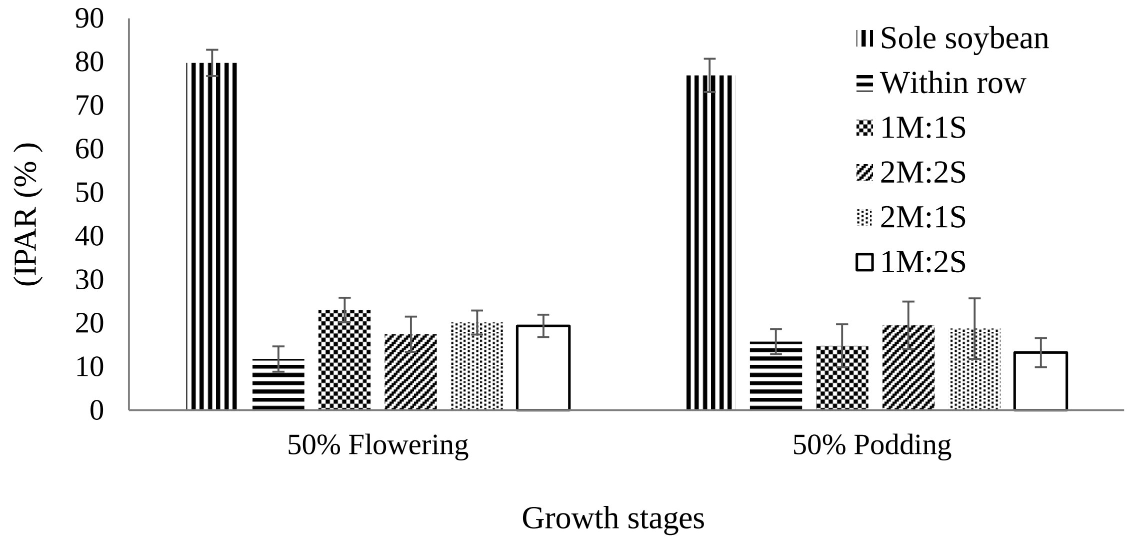


Figure 6.11 Effect of maize-soybean intercropping on soybean intercepted photosynthetically active radiation. Error bars represent ± standard error. Values significantly different at $p < 0.001$. M = maize row, S = soybean row.

### 6.4.3 Effect of maize-soybean intercropping on soybean gas exchange

***Chlorophyll content***

The interaction of spatial row arrangement and sites had a significant effect on soybean leaf chlorophyll content at 50% flowering ($p < 0.001$) and at 50% pod development ($p < 0.05$) stages (Table 6.5). Highest leaf chlorophyll content at 50% flowering was under 2M: 2S treatment at Egerton University while sole soybean treatment in Busia had the lowest chlorophyll content index. At 50% pod development stage, highest chlorophyll content was under 2M: 1S treatment in Siaya while the least chlorophyll content was under 2M: 1S treatment in Busia.

Table 6.4 Effect of maize-soybean intercropping on soybean leaf chlorophyll content

| | Soybean leaf chlorophyll content (CCI) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 50% Flowering stage | | | | 50% Podding stage | | | |
| Treatments | Busia | Egerton | Siaya | Mean | Busia | Egerton | Siaya | Mean |
| Sole soybean | 28.49 | 33.65 | 38.23 | 33.46 | 42.85 | 39.90 | 39.54 | 40.76 |
| Within row | 46.05 | 56.59 | 34.79 | 45.81 | 49.60 | 46.87 | 48.55 | 48.34 |
| 1M:1S | 49.76 | 55.10 | 34.04 | 46.30 | 38.37 | 49.91 | 47.14 | 45.14 |
| 2M:2S | 43.73 | 59.40 | 36.84 | 46.66 | 46.50 | 44.92 | 46.47 | 45.98 |
| 2M:1S | 44.49 | 55.18 | 36.80 | 45.49 | 37.98 | 48.55 | 58.21 | 48.25 |
| 1M:2S | 46.15 | 55.48 | 37.15 | 46.26 | 45.55 | 47.86 | 46.68 | 46.70 |
| Mean | 43.11 | 52.56 | 36.31 | | 43.48 | 46.34 | 47.76 | |
| | *p*-value | SED | CV (%) | | *p*-value | SED | CV (%) | |
| Row pattern | <0.001 | 2.169 | | | 0.047 | 2.484 | | |
| Site | <0.001 | 1.534 | | | 0.059 | 1.756 | | |
| Interaction | <0.001 | 3.758 | 10.1 | | 0.021 | 4.302 | 11.5 | |

SED = ± Standard error of difference of means; CV = Coefficient of variation; M = Maize row; S = Soybean row.

***Stomata conductance and stomata resistance***

Results of the study indicate that stomata conductance significantly varied with the interaction of spatial row arrangement and sites at 50% flowering ($p < 0.01$) and 50% pod development ($p < 0.001$) stages (Table 6.6). Highest stomata conductance was registered under sole soybean treatment in Busia at both growth stages. Within row intercropping treatment at Egerton University had lowest stomata conductance at 50% flowering stage while 2M: 2S treatment in Busia had the lowest stomata conductance level at 50% pod development stage. Conversely, stomata resistance at 50% flowering stage was highest ($p < 0.01$) under within row intercropping at Egerton University while the lowest level of stomata resistance at the same growth stage was under sole soybean treatment in Busia (Table 6.7). At 50% pod development stage, highest level of stomata resistance was registered under 2M: 2S treatment at Egerton University while the lowest was under sole maize treatment in Busia.

Table 6. 5 Effect of maize-soybean intercropping on soybean stomata conductance

| | Soybean stomata conductance (mmol $m^{-2}$ $s^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 50% Flowering stage | | | | 50% Podding stage | | | |
| Treatments | Busia | Egerton | Siaya | Mean | Busia | Egerton | Siaya | Mean |
| Sole soybean | 75.6 | 51.2 | 62.0 | 62.9 | 91.0 | 48.1 | 71.9 | 70.6 |
| Within row | 53.0 | 25.3 | 71.9 | 50.1 | 33.6 | 24.7 | 60.6 | 39.6 |
| 1M:1S | 62.6 | 41.8 | 69.1 | 57.8 | 52.0 | 39.9 | 64.5 | 52.1 |
| 2M:2S | 47.6 | 32.1 | 49.8 | 43.2 | 23.1 | 24.1 | 47.0 | 31.4 |
| 2M:1S | 68.1 | 43.9 | 63.2 | 58.4 | 43.2 | 33.2 | 52.0 | 42.8 |
| 1M:2S | 42.2 | 37.8 | 57.5 | 45.8 | 39.5 | 25.5 | 49.9 | 38.3 |
| Mean | 58.2 | 38.7 | 62.2 | | 47.2 | 32.6 | 57.7 | |
| | *p*-value | SED | CV (%) | | *p*-value | SED | CV (%) | |
| Row pattern | <0.001 | 3.61 | | | <0.001 | 3.84 | | |
| Site | <0.001 | 2.55 | | | <0.001 | 2.71 | | |
| Interaction | 0.005 | 6.25 | 14.40 | | <0.001 | 6.65 | 17.8 | |

SED = ± Standard error of difference of means; CV = Coefficient of variation; M = Maize row; S = Soybean row.

Table 6.6 Effect of maize-soybean intercropping on soybean stomata resistance

| | Soybean stomata resistance (s $cm^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 50% Flowering stage | | | | 50% Podding stage | | | |
| Treatments | Busia | Egerton | Siaya | Mean | Busia | Egerton | Siaya | Mean |
| Sole soybean | 0.013 | 0.020 | 0.017 | 0.016 | 0.011 | 0.021 | 0.013 | 0.015 |
| Within row | 0.019 | 0.040 | 0.014 | 0.024 | 0.030 | 0.041 | 0.016 | 0.028 |
| 1M:1S | 0.017 | 0.024 | 0.014 | 0.019 | 0.020 | 0.025 | 0.016 | 0.020 |
| 2M:2S | 0.021 | 0.030 | 0.020 | 0.024 | 0.043 | 0.046 | 0.023 | 0.036 |
| 2M:1S | 0.015 | 0.023 | 0.016 | 0.019 | 0.023 | 0.030 | 0.019 | 0.024 |
| 1M:2S | 0.023 | 0.027 | 0.018 | 0.023 | 0.026 | 0.044 | 0.021 | 0.030 |
| Mean | 0.018 | 0.027 | 0.016 | | 0.025 | 0.034 | 0.018 | |
| | *p*-value | SED | CV (%) | | *p*-value | SED | CV (%) | |
| Row pattern | <0.001 | 0.0024 | | | <0.001 | 0.0044 | | |
| Site | <0.001 | 0.0017 | | | <0.001 | 0.0031 | | |
| Interaction | <0.001 | 0.0042 | 12.3 | | 0.223 | 0.0076 | 14.0 | |

SED = ± Standard error of difference of means; CV = Coefficient of variation; M = Maize row; S = Soybean row.

***Photosynthesis rate***

Photosynthetic rate results (Figure 6.12) from Egerton University experiment indicate that sole soybean had highest ($p < 0.05$) photosynthesis rate compared to all intercropping treatments. Amongst intercropping treatments, 2M: 1S planting pattern had the lowest photosynthesis rate which corresponded to a 75.29% reduction compared to sole soybean treatment.

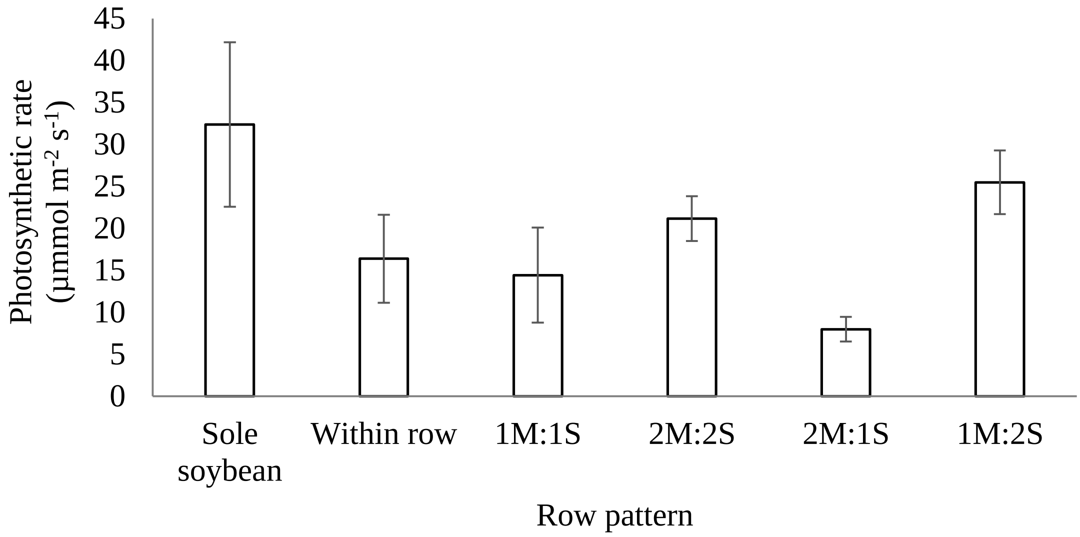


Figure 6.12 Effect of maize-soybean intercropping on soybean photosynthetic rate at 50% flowering stage at Egerton University, Njoro. Error bars represent ± standard error. Values significantly different at $p < 0.05$. M = maize row, S = soybean row.

***Transpiration rate***

Results for Egerton University experiment (Figure 6.13) show that intercropping of maize and soybean in 2M: 2S, 2M: 1S and 1M: 2S row arrangement reduced ($p < 0.05$) soybean transpiration rate relative to monocropped soybean. Non-significant differences existed amongst intercropping treatments in the rate at which soybean transpiration rate was taking place at 50% flowering stage.

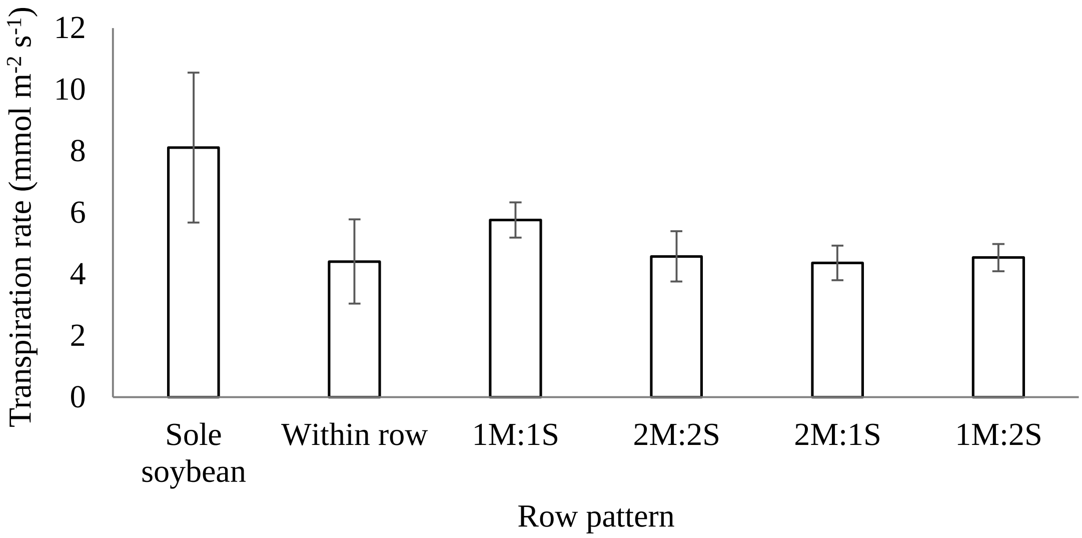


Figure 6.13 Effect of maize-soybean intercropping on soybean transpiration rate at 50% flowering stage at Egerton University, Njoro. Error bars represent ± standard error. Values significantly different at $p < 0.05$. M = maize row, S = soybean row.

### 6.4.4 Effect of maize-soybean intercropping on soybean reproductive growth

***Number of days to 50% flowering***

Number of days for soybean plants to attain 50% flowering at Egerton University and Siaya significantly ($p < 0.01$) varied with the interaction of spatial row arrangement and sites (Table 6.8). Sole soybean flowered earlier at both sites compared to intercropped treatments. Overall, soybean plants flowered earlier in Siaya compared to Egerton University.

Table 6.7 Effect of maize-soybean intercropping on number of days to 50% soybean flowering at Egerton University and Siaya

| Number of days to 50% soybean flowering | | | |
|---|---|---|---|
| Treatments | Egerton | Siaya | Mean |
| Sole soybean | 76.0 | 45.3 | 60.7 |
| Within row | 85.3 | 48.3 | 66.8 |
| 1M:1S | 84.0 | 47.3 | 65.7 |
| 2M:2S | 85.3 | 48.0 | 66.7 |
| 2M:1S | 83.0 | 48.0 | 65.5 |
| 1M:2S | 84.0 | 48.6 | 66.3 |
| Mean | 82.9 | 47.6 | |
| | *p*-value | SED | CV (%) |
| Row pattern | <0.001 | 0.843 | |
| Site | <0.001 | 0.487 | |
| Interaction | 0.007 | 1.193 | 2.2 |

SED = ± Standard error of difference of means; CV = Coefficient of variation; M = Maize row; S = Soybean row.

***Number of days to 50% pod maturity***

Number of days for soybean to attain 50% physiological maturity were significantly ($p < 0.001$) influenced by interaction of row arrangement and sites (Table 6.9). Soybean planted in 2M: 2S and 1M: 2S row arrangements at Egerton University matured late compared to monocropped soybean and other intercropping treatments. Soybean matured earlier in Siaya than at Egerton University.

Table 6.8 Effect of maize and soybean intercropping on number of days to 50% soybean maturity

| Number of days to 50% soybean maturity | | | |
|---|---|---|---|
| Treatments | Egerton | Siaya | Mean |
| Sole soybean | 122.33 | 73.00 | 97.67 |
| Within row | 132.67 | 73.67 | 103.17 |
| 1M:1S | 132.00 | 74.67 | 103.33 |
| 2M:2S | 139.33 | 75.00 | 107.17 |
| 2M:1S | 133.00 | 75.00 | 104.00 |
| 1M:2S | 139.00 | 74.00 | 106.50 |
| Mean | 133.06 | 74.22 | |
| | *p*-value | SED | CV (%) |
| Row pattern | <0.001 | 0.672 | |
| Site | <0.001 | 0.388 | |
| Interaction | <0.001 | 0.95 | 1.1 |

SED = ± Standard error of difference of means; CV = Coefficient of variation; M = Maize row; S = Soybean row.

### 6.4.6 Effect of maize-soybean intercropping on soybean root nodulation

***Number of nodules***

Spatial row arrangement and sites had significant ($p < 0.001$) independent effects on number of nodules per plant (Figure 6.14). Monocropped soybean had highest number of nodules per plant though not significantly different from number of nodules formed under 1M: 1S and 2M: 1S treatments. Within row intercropping had a significantly lower number of nodules per plant compared to all other treatments. Across sites, Siaya had highest number of nodules per plant (50.13) while mean number of nodules per plant between Egerton University (26.21) and Busia (16.56) were not significantly different.

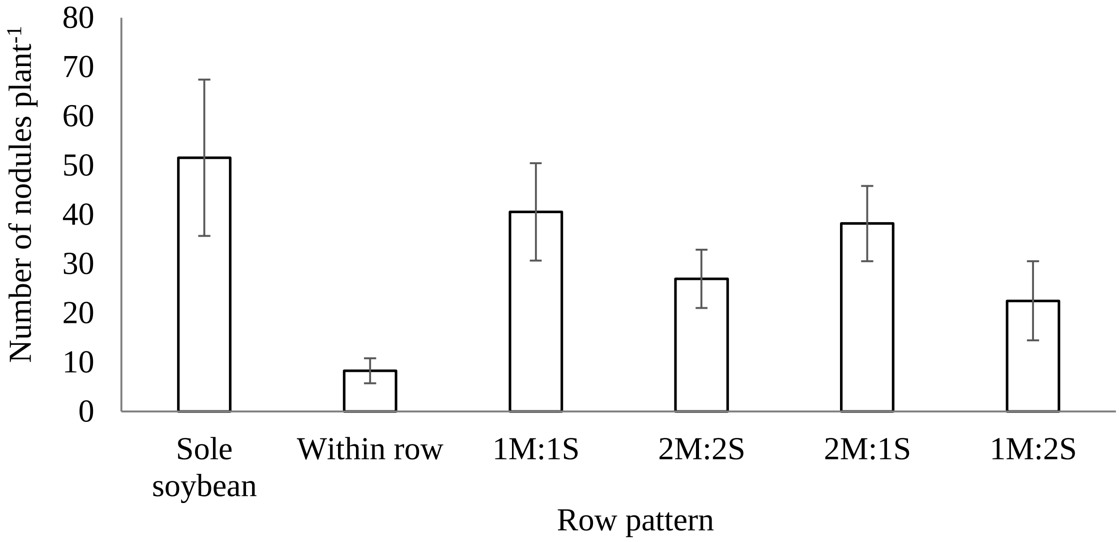


Figure 6.14 Effect of maize-soybean intercropping on number of soybean nodules per plant at 50% flowering stage. Error bars represent ± standard error. Values significantly different at $p < 0.01$. M = maize row, S = soybean row.

***Nodule biomass***

Nodule biomass per plant was significantly ($p < 0.001$) dependent on spatial row arrangement and sites (Figure 6.15). Highest nodule biomass per plant was attained by soybean plants in monocropping though not significantly different from nodule biomass registered when one row of soybean was planted in-between maize plants (1M: 1S and 2M: 1S). Within row intercropping had lowest nodule biomass per plant. Effect of sites on nodule biomass indicated that Siaya had highest nodule biomass per plant (0.31g $plant^{-1}$) followed by Egerton University (0.27g $plant^{-1}$) and then Busia (0.14g $plant^{-1}$).

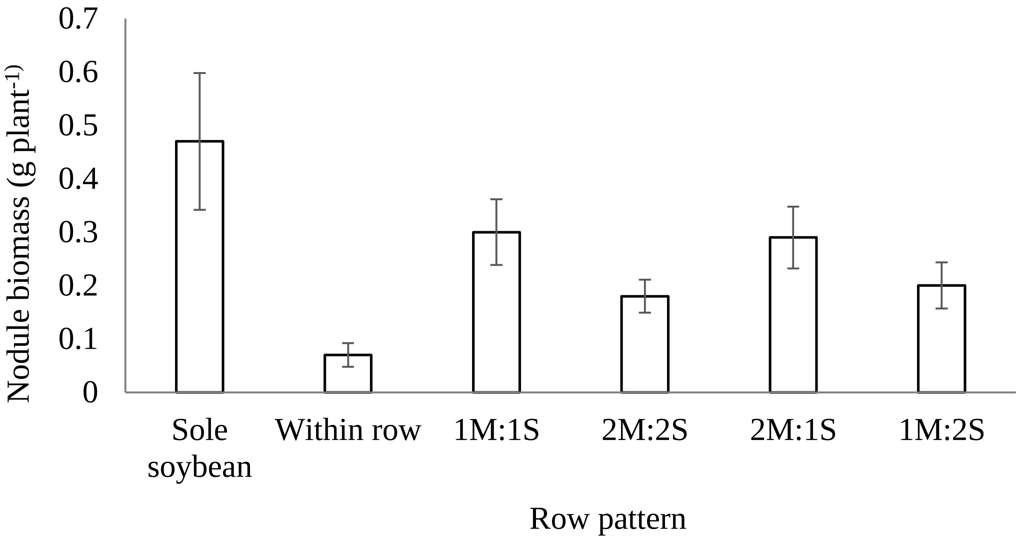


Figure 6.15 Effect of maize-soybean intercropping on soybean nodule biomass. Error bars represent ± standard error. Values significantly different at $p < 0.001$. M = maize row, S = soybean row.

#### 6.4.7. Effect of maize and soybean intercropping on soil moisture content

At 50% flowering stage, soil moisture content was significantly ($p < 0.05$) responsive to the interaction of spatial row arrangement and sites (Table 6.10). Planting of soybean and maize in 2M: 2S row arrangement at Egerton University increased soil moisture retention compared to all other treatments. At 50% pod development stage, soil moisture content significantly ($p < 0.001$) varied with sites. Overall, Egerton University had highest soil moisture content of 39.74% compared to 28.17% for Siaya and 25.75% for Busia.

Table 6.9 Effect of maize and soybean intercropping on soil moisture content

| | Soil moisture content (% v/v) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 50% Flowering stage | | | | 50% Podding stage | | | |
| Treatments | Busia | Egerton | Siaya | Mean | Busia | Egerton | Siaya | Mean |
| Sole soybean | 14.66 | 36.59 | 17.13 | 21.83 | 24.65 | 38.13 | 27.11 | 29.66 |
| Within row | 18.46 | 37.96 | 23.70 | 26.09 | 26.13 | 39.43 | 27.11 | 30.63 |
| 1M:1S | 22.38 | 41.23 | 15.25 | 25.19 | 23.19 | 39.11 | 27.43 | 29.55 |
| 2M:2S | 22.60 | 41.15 | 15.56 | 24.95 | 27.91 | 41.87 | 27.28 | 32.04 |
| 2M:1S | 21.03 | 38.55 | 14.21 | 23.57 | 27.52 | 38.76 | 28.46 | 31.38 |
| 1M:2S | 23.64 | 42.36 | 19.04 | 27.51 | 25.23 | 41.22 | 31.76 | 32.41 |
| Mean | 20.34 | 39.61 | 17.16 | | 25.75 | 39.74 | 28.17 | |
| | *p*-value | SED | CV (%) | | *p*-value | SED | CV (%) | |
| Row pattern | 0.038 | 0.172 | | | 0.465 | 1.657 | | |
| Site | <0.001 | 0.122 | | | <0.001 | 1.171 | | |
| Interaction | 0.015 | 0.298 | 7.3 | | 0.864 | 2.869 | 6.0 | |

SED = ± Standard error of difference of means; CV = Coefficient of variation; M = Maize row; S = Soybean row.

### 6.4.8 Effect of maize-soybean intercropping on soybean lodging

Lodging of soybean was significantly ($p < 0.05$) influenced by the interaction effect of spatial row arrangement and sites (Table 6.11). Highest incidence of soybean lodging occurred in intercropped treatments with 1M: 2S treatment at Egerton University having highest lodging occurrence. Sole soybean treatment at all three sites did not register any soybean lodging incidence.

Table 6.10 Effect of maize and soybean intercropping on soybean lodging

| | Lodging score (1-5) | | | |
|---|---|---|---|---|
| Treatments | Busia | Egerton | Siaya | Mean |
| Sole soybean | 1.0 | 1.0 | 1.0 | 1.0 |
| Within row | 2.64 | 1.63 | 2.0 | 2.07 |
| 1M:1S | 1.99 | 1.63 | 2.31 | 1.97 |
| 2M:2S | 2.59 | 2.64 | 2.0 | 2.53 |
| 2M:1S | 2.00 | 1.30 | 2.0 | 1.75 |
| 1M:2S | 2.64 | 3.32 | 2.0 | 2.63 |
| Mean | 2.30 | 1.84 | 1.86 | |
| | *p*-value | SED | CV (%) | |
| Row pattern | <0.001 | 0.073 | | |
| Site | 0.151 | 0.051 | | |
| Interaction | 0.012 | 0.126 | 11.2 | |

SED = ± Standard error of difference of means; CV = Coefficient of variation; M = Maize row; S = Soybean row; lodging index: 1 = almost all plants erect; 2 = < 25% lodged or lean > 60° from ground; 3 = 25-50% plants lodged or lean 45° from ground; 4 = 50-80% plants lodged or lean < 45° from ground; 5 = all plants lodged (Lommel, 2016).

### 6.4.9 Effect of maize-soybean intercropping on soybean yield and grain quality

***Number of pods per plant***

The interaction of spatial row arrangement and sites significantly ($p < 0.001$) influenced number of soybean pods per plant (Table 6.12). Sole cropping treatment in Siaya had more pods per plant followed by sole soybean treatment in Busia and then sole treatment at Egerton University. Lowest number of pods per plant were obtained in Siaya under 2M: 1S treatment.

Table 6.11 Effect of maize-soybean intercropping on number of soybean pods per plant

| | Number of pods plant $^{-1}$ | | | |
|---|---|---|---|---|
| Treatments | Busia | Egerton | Siaya | Mean |
| Sole soybean | 50.89 | 47.40 | 79.44 | 58.43 |
| Within row | 28.15 | 21.42 | 20.29 | 23.17 |
| 1M:1S | 34.85 | 26.38 | 30.57 | 30.50 |
| 2M:2S | 25.35 | 20.50 | 23.06 | 22.92 |
| 2M:1S | 36.01 | 29.31 | 17.56 | 27.06 |
| 1M:2S | 20.94 | 20.74 | 23.63 | 21.75 |
| Mean | 32.02 | 26.95 | 29.89 | |
| | *p*-value | SED | CV (%) | |
| Row pattern | <0.001 | 0.265 | | |
| Site | 0.055 | 0.188 | | |
| Interaction | <0.001 | 0.459 | 10.3 | |

SED = ± Standard error of difference of means; CV = Coefficient of variation; M = Maize row; S = Soybean row.

***Number of pods per node***

Number of pods per node was significantly ($p$ < 0.001) affected by main effects of spatial row arrangement and sites (Figure 6.16). Sole soybean treatment had highest number of pods per node. Intercropping soybean and maize in 1M: 2S row arrangement reduced number of pods per node though not significantly different from number of pods registered under within row and 2M: 2S treatments. Lowest number of pods per node was registered at Egerton University (2.03) which corresponded to a 25.56% and 23.19% reduction in number of pods per node compared to Busia and Siaya respectively.

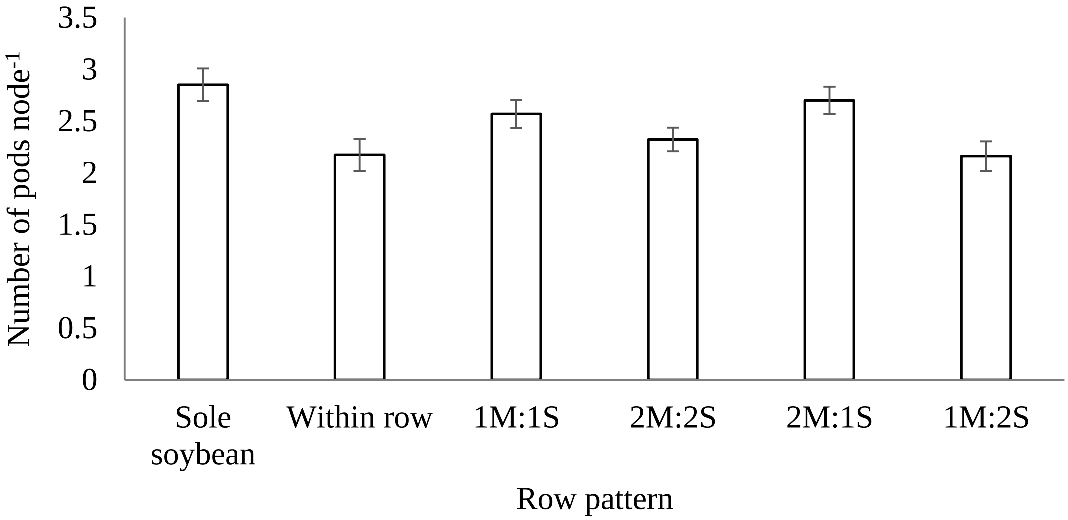


Figure 6.16 Effect of maize-soybean intercropping on number of pods per node. Error bars represent ± standard error. Values significantly different at $p$ < 0.001. M = maize row, S = soybean row.

***Pod length***

Soybean pod length was significantly ($p$ < 0.001) dependent on spatial row arrangement and sites (Figure 6.17). Sole soybean had longest pods compared to all other treatments though not significantly different from 1M: 1S and 2M: 1S treatments. On the other hand, within row intercropping had shortest pods. Planting one row of soybean in-between maize rows relatively increased soybean pod length though not significantly different from pod lengths obtained when two rows of soybean were planted in-between maize rows. Across sites, longest (3.77 cm) and shortest (3.58 cm) pod lengths were registered in Busia and Egerton University respectively.

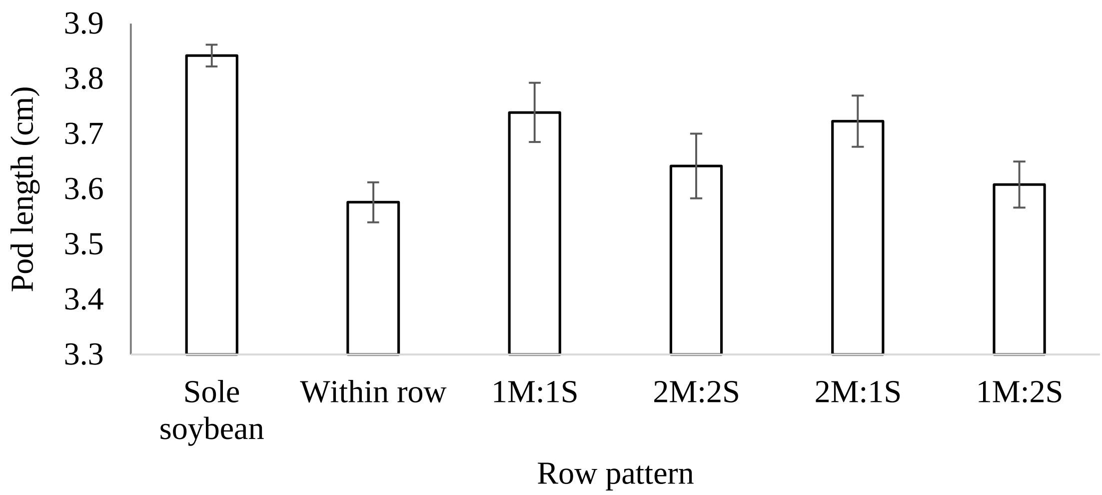


Figure 6.17 Effect of maize-soybean intercropping on soybean pod length. Error bars represent ± standard error. Values significantly different at $p < 0.001$. M = maize row, S = soybean row.

***Maize Cob length***

Spatial row arrangement did not have a significant effect on maize cob length. However, sites significantly ($p < 0.01$) contributed to differences in maize cob lengths with Siaya having longest cobs which corresponded to 4.80 and 7.91% increase over pod lengths registered at Egerton University and Busia, respectively (Figure 6.18).

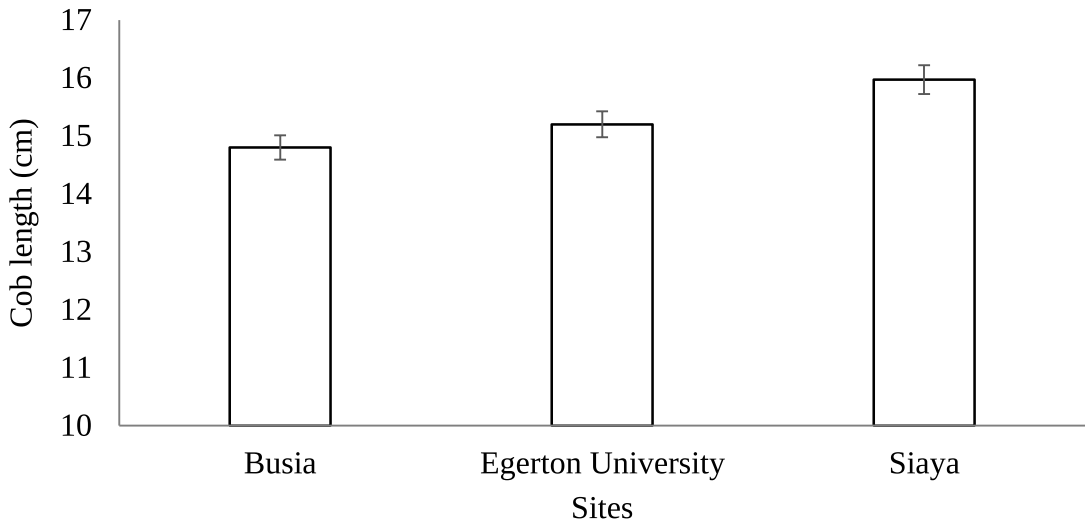


Figure 6.18 Effect of sites on maize cob length. Error bars represent ± standard error. Values significantly different at $p < 0.01$.

***Number of seeds per pod***

Number of soybean seeds per pod significantly ($p < 0.01$) responded to different spatial row arrangements and sites (Figure 6.19). Highest number of seeds per pod was registered under 1M: 1S row arrangement while within row intercropping had the lowest. Differences in sites resulted into a significantly ($p < 0.001$) higher number of seeds per pod in Busia (2.49), followed by Siaya (2.41) and lastly by Egerton University (2.17).

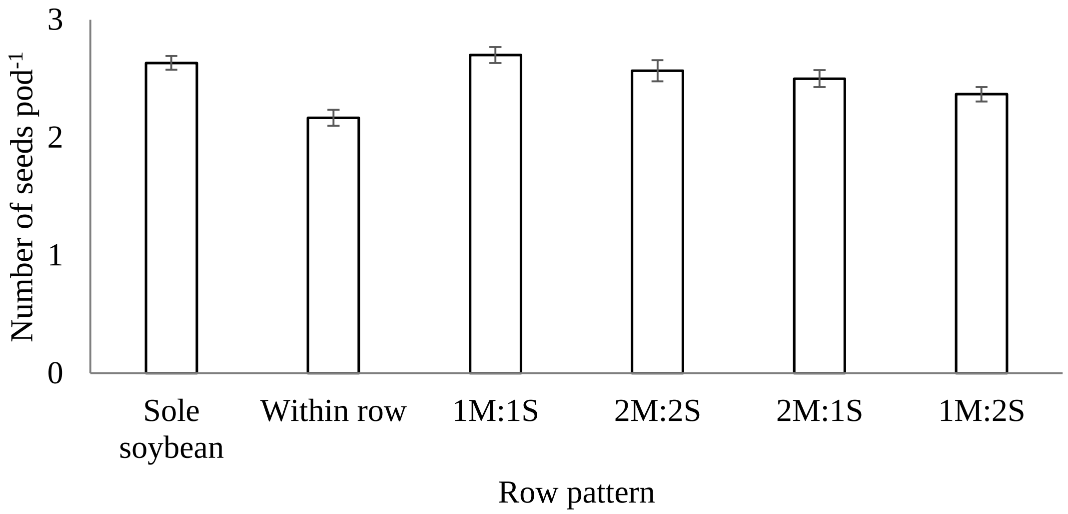


Figure 6.19 Effect of maize-soybean intercropping on number of soybean seeds per pod. Error bars represent ± standard error. Values significantly different at $p < 0.01$. M = maize row, S = soybean row.

***Shelling percent***

Soybean shelling percent was not significantly responsive to different spatial row arrangements but significantly ($p < 0.001$) changed with sites (Figure 6.20). Highest shelling percentage was registered at Siaya though not significantly different from shelling percent registered at Egerton University. Busia had the lowest shelling percent amongst the sites.

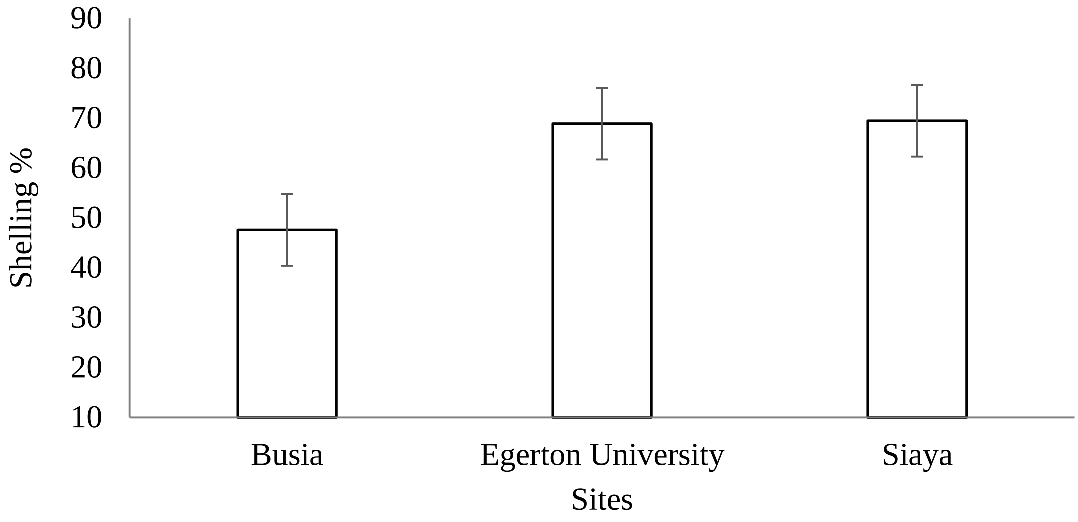


Figure 6.20 Effect of sites on soybean shelling %. Error bars represent ± standard error. Values significantly different at $p < 0.001$.

***100 seed weight***

Interaction of spatial row arrangement and sites significantly ($p < 0.001$) contributed to differences in soybean 100 seed weight (Table 6.13). All treatments had lower 100 seed weight at Egerton University. Maize 100 seed weight varied significantly ($p < 0.001$) with sites, with spatial row arrangements having a non-significant effect. Highest maize seed weight of was registered at Egerton University (32.85g) followed by Siaya (30.07g) and then Busia (21.67g).

Table 6.12 Effect of maize-soybean intercropping on soybean 100 grain weight

| | Soybean 100 grain weight (g) | | | |
|---|---|---|---|---|
| Treatments | Busia | Egerton | Siaya | Mean |
| Sole soybean | 12.57 | 9.49 | 12.79 | 11.57 |
| Within row | 13.13 | 7.72 | 13.43 | 11.26 |
| 1M:1S | 12.79 | 9.93 | 13.11 | 11.90 |
| 2M:2S | 13.13 | 7.73 | 13.18 | 11.19 |
| 2M:1S | 13.21 | 9.81 | 12.90 | 11.92 |
| 1M:2S | 13.37 | 8.19 | 13.26 | 11.47 |
| Mean | 13.03 | 8.79 | 13.11 | |
| | *p*-value | SED | CV (%) | |
| Row pattern | 0.021 | 0.037 | | |
| Site | <0.001 | 0.026 | | |
| Interaction | <0.001 | 0.064 | 2.3 | |

SED = ± Standard error of difference of means; CV = Coefficient of variation; M = Maize row; S = Soybean row.

***Grain yield***

The interaction of spatial row arrangement and sites had significant ($p < 0.01$) influence on soybean grain yield (Table 6.14). Sole soybean treatment had highest grain yield at all sites with grain yield being significantly higher at Siaya. Within row intercropping treatment at Egerton University had lowest yields. Spatial row arrangement did not have a significant effect on maize grain yield. Maize grain yield was however significantly ($p < 0.001$) different across sites. Egerton University had highest maize grain yield of 7,951 kg ha$^{-1}$ followed by 6,160 kg ha$^{-1}$ at Siaya and 4,284 kg ha$^{-1}$ at Busia.

Table 6.13 Effect of maize-soybean intercropping on soybean grain yield

| | | Soybean grain yield (Kg ha$^{-1}$) | | |
|---|---|---|---|---|
| Treatments | Busia | Egerton | Siaya | Mean |
| Sole soybean | 1767 | 1450 | 2600 | 1910 |
| Within row | 310 | 80 | 237 | 195 |
| 1M:1S | 714 | 339 | 479 | 499 |
| 2M:2S | 667 | 241 | 672 | 503 |
| 2M:1S | 428 | 136 | 240 | 254 |
| 1M:2S | 540 | 217 | 450 | 389 |
| Mean | 667 | 320 | 633 | |
| | *p*-value | SED | CV (%) | |
| Row pattern | <0.001 | 1.228 | | |
| Site | <0.001 | 0.868 | | |
| Interaction | 0.004 | 2.126 | 11.3 | |

SED = ± Standard error of difference of means; CV = Coefficient of variation; M = Maize row; S = Soybean row.

***Protein content***

Protein content of soybean grains did not significantly respond to spatial row arrangement but was significantly ($p < 0.001$) influenced by site differences. Soybean grain at Egerton University had highest protein content which corresponded to a 21.19% and 22.69% increase over protein content at Siaya and Busia respectively (Figure 6.21).

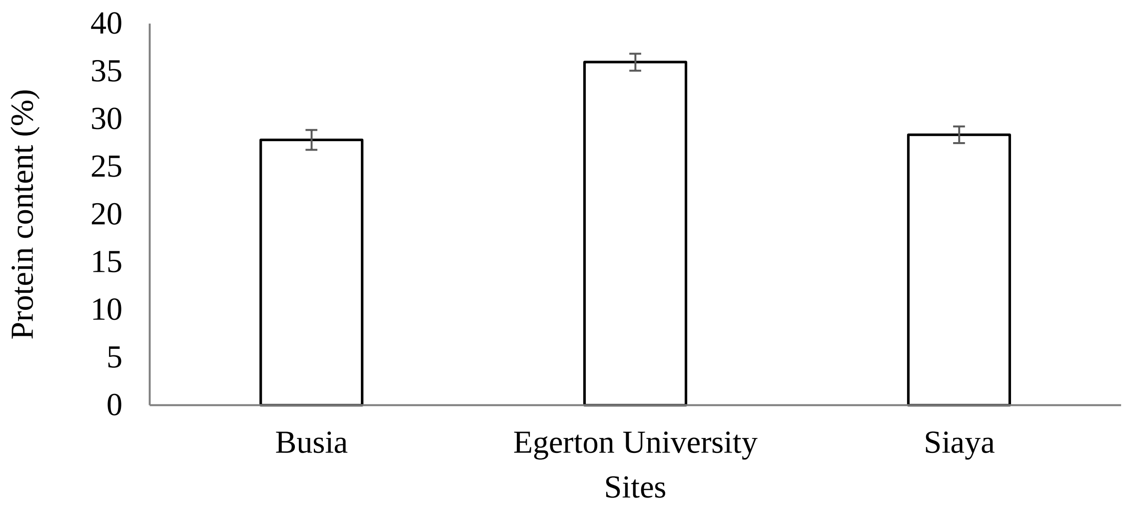


Figure 6.21 Effects of sites on soybean grain protein content. Error bars represent ± standard error. Values significantly different at $p < 0.001$.

***Soybean yield and yield components correlations***

Soybean yield components and grain yield correlations show that grain yield positively and highly correlated with number of pods per plant, number of pods per node and pod length; and low positive correlation with shelling percent and 100 seed weight (Table 6.15). Coefficients of determination ($r^2$) show that 79.58, 32.59, 28.99, and 5.0% yield variations amongst spatial row arrangements are attributed to differences in number of pods per plant, number of pods per node, pod length, and 100 seed weight respectively.

Table 6. 14 Correlation of soybean grain yield with selected quantitative yield components traits

| | Grain yield | Pods plant$^{-1}$ | Pods node $^{-1}$ | Pod length | 100 seed weight |
|---|---|---|---|---|---|
| Grain yield | - | - | - | - | - |
| Pods plant$^{-1}$ | 0.8921$^{***}$ (0.7958) | - | - | - | - |
| Pods node$^{-1}$ | 0.5709$^{***}$ (0.3259) | 0.5983$^{***}$ (0.3580) | - | - | - |
| Pod length | 0.5384$^{***}$ (0.2899) | 0.4705$^{***}$ (0.2214) | 0.6923$^{***}$ (0.4793) | - | - |
| 100 seed weight | 0.2246$^{ns}$ (0.050) | 0.1276$^{ns}$ (0.0163) | 0.6462$^{***}$ (0.4175) | 0.5337$^{***}$ (0.2848) | - |

*** Represents significance at $p < 0.001$; ns = non-significance; figures in parentheses represent coefficient of determination, ($r^2$).

### 6.4.10 Effect of maize and soybean intercropping on intercropping productivity

Results in Table 6.16 show that total land equivalent ratio values were more than one indicating that intercropping was more productive than monocropping. Maize had higher partial land equivalent ratio values compared to soybean. Relatedly, competitive ratio (CR) index values indicate that intercropped maize registered higher CR values in all row patterns compared to soybean.

Table 6.15 Effect of maize and soybean intercropping on land equivalent ratio (LER)

| Row pattern | $PLER_{soybean}$ | $PLER_{Maize}$ | $Total_{LER}$ | $CR_{maize}$ | $CR_{soybean}$ |
|---|---|---|---|---|---|
| Within row | 0.10 | 1.06 | 1.16 | 8.48 | 0.12 |
| 1M:1S | 0.26 | 1.02 | 1.28 | 1.96 | 0.51 |
| 2M:2S | 0.26 | 1.00 | 1.27 | 1.92 | 0.52 |
| 2M:1S | 0.13 | 0.99 | 1.12 | 2.51 | 0.40 |
| 1M:2S | 0.20 | 1.08 | 1.28 | 5.4 | 1.54 |

PLER= Partial land equivalent ratio; LER= land equivalent ratio, CR = Competitive ratio.

## 6.5 Discussion

### Effect of maize and soybean intercropping on shoot growth

Results of the study have shown that maize and soybean intercropping suppressed soybean shoot growth by reducing canopy spread, stem thickness, number of leaves per plant, leaf area and number of primary branches. Intercropping however increased soybean plant height and leaf area index. Overall, intercropping treatments had a faster leaf expansion rate (22.80%) compared to monocropped soybean. Maize shoot growth and leaf area index were not affected by intercropping of maize and soybean. Soybean and maize shoot growth also varied with sites. These results are in agreement with observations by Gong *et al*. (2015) and Tsujimoto *et al*. (2015) who reported reduced soybean number of leaves, leaf biomass, stem thickness and an increased elongation of soybean plants under intercropping with maize. Results however contradict findings by Fan *et al*. (2018) who reported reduced soybean plant height in response to intercropping with maize. Variant results to current findings were also observed by El-Shellif *et al*. (2015) who reported reduced maize plant height in response to intercropping with soybean. Nonetheless, Muoneke *et al*. (2007) and Peng *et al*. (2009) indicated that maize and soybean intercropping did not have a significant effect on maize plant height which is in line with findings of this study. Rahman *et al*. (2017) indicated that maize and soybean intercropping increased maize leaf area and leaf area index which is in contradiction with current findings.

Results of this study indicate that intercropping reduced intercepted photosynthetically active radiation which led to reduced production of photoassimilates for soybean growth. This led to reduced branching which translated into related reductions in number of leaves per plant, reduced leaf area and leaf biomass. Increased plant height, reduced branching and suppressed leaf production in intercropped soybean plants may be viewed as a shade avoidance mechanism by plants in order to optimize light interception for photosynthesis (Kozuka *et al*., 2005; Casal, 2012). Casal (2012) indicated that shading may arise from component crops grown in a mixture and that increased plant height and leaf petiole elongation in plants under shade is a hyponastic response that allows plants to reach out for light to optimize photosynthesis. Under shade, it has been reported that there is increased concentration of auxin above optimal soybean plant requirement levels which leads to inhibition of cell expansion (Wu *et al.*, 2017a) and this could explain production of smaller leaves and reduced plant growth under intercropping treatments compared to sole soybean treatment. Increased leaf expansion rate for within row treatment relative to other treatments may be a result of soybean plants benefitting from inorganic fertilizers applied to maize. On average, intercropped treatments had 10% more soil moisture levels compared to sole treatment. This could have contributed to increased leaf expansion rates for intercropping treatments, in addition to increased ground cover from both maize and soybean. This is in line with an observation by Pantin *et al*. (2011) which linked increased leaf expansion rate to soil moisture availability.

**Effect of maize and soybean intercropping on dry matter partition and interception of photosynthetically active radiation**

Soybean leaf biomass and intercepted photosynthetically active radiation (IPAR) were lower under intercropping with maize. Studies by Tsujimoto *et al*. (2015), Kamara *et al*. (2017) and Wu *et al.* (2017b) reported reduced soybean leaf biomass and IPAR under intercropping with maize which concurs with findings of this study. Non-significant effect of maize and soybean intercropping on soybean leaf biomass was reported by Meng *et al.* (2015) which differs from results of this study.

Sole soybean plants had highest number of leaves per plant and largest leaf area which translated into higher leaf biomass. Equally, soybean plants in Busia had highest number of leaves and leaf area compared to other sites which explains a related higher leaf biomass in Busia compared to Egerton University and Siaya. Soybean plants under shade from a taller component crop in intercropping will decrease leaf dry mass per unit area to improve light interception for photosynthesis (Wu *et al*., 2017b). Lower biomass partitioning to leaves under intercropping also indicates that soybean plants invested more resources in stem growth at the expense of leaf expansion. Reduced IPAR by soybean plants under intercropping may be associated with shading effect from taller maize plants which limited light penetration down to soybean plant canopy. In addition, soybean plants under intercropping had suppressed branching, reduced leaf production and narrower plant canopy spread which contributed to lower IPAR. Higher IPAR by soybean in Busia compared to other sites could be a result of stunted maize crop due to low soil acidity and high infestation of witchweed (*Striga asiatica*). Fall armyworm damage of maize leaves was highest in Busia which could have also contributed to increased light penetration to understorey soybean.

**Effect of maize and soybean intercropping on chlorophyll content and leaf gaseous exchange**

Intercropping of maize and soybean increased leaf chlorophyll content of soybean plants grown in association with maize while soybean stomata conductance, net photosynthesis and transpiration rates were reduced due to intercropping. Increased levels of chlorophyll content in intercropped soybean was reported by Zhang *et al*. (2013) and Gong *et al*. (2015) which is in agreement with results of this study. Contrary to current findings are the reports by Fan *et al*. (2018) and Gou *et al.* (2018) which indicated reduced chlorophyll content in intercropped soybean and maize respectively. Increased stomata conductance, net photosynthesis and transpiration rates in monocropped soybean relative to intercropping as found in this study were reported by Tsujimoto *et al*. (2015) and Fan *et al*. (2018). Nonetheless, other studies have indicated increased stomata conductance, net photosynthesis and transpiration rates in soybean intercropped with maize (Zhang *et al.,* 2013) and intercropped maize and wheat (Gou *et al.,* 2018) relative to monocropping.

Plants use chlorophyll to absorb light to convert water and carbon dioxide to carbohydrates for plant growth. Quantification of chlorophyll serves as an important determinant of light absorption (Fan *et al*., 2018). Increased chlorophyll content in soybean plants grown under intercropping may therefore be viewed as a shade tolerance response to help plants optimize light interception and utilization for photosynthesis (Wu *et al*., 2017a). Reduced soybean stomata conductance, photosynthesis and transpiration rates under intercropping in this study may also be a result of reduced exposure of understory soybean to direct sunlight. Reduced exposure from direct sunlight increases far red light which leads to reduction in leaf stomata density translating into lower levels of stomata conductance and transpiration (Maliakal *et al*.,1999). Tardieu (2013) reported a linear relationship between photosynthesis rate and light intensity in IPAR. Higher stomata conductance and larger leaf area under monocropping contributed to increased photosynthesis rate for sole soybean. At microclimate level, He *et al*. (2012) indicated that day-time relative humidity is higher in intercropping relative to monocropping which further explains reduced stomata conductance, phosynthesis and transpiration rates in intercropped soybean. Reduced stomata conductance at Egerton University compared to Busia and Siaya may be associated with differences in temperatures and relative humidity of the areas. Being at a higher altitude (2267 meters) than Busia (1253 meters) and Siaya (1270 meters), Egerton University has relatively lower mean annual temperature and higher relative humidity compared to other two sites. Nakano *et al*.

(2015) reported increased transpiration rate in soybean at higher temperature while reduced stomata conductance by soybean plants at higher relative humidity was reported by Bunce, (2000).

**Effect of maize and soybean intercropping on root nodulation**

Sole soybean registered the highest number of nodules per plant which also translated into an equally higher nodule biomass for the treatment. Within row intercropping had a significantly lower number of nodules and nodule biomass compared to other treatments. Reduced number of nodules per plant under intercropping relative to monocropping were reported by Gosh *et al*. (2004) which is in agreement with findings of this study. Meng *et al*. (2015) however reported increased nodulation by soybean intercropped with maize. This finding, in addition to an observation by El-Shellif *et al*. (2015) which reported a non-significance effect of intercropping on soybean nodulation, differs from current results.

Soybean in within row treatment were planted in-between two maize plants which led to soybean plants having an advantage of utilizing nitrogen applied to maize through inorganic fertilizers. Nitrogenous fertilizer inhibits nodulation and biological nitrogen fixation in leguminous crops (Ogutcu *et al*., 2008; Namvar *et al*., 2011). Reduced nodule biomass in Busia was a result of lower number of nodules per plant compared to other sites which may be associated with acidic soil conditions. Mean soil pH in Busia was 5.87 which was lower than optimal pH range of 6 -7 needed for optimum nodulation in soybeans (Bekere *et al*., 2013). Acidic soil conditions suppress biological nitrogen fixation (BNF) in soybean by limiting bacterial infection of roots to form nodules (Ferguson *et al*., 2013).

**Effect of maize and soybean intercropping on reproductive growth**

Intercropping delayed soybean flowering and pod maturity compared to monocropping. This contradicts a report by Muoneke *et al*. (2007) that alluded to a non-significant effect of soybean and maize intercropping on number of days for soybean to attain 50% flowering which also showed that intercropped soybean attained 50% pod development earlier than sole soybean. Pierre *et al.* (2017) reported a non-significant effect of maize and soybean intercropping on both 50% flowering and 75% pod maturity durations of soybeans.

Bing and De-Ning (2015) reported that shading increases soybean flowering and pod development periods compared to soybean plants grown under natural light. Reduction in IPAR in intercropped soybean as shown in this study suggests that soybean plants were exposed to shading from taller maize plants which contributed to extended periods of flowering and pod maturity. Low red/ far red ratios prevalent under high plant population, as is the case with intercropping, have also been reported to delay flowering in soybean (Casal, 2012). In addition, extended periods of flowering and pod setting under stressful environments, as was the case with reduced IPAR in this study, is a mechanism by plants to produce and sustain higher number of pods per plant (Egli and Bruening, 2005). Increased depletion of soil moisture in monocropped soybean relative to intercropping as current results have shown contributed to accelerated pod maturity in sole soybean compared to intercropping. In addition, He *et al*. (2012) indicated that day-time relative humidity is higher under intercropping relative to monocropping which suggests existence of lower temperatures under intercropping which could have contributed to delayed pod maturity. Delayed flowering and pod maturation were observed at Egerton University compared to Siaya which can be explained by differences in elevations of the two sites. Being a high-altitude area, Egerton University had lower temperatures (18.9°C) compared to Siaya (21°C). Lower temperature delays growth and reproductive development of plants due to reduced activity of plant growth hormones which are catalysts for physiological, metabolic and molecular processes to take place in plants (Heinemann *et al*., 2006; Hatfield and Prueger, 2015).

**Effect of maize and soybean intercropping on soil moisture content and lodging of soybeans**

Soil moisture status was relatively lower under monocropping compared to intercropping at 50% flowering stage. Harvest lodging of soybean was significantly increased with intercropping of soybean and maize. Reduction in soil moisture content under monocropping conforms to an observation by Ndiso *et al*. (2017) which indicated reduced moisture levels in sole cowpea relative to intercropped cowpea with maize. The results, however, contradict report by Mushagalusa *et al*. (2008) that indicated a non-significant effect of maize and potato intercropping on soil moisture content. Increased soil moisture depletion by soybean in a tree-based agroforestry intercropping system was reported by Reynolds *et al.* (2007) which is also at variance with current results.

Increased plant population in intercropping treatments provided a better soil cover that reduced the amount of sunlight reaching the soil thus minimizing the evaporation potential of soil moisture compared to monocropping. Vigorous plant growth as reflected by high number of leaves per plant, larger leaf area and related higher transpiration rate led to an increased water uptake from the soil in sole soybean compared to intercropping which contributed to lower moisture levels under monocropping (Tsujimoto *et al*., 2013). Across sites, lower daytime temperatures led to higher volumetric soil moisture content at Egerton University compared to Busia and Siaya. Soybean plants under intercropping treatments were taller but with thinner stems which led to increased incidence of lodging.

**Effect of maize and soybean intercropping on yield and intercropping productivity**

Maize and soybean intercropping reduced number of soybean pods per plant, number of pods per node, number of seeds per pod and pod length translating into reduced intercropped soybean yields compared to sole soybean. Maize and soybean intercropping did not have a significant effect on maize grain yield. Results have also indicated that intercropping of maize and soybean was more productive compared to monocropping. Reduced soybean yields under intercropping with maize as found out in this study were also reported by Matusso *et al*. (2013); Obiero *et al*. (2013) and Paudel *et al*. (2015). Contradictory results to current findings were reported by El-Shamy *et al.* (2015) who found increased soybean and maize yields under intercropping compared to sole cropping. Reduced maize grain yield under intercropping with castor and higher productivity of intercropping system relative to monocropping were reported by Obiero *et al*. (2013).

Photosynthesis rate in soybean plants has been reported to be positively associated with increased soybean yields and that the degree of photosynthesis dictates pods and grain development (Casal, 2012). Results from this study have shown that intercropping reduced interception of photosynthetically active radiation by soybean plants which negated photosynthesis rate. Reduce photosynthesis rate led to a reduction in the production and assimilation of photosynthates for pod and seed development, the result of which was reduced seed size and grain yield. This explains why soybean grains at Egerton had lower seed size despite extended growth periods of soybean. In addition, plants grown under shade conditions optimize light interception for photosynthesis by increasing chlorophyll content (Wittmann *et al.,* 2001). Increases in chlorophyll content however means that plants are reallocating nitrogen from Calvin cycle enzymes and investing in chlorophyll biosynthesis leading to reduction in nitrogen use efficiency for plant growth and productivity (Zhu *et al.*, 2007. Reduced soybean grain yield under intercropping may also be related to suppressed branching due to increase in quantities of far red light under canopy shading which could have contributed to reduced number of pods per plant (Hirose, 2005). Liu *et al*. (2008), Bing and De-Ning (2015) indicated that shading limits soybean flowering and increases flower abscission. In this study, understory soybean was exposed to shading as evidenced from lower IPAR in intercropping treatments.

This possibly reduced flowering and increased flower abscission in intercropped soybean translating into lower number of pods per plant and number of pods per node. Much as photosynthetic rate was not measured in Busia and Siaya, studies have shown a positive correlation between stomata conductance, IPAR and photosynthetic rate (Zhang *et al*., 2013; Gong *et al*., 2015; *Kamara et al*., 2017; Fan *et al*., 2018). Higher seed protein content at Egerton University compared to Busia and Siaya may be attributed to differences in available nitrogen in the soils. Egerton University soils had 50 and 43% more nitrogen compared to Busia and Siaya soils, respectively. This meant that there was increased availability of nitrogen in developing seeds at Egerton University compared to other sites (Song *et al.*, 2016).

Higher productivity of intercropping over monocropping as evidenced from higher than unity land equivalent ratio values may be attributed to relatively higher maize yields under intercropping compared to sole maize. Higher productivity of intercropping may be a result of reduced competition for growth resources between maize and soybean due to differences in peak demand for growth resources. Differences in peak demand for growth resources emanated from differences in growth duration of the crops considering that soybean cultivar DPSB 19, which was used in the study, matured much earlier than maize.

Overall, results of the study have shown that intercropping maize and soybean led to significant reduction in soybean yield which may be attributed to reduced stomata conductance, IPAR, photosynthetic rate, transpiration and soybean nodulation. Crop yield is influenced principally by photoassimilates synthesis and partitioning by plants (Campillo *et al*., 2012) which has been demonstrated in the current maize-soybean intercropping study. Intercropped soybean had low stomata conductance which could have limited the ability of soybean canopy to access carbon dioxide for photosynthesis. This was exacerbated by reduced light reaching soybean canopy. Soybean under maize received about 25% of incoming PAR which means that understorey soybean experienced reduced capacity to synthesise photoassimilates to support both growth and yield formation. Results suggests that intercropping maize and soybean at current plant spacings and row patterns suppressed soybean growth. Nonetheless intercropping of soybean and maize in 1M: 1S row pattern gave relatively higher soybean yields compared to other row patterns. Further studies on wider row spacings for maize and soybean intercropping would give more insights on the suitability of soybean and maize intercropping.

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# CHAPTER SEVEN

## GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The study was aimed at determining the response of soybean to soil moisture stress and also establish the response of selected soybean cultivars to different planting densities and with intercropping with maize.

Results have shown that soil moisture limitation reduced soybean plant growth by suppressing plant height, canopy development, stem thickness, production of leaves and branches and leaf area. Reduced plant growth under soil moisture limitation led to a related reduction in interception of photosynthetically active radiation. There was increased root growth at optimal soil moisture level of 80% FC than under soil moisture stressed conditions. Overall, soil moisture stress reduced stomatal conductance which led to corresponding reductions in sub-stomatal carbon dioxide concentration, transpiration and photosynthetic rates. Leaf temperature increased with soil moisture stress. Number of pods per plant, number of seeds per pod, pod length, seed weight and grain yield were all higher at optimal soil moisture level than under soil moisture stress. Increased number of root nodules at higher soil moisture regimes gave a corresponding increase in soybean protein content. Response to soil moisture stress varied with type of soybean cultivar used. It was generally observed that cultivars DPSB 19 and EAI 3600 exhibited higher leaf relative water content, stomatal conductance and higher grain yield at lower soil moisture regimes compared to other test cultivars.

Soybean plant height increased with increased plant density though at the expense of canopy development, stem thickness, number of leaves, number of branches and leaf area. High plant population per unit area optimized interception of photosynthetically active radiation. Stomatal conductance, sub-stomatal carbon dioxide concentration and photosynthetic rate were higher at lower plant density while total leaf chlorophyll content was not responsive to variations in plant density. Soil moisture levels were higher at lower plant density than at higher plant density. Highest soybean yields were obtained at the highest plant density of 80 plants $m^{-2}$ though number of pods per plant, number of seeds per pod and seed weight were optimized at 10 plants $m^{-2}$. High incidences of lodging were registered at 80 plants $m^{-2}$ which disadvantages growing soybean at this plant population. Soybean yields were not significantly different at 20 and 40 plants $m^{-2}$. However due to close spacing of 25 cm x 5 cm, it would be difficult to implement the plant density of 40 plants $m^{-2}$ by farmers. The compromise planting density of 45 cm 10 cm (20 plants $m^{-2}$) is a viable option for optimization of soybean yields.

Determinate soybean cultivar EAI 3600 registered highest number of leaves, number of branches and leaf area compared to indeterminate cultivar DPSB 19. Indeterminate cultivar DPSB 19 had higher concentration of sub-stomatal carbon dioxide concentration and photosynthetic rate than determinate cultivar EAI 3600.

Intercropping maize and soybean led to significant reduction in soybean yield. Intercropping soybean with maize reduced soybean stomata conductance by 31.16% which could have limited the ability of soybean canopy to access carbon dioxide for photosynthesis. This was exacerbated by reduced light reaching soybean canopy. Soybean under maize received about 25% of incoming PAR which means that understorey soybean experienced reduced capacity to synthesise photoassimilates to support both growth and yield formation. Intercropping maize and soybean reduced soybean nodulation by about 47.0% relative to sole soybean while soybean leaf chlorophyll content was higher under intercropping compared to sole cropping. Overall intercropping maize and soybean was more productive than monocropping as evidenced from LER values of greater than one. Maize was more aggressive than soybean in all intercropping treatments.

From results obtained, it is concluded that:

i Soil moisture stress reduces carbon dioxide assimilation, growth, yield and yield components of soybean.

ii High plant density increases soybean yield but reduces number of pods per plant, number of seeds per pod and seed size.

iii Intercropping soybean and maize reduces growth, stomatal conductance and yield of soybean.

Based on the results of this study, it is recommended that:

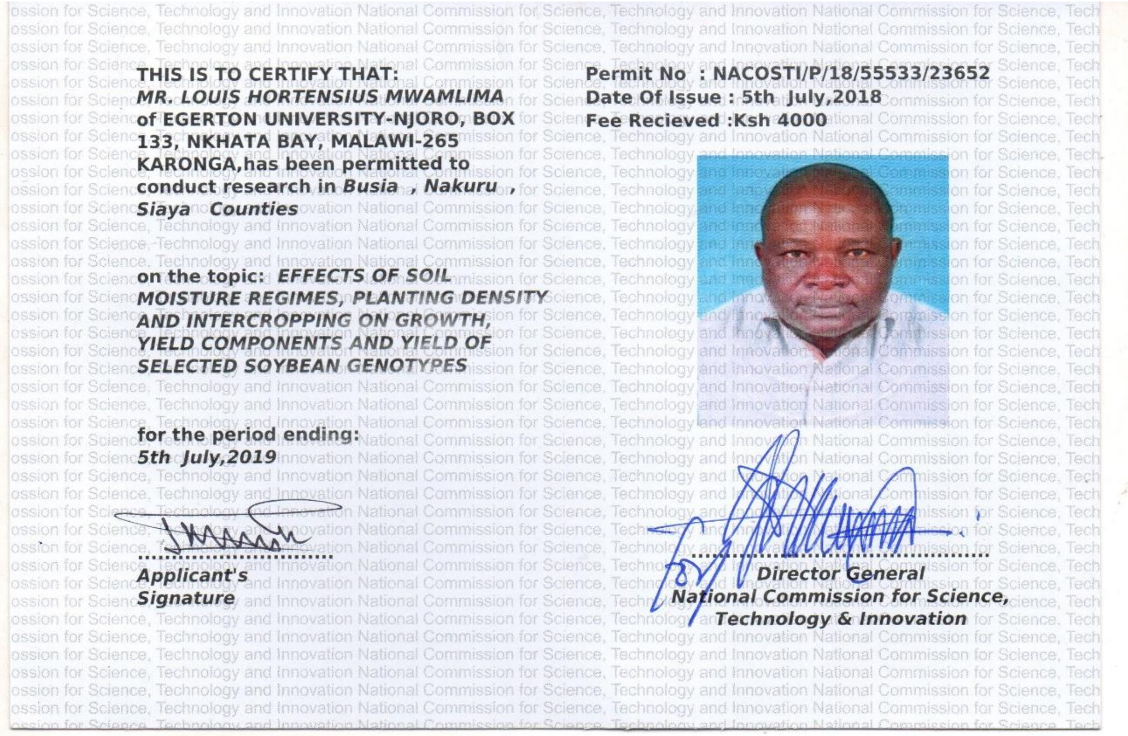
i Cultivar DPSB 19 may is recommended for production under soil moisture limiting conditions. Soil moisture levels at 40% FC and 50% CWR be a cut-off points for optimal soybean production beyond which appropriate agronomic practices like supplementary irrigation be employed to optimize soybean yields. Further multi-locational studies are however necessary to ascertain the responses of tested cultivars to soil moisture stress.

ii Planting soybean at 20 plants $m^{-2}$ should be used for optimum soybean yields.

iii 1M: 1S row pattern is recommended for soybean and maize intercropping. Further studies on wider row spacings are however necessary to get more insights on productivity of soybean under intercropping with maize.

**APPENDICES**

Appendix 1. 1 Research permit



THIS IS TO CERTIFY THAT:
*MR. LOUIS HORTENSIUS MWAMLIMA*
of EGERTON UNIVERSITY-NJORO, BOX 133, NKHATA BAY, MALAWI-265 KARONGA,has been permitted to conduct research in *Busia* , *Nakuru* , *Siaya* *Counties*

on the topic: *EFFECTS OF SOIL MOISTURE REGIMES, PLANTING DENSITY AND INTERCROPPING ON GROWTH, YIELD COMPONENTS AND YIELD OF SELECTED SOYBEAN GENOTYPES*

for the period ending:
*5th July,2019*

Permit No : NACOSTI/P/18/55533/23652
Date Of Issue : 5th July,2018
Fee Recieved :Ksh 4000

..............................
*Applicant's Signature*

..............................
*Director General*
*National Commission for Science, Technology & Innovation*

**Appendix 2 Analysis of variance (ANOVA) sample outputs**

Appendix 2. 1 Soil moisture stress greenhouse experiment ANOVA output

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep | 2 | 0.2919 | 0.1460 | 1.36 | |
| Moisture | 3 | 89.9418 | 29.9806 | 279.87 | <.001 |
| Variety | 5 | 17.2035 | 3.4407 | 32.12 | <.001 |
| Moisture. Variety | 15 | 20.7835 | 1.3856 | 12.93 | <.001 |
| Residual | 46 | 4.9276 | 0.1071 | | |
| Total | 71 | 133.1484 | | | |

Appendix 2. 2 Soil moisture stress field experiment ANOVA output

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| Rep | 2 | 25.210 | 12.605 | 6.20 | |
| | | | | | |
| Season | 1 | 619.263 | 619.263 | 304.73 | 0.003 |
| Residual | 2 | 4.064 | 2.032 | 1.15 | |
| | | | | | |
| Moisture | 3 | 55.966 | 18.655 | 10.53 | 0.001 |
| Season. Moisture | 3 | 21.362 | 7.121 | 4.02 | 0.034 |
| Residual | 12 | 21.263 | 1.772 | 1.32 | |
| | | | | | |
| Variety | 5 | 764.576 | 152.915 | 113.93 | <.001 |
| Season. Variety | 5 | 23.228 | 4.646 | 3.46 | 0.007 |
| Moisture. Variety | 15 | 23.886 | 1.592 | 1.19 | 0.299 |
| Season. Moisture. Variety | 15 | 24.075 | 1.605 | 1.20 | 0.292 |
| Residual | 80 | 107.374 | 1.342 | | |
| | | | | | |
| Total | 143 | 1690.268 | | | |

Appendix 2.3 Planting density experiment ANOVA output

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| rep | 2 | 1032022. | 516011. | 2.03 | |
| | | | | | |
| Density | 4 | 28174809. | 7043702. | 27.70 | <.001 |
| Variety | 1 | 17680300. | 17680300. | 69.52 | <.001 |
| Season | 1 | 436867. | 436867. | 1.72 | 0.198 |
| Density.Variety | 4 | 4034130. | 1008532. | 3.97 | 0.009 |
| Density.Season | 4 | 1296882. | 324220. | 1.27 | 0.297 |
| Variety. Season | 1 | 8701328. | 8701328. | 34.22 | <.001 |
| Density.Variety. Season | 4 | 2587545. | 646886. | 2.54 | 0.055 |
| Residual | 38 | 9663688. | 254308. | | |
| | | | | | |
| Total | 59 | 73607570. | | | |

Appendix 2.4 Intercropping experiment ANOVA output

| Source of variation | d.f. | s.s. | m.s. | v.r. | F pr. |
|---|---|---|---|---|---|
| rep | 2 | 22.85 | 11.43 | 0.69 | |
| Row pattern | 5 | 600.53 | 120.11 | 7.26 | <.001 |
| site | 2 | 1146.84 | 573.42 | 34.64 | <.001 |
| Row pattern. Site | 10 | 172.73 | 17.27 | 1.04 | 0.430 |
| Residual | 34 | 562.85 | 16.55 | | |
| Total | 53 | 2505.80 | | | |

**Appendix 3. Experiment 1**

Appendix 3. 1 Chemical and physical characteristics of soil used for potting at Egerton University

| Soil depth (cm) | pH | % N | P (ppm) | K (ppm) | Soil texture |
|---|---|---|---|---|---|
| 0-15 | 6.49 | 0.48 | 45.25 | 20.19 | |
| 15-30 | 6.15 | 0.42 | 43.50 | 19.82 | Clay loam |
| Mean | 6.32 | 0.45 | 44.38 | 20.01 | |

N = nitrogen, P = phosphorous, K = potassium

Appendix 3. 2. Maximum and minimum temperatures in the greenhouse during 2017 and 2018 seasons at Egerton University

| 2017 | | August | September | October | November | December | Mean |
|---|---|---|---|---|---|---|---|
| | Max. (°C) | 42.04 | 43.16 | 40.09 | 43.81 | 44.81 | 42.94 |
| | Min. (°C) | 8.73 | 8.87 | 9.48 | 7.11 | 7.45 | 8.33 |
| 2018 | | February | March | April | May | June | Mean |
| | Max. (°C) | 44.70 | 41.31 | 40.72 | 42.23 | 42.58 | 42.31 |
| | Min. (°C) | 6.83 | 9.33 | 10.41 | 8.61 | 8.08 | 8.65 |

Max, min, °C = maximum temperature, minimum temperature and degrees Celsius respectively.

**Appendix 4 Experiment 2**

Appendix 4. 1 Temperature and relative humidity for KALRO-Njoro during 2018 and 2019 season

| | Temperature (°C) | | Relative Humidity (%) | |
|---|---|---|---|---|
| Month | 2018 | 2019 | 2018 | 2019 |
| November | 19.2 | 20.9 | 70.0 | 57.0 |
| December | 20.9 | 19.7 | 57.0 | 70.0 |
| January | 21.2 | 20.9 | 49.0 | 53.0 |
| February | 22.6 | 21.7 | 54.0 | 38.0 |
| March | 19.6 | 22.8 | 70.0 | 40.0 |
| Mean | 20.7 | 21.2 | 60.0 | 51.6 |

**Appendix 4 Experiment 3**

Appendix 5. 1 Chemical and physical properties of soils at Agronomy Teaching and Research Field, Egerton University

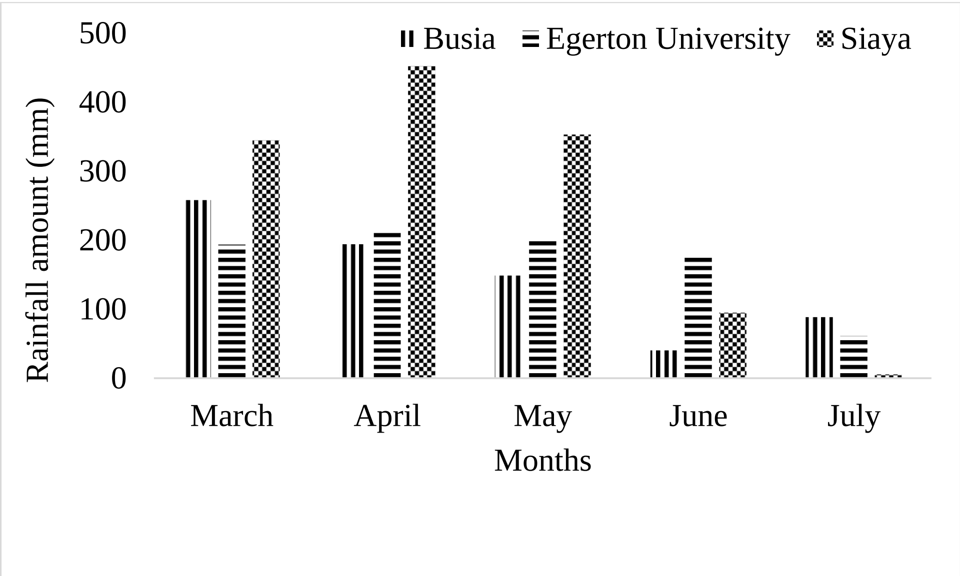
| Depth (cm) | pH | N (%) | P (ppm) | K (ppm) | Soil texture |
|---|---|---|---|---|---|
| 0-15 | 6.94 | 1.05 | 48.29 | 28.88 | |
| 15-30 | 6.85 | 0.95 | 45.57 | 28.88 | Loam |
| Mean | 6.90 | 1.00 | 46.93 | 28.88 | |

Appendix 5. 2 Total rainfall, mean temperature and relative humidity of Egerton University during long rains, 2018

| Month | Rainfall (mm) | Temperature (°C) | Relative Humidity (%) |
|---|---|---|---|
| March | 194.0 | 19.6 | 70.0 |
| April | 214.4 | 19.2 | 75.0 |
| May | 200.8 | 19.5 | 80.0 |
| June | 177.4 | 18.4 | 74.0 |
| July | 61.3 | 17.8 | 78.0 |
| Total/mean | 847.9 | 18.9 | 75.4 |

Appendix 5. 3 Total rainfall, mean temperature and relative humidity of Egerton University during short rains, 2018

| Month | Rainfall (mm) | Temperature (°C) | Relative Humidity (%) |
|---|---|---|---|
| August | 125.0 | 18.9 | 69.0 |
| September | 17.1 | 20.7 | 57.0 |
| October | 50.7 | 20.4 | 57.0 |
| November | 24.0 | 20.9 | 57.0 |
| December | 60.6 | 19.7 | 70.0 |
| Total/mean | 277.4 | 20.12 | 62.0 |




Appendix 6. 1 Monthly rainfall for Busia, Egerton University and Siaya during 2018 season.

Appendix 6. 2 Chemical and physical characteristics of soil for Busia, Egerton University and Siaya

| Parameter | Soil depth (cm) | Busia | Egerton University | Siaya |
|---|---|---|---|---|
| pH | 0-15 | 5.90 | 6.94 | 6.08 |
| | 15-30 | 5.84 | 6.85 | 6.08 |
| | Mean | 5.87 | 6.90 | 6.08 |
| N (%) | 0-15 | 0.56 | 1.05 | 0.64 |
| | 15-30 | 0.43 | 0.95 | 0.50 |
| | Mean | 0.50 | 1.00 | 0.57 |
| P (ppm) | 0-15 | 41.39 | 48.29 | 41.73 |
| | 15-30 | 41.95 | 45.57 | 46.74 |
| | Mean | 41.67 | 46.93 | 44.24 |
| K (ppm) | 0-15 | 21.13 | 28.88 | 18.00 |
| | 15-30 | 20.0 | 28.88 | 17.25 |
| | Mean | 20.57 | 28.88 | 17.63 |
| Soil texture | | Clay loam | Loam | Clay loam |

N = Nitrogen; P = Phosphorous; K = Potassium

Appendix 7. 1 Publications

J. Crop Sci. Biotech. 2019 (June) 22 (2) : 153 ~ 159
DOI No. 10.1007/s12892-019-0045-0



RESEARCH ARTICLE

# Soybean (*Glycine max* (L) Merrill) Root Growth and Nodulation Responses to Different Soil Moisture Regimes

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## Abstract

Climate change due to global warming is contributing to upward shifts in temperatures and reductions in rainfall leading to increased incidences of soil moisture stress. A greenhouse experiment was conducted over two seasons to determine the effect of varying soil moisture regimes on root growth and nodulation of selected soybean (*Glycine max* (L.) Merrill) cultivars. The experiment was conducted as a Randomized Complete Block Design (RCBD) in a 4 x 6 factorial treatment arrangement with moisture regimes (80, 60, 40, and 20% of field capacity) as first factor and cultivars (Gazelle, Nyala, EAI 3600, DPSB 8, Hill, and DPSB 19) as second factor. Collected data on root diameter, root length, root surface area, root volume, and nodulation were subjected to Analysis of Variance (ANOVA) using Linear Mixed Model in GENSTAT. Significantly different treatment means were separated using Tukey's test at 0.05 level of significance. Moisture stress significantly reduced soybean root diameter, root length, root surface area, root volume, root biomass, root to shoot ratio, and nodulation of all tested cultivars. The degree of stress however varied with soybean cultivars tested with cultivar EAI 3600 having highest root volume, root biomass, and number of nodules per plant compared to other cultivars. Results suggest that 40% moisture at field capacity could be a threshold moisture stress level for soybean beyond which adaptive soil moisture mitigation practices like supplementary irrigation and use of appropriate agronomic practices be employed to improve soybean yields.

**Key words :** Photosynthates, root nodules, seasons, soybean cultivars, soil moisture limitation

## Introduction

Soybean [*Glycine max* (L) Merrill] is one of the most traded amongst tropical legumes contributing 83.3% annual revenue from legume crops which is valued at US $30.0 billion (Abate et al. 2012). Soybean is a good source of proteins (40%), carbohydrates (30%), oils (20%), vitamins, and minerals making the crop suitable for human consumption and livestock feed (Singh and Shivakumar 2010). Annual demand for soybean in Kenya exceeds 100,000 metric tons, the highest in the East African region (Tinsley 2009). However, annual production of the crop in the country is at 4,335 metric tons leaving a deficit of close to 95% (FAO 2013). Yields amongst smallholder farmers, which are key producers of the crop in Kenya, are low and range from 445-1200 kg per hectare (Collombert 2013). These low yields are largely attributed to soil moisture stress which, in recent times, has been associated with global climate change which has led to upward shifts in temperatures and reduction in rainfall (Hartman et al. 2011; Rosenzweig et al. 2001). Moisture stress is synonymous with soil compaction which affects soil air and water relations leading to limitation in plant growth (Sartoli et al. 2016). It is estimated that soil moisture stress cause between 28-45% reductions in soybean yields (Hartman et al. 2011), contributing to food insecurity at the household level.

Roots play a critical role in plant nutrition by absorbing water and mineral nutrients from the soil and conducting them to shoot system for production of assimilates for plant growth (Ryan et al. 2016). In leguminous crops like soybean, root nodulation defines extent of biological nitrogen fixation which serves as an important source of nitrogen for plant nutrition (Ciampitti and Salvagiotti 2018). In soybean, roots

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ACADEMIC JOURNALS

African Journal of Agricultural Research

Full Length Research Paper

# Physiological response of soybean [*Glycine max* (L) Merrill] to soil moisture stress

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**This study was done to determine the effects of varying soil moisture regimes on $CO_2$ assimilation of soybean [*Glycine max* (L.) Merrill] in pots under greenhouse conditions during 2017 and 2018 cropping seasons. The experiment was conducted as a Randomized Complete Block Design (RCBD) in a 4 x 6 factorial treatment arrangement and replicated 3 times. Soil moisture regimes (80, 60, 40 and 20% of field capacity) and cultivars (Gazelle, Nyala, EAI 3600, DPSB 8, Hill and DPSB 19) were first and second factors, respectively. Collected data were subjected to Analysis of Variance (ANOVA) using Linear Mixed Model in GENSTAT. Significantly different treatment means were separated using Tukey's test at 0.05 significance level. Leaf relative water content, stomata conductance, photosynthesis rate and sub-stomatal $CO_2$ concentrations significantly ($P < 0.001$) declined with increasing soil moisture stress. Total leaf chlorophyll content increased ($P < 0.001$) with increased soil moisture stress. Cultivars DPSB 19 and DPSB 8 had relatively higher leaf relative water content and stomata conductance at reduced soil moisture regime at 20% moisture from field capacity indicating moisture stress tolerance potential of the cultivars.**

**Key words:** Flowering stage, podding stage, seasons, soil moisture regimes, soybean cultivars.

## INTRODUCTION

Soybean [*Glycine max* (L.) Merrill] is one of the most important legume crops with total production of 261.6 million metric tonnes worldwide (FAOSTAT, 2013). Soybean is a main source of protein, carbohydrates, vegetable oils, vitamins and minerals for human consumption and production of livestock feed. Soybean farming is also the most cost-effective ways resource-constrained smallholder farmers can use to maintain soil fertility of their lands as soybean helps to improve soil fertility through biological nitrogen fixation of soybean between 44 and 103 kg N $ha^{-1}$ (Kananji et al., 2013; Ciampitti and Salvagiotti, 2018). The potential of soybean to significantly contribute to food and nutrition security and to generate substantial income for farmers is however constrained by low yields arising from soil moisture stress effects amongst other biotic and abiotic stresses. Soil moisture stress has become a recurring event due to unpredictable weather patterns arising from changes in climatic conditions occasioned by global warming (Abedinpour, 2012). Understanding the response of soybean to limited soil moisture stress, identification and use of moisture stress tolerant cultivars

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1. **THE AFRICAN HIGHER EDUCATION WEEK AND SIXTH RUFORUM BIENNIAL CONFERENCE POSTER PRESENTATION**

THE AFRICAN HIGHER EDUCATION WEEK AND SIXTH RUFORUM BIENNIAL CONFERENCE

EGERTON UNIVERSITY

Government of Malawi

# Moisture stress reduces stomata conductance, growth and yield of soybean

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## Introduction

- Soybean (*Glycine max* L. Merrill) is an important legume crop as a source of protein, income, soil fertility improvement & livestock feed.
- Current yields low, ranging from 445-1200 Kg ha$^{-1}$ against potential of 3500 kg ha$^{-1}$ (Chianu et al., 2009).
- Low yields are attributed to soil moisture stress leading to 28-45% yield reduction (Ohashi *et al.*, 2006).
- Reduced moisture due to reduced rainfall arising from climate change
- Low yields lead to food & income insecurity at household level.

## Objective

To determine the effect of soil moisture regimes on stomata conductance, growth and yield of selected soybean cultivars in Kenya.

## Materials and Methods

- Greenhouse experiment conducted at Egerton University in Njoro, Kenya during 2017/2018 season.
- Randomized complete block design (RCBD) with a 4x6 factorial treatment arrangement; replicated 3 times.
- Soil moisture regimes: 80% , 60% , 40% & 20% of moisture at field capacity (FC).
- Cultivars: Gazelle, Nyala, EAI 3600, DPSB 8, Hill & DPSB 19.
- Soil moisture regimes were monitored using IMKO-HD2 time domain reflectometer (TDR)
- Data were analyzed using analysis of variance (ANOVA) in Genstat 18$^{th}$ Edition.
- Significantly different treatment means were separated using Tukeys test at 0.05 significance level.

## Results

- Interaction between soil moisture regimes and cultivars significantly influenced (p<0.001) stomata conductance, leaf area and grain yield. Highest interactive effects on stomata conductance, leaf area and grain yield for all cultivars were attained at 80% FC (Table 1).
- Soil moisture stress significantly reduced (p <0.001) total number of nodules and number of effective nodules in soybean (Figure 1).

**Table 1.** Effect of soil moisture regimes on stomata conductance, leaf area, grain yield and protein content of soybean under greenhouse conditions at Egerton University, Kenya

| Soil water (FC %) | Cultivar | Stomata conductance mmol/m$^{-2}$s$^{-1}$ | Leaf area (cm$^2$) | Grain yield (g plant$^{-1}$) | Seed protein content (%) |
|---|---|---|---|---|---|
| 80 | Gazelle | 21.51$^{bcd}$ | 633.4$^{cde}$ | 3.01$^{bc}$ | 28.04 |
| | Nyala | 18.23$^{cdef}$ | 692.4$^{bcd}$ | 2.44$^{cde}$ | 27.42 |
| | EAI 3600 | 30.14$^{a}$ | 616.0$^{cde}$ | 3.00$^{bcd}$ | 29.60 |
| | DPSB 8 | 21.23$^{bcd}$ | 880.6$^{a}$ | 3.79$^{b}$ | 28.92 |
| | Hill | 14.66$^{defg}$ | 772.7$^{abc}$ | 3.53$^{b}$ | 28.35 |
| | DPSB 19 | 28.72$^{ab}$ | 845.8$^{ab}$ | 6.16$^{a}$ | 28.02 |
| 60 | Gazelle | 14.68$^{defg}$ | 532.0$^{defg}$ | 2.89$^{bcd}$ | 28.65 |
| | Nyala | 18.02$^{cdef}$ | 611.9$^{cde}$ | 1.97$^{def}$ | 26.25 |
| | EAI 3600 | 25.22$^{abc}$ | 568.9$^{def}$ | 2.82$^{bcd}$ | 27.16 |
| | DPSB 8 | 9.18$^{hi}$ | 623.87$^{cde}$ | 1.79$^{efg}$ | 28.00 |
| | Hill | 20.42$^{cde}$ | 565.2$^{def}$ | 2.42$^{cde}$ | 27.58 |
| | DPSB 19 | 13.37$^{efgh}$ | 521.2$^{efg}$ | 3.85$^{b}$ | 26.25 |
| 40 | Gazelle | 13.77$^{defg}$ | 307.9$^{hij}$ | 1.50$^{efgh}$ | 26.40 |
| | Nyala | 10.49$^{fghi}$ | 333.4$^{hij}$ | 1.49$^{efgh}$ | 25.71 |
| | EAI 3600 | 14.57$^{defg}$ | 316.7$^{hij}$ | 1.63$^{efg}$ | 28.00 |
| | DPSB 8 | 10.02$^{fghi}$ | 422.6$^{fgh}$ | 0.54$^{hi}$ | 27.77 |
| | Hill | 12.49$^{fgh}$ | 394.3$^{ghi}$ | 1.25$^{fghi}$ | 26.10 |
| | DPSB 19 | 10.62$^{fghi}$ | 395.0$^{ghi}$ | 1.64$^{efg}$ | 24.69 |
| 20 | Gazelle | 2.88$^{i}$ | 243.0$^{j}$ | 0.59$^{hi}$ | 27.71 |
| | Nyala | 2.57$^{i}$ | 201.5$^{j}$ | 0.99$^{ghi}$ | 26.83 |
| | EAI 3600 | 3.31$^{i}$ | 216.8$^{j}$ | 1.03$^{ghi}$ | 26.69 |
| | DPSB 8 | 4.59$^{i}$ | 242.9$^{j}$ | 0.34$^{i}$ | 26.15 |
| | Hill | 3.02$^{i}$ | 238.2$^{j}$ | 0.94$^{ghi}$ | 25.35 |
| | DPSB 19 | 3.20$^{i}$ | 201.8$^{j}$ | 0.83$^{ghi}$ | 26.83 |
| *p*-value | | <.001 | <.001 | <.001 | 0.508 |
| **Main Effects** | | | | | |
| FC % | 80 | 22.41$^{a}$ | 740.3$^{a}$ | 3.66$^{a}$ | 28.39$^{a}$ |
| | 60 | 16.82$^{b}$ | 570.5$^{b}$ | 2.62$^{b}$ | 27.37$^{ab}$ |
| | 40 | 11.99$^{c}$ | 361.7$^{c}$ | 1.34$^{c}$ | 26.44$^{b}$ |
| | 20 | 3.28$^{d}$ | 224.0$^{d}$ | 0.79$^{d}$ | 26.59$^{b}$ |
| *p*-value | | <.001 | <.001 | <.001 | <.001 |
| Cultivar | Gazelle | 13.24$^{bc}$ | 429.1$^{b}$ | 1.99$^{bc}$ | 27.70 |
| | Nyala | 12.33$^{bc}$ | 459.8$^{b}$ | 1.72$^{bc}$ | 26.55 |
| | EAI 3600 | 18.31$^{a}$ | 429.8$^{b}$ | 2.12$^{b}$ | 27.85 |
| | DPSB 8 | 11.26$^{c}$ | 542.5$^{a}$ | 1.62$^{c}$ | 27.71 |
| | Hill | 12.64$^{bc}$ | 492.6$^{ab}$ | 2.03$^{b}$ | 26.85 |
| | DPSB 19 | 13.98$^{b}$ | 491.0$^{ab}$ | 3.12$^{a}$ | 26.45 |
| *p*- value | | <.001 | <.001 | <.001 | 0.064 |

Means followed by the same letters within a column do not differ significantly at (P < 0.05); FC = Field Capacity

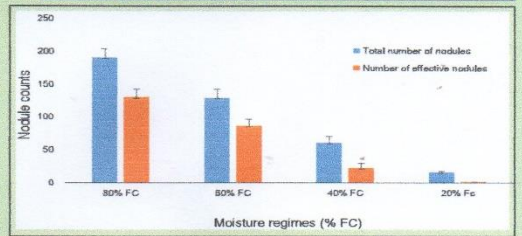


Figure 1. Root nodule counts at 4 moisture regimes

## Conclusion and Recommendations

- Moisture stress reduced soybean stomata conductance, leaf area, grain yield, seed protein content and root nodulation.
- Cultivars DPSB 19 gave highest yields and maybe considered for production under limited soil moisture conditions.
- There is need for repeat studies to validate these preliminary findings both under greenhouse and field conditions.

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