GRAIN SORGHUM-COWPEA INTERCROP: A CLIMATE-SMART APPROACH FOR ENHANCED PRODUCTIVITY, PHYSIOLOGICAL RESPONSES, AND CARBON DYNAMICS UNDER PLANTED AND SIMULATED NO-TILL CONDITIONS

by

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THESIS

Submitted in fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

PLANT PRODUCTION

in the

FACULTY OF SCIENCE AND AGRICULTURE

(School of Agricultural and Environmental Sciences)

at the

UNIVERSITY OF LIMPOPO

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2022

DECLARATION

I declare that **Grain sorghum-cowpea intercrop: a climate-smart approach for enhanced productivity, physiological responses, and carbon dynamics under planted and simulated no-till conditions** hereby submitted to the University of Limpopo, for the degree of **Doctor of Philosophy in Plant Production** has not been submitted before for any other degree at any other institution; is my work in design and in execution, and that all the sources that I have used or quoted have been indicated and acknowledged using references.

Mogale T.E 12 October 2022

ACKNOWLEDGEMENTS

Firstly and most importantly, I would like to thank the Almighty God for the strength, and wisdom and for making it possible for me to start and complete my studies. I would have not made it without Him.

I would like to express heartfelt gratitude to the following people and organizations for the support they have given me throughout my research:

- My hardworking supervisor Prof KK Ayisi for the words of encouragement and comments on my work.
- My co-supervisors Dr. L Munjonji and Prof YG Kifle, for giving me support and taking time off their work to go through my work despite their busy schedules.
- I would like to thank the National Research Foundation (NRF), Departments of Science and Innovation (DSI) and VLIR-IUC (Belgium) for their financial support throughout the study.
- Also, the University of Limpopo for allowing me to further my studies.
- To the Risk and Vulnerability Science Centre (RVSC) research team, thank you all for the warm welcome and for the support you have given me. Special thanks to Kabisheng Mabitsela, Carol Lehutjo, Mpho Phetla and Lesetja Lekgothoane, for their help with data collection and transport to the research sites. Also, special thanks to Frederick Mashao and Phumulani Zwane for their help with the maps of the study areas. I would also like to thank all RVSC field workers for their help with field management and data collection. Special thanks also to Principal Administrator Aus Josephine Khosa for helping me with all the necessary administrative work needed to continue with my research.
- I would like to thank fellow Ph.D. students Vincent Mokoka, Sanari Moriri, Lesego Motshekga and Makgabo Mashala for encouraging me to work hard and for their support during my writing stages. Together we have pushed each other to work hard on our research studies.
- Special thanks to members of the Young Researchers Club of RVSC, the teamwork has helped me put more effort into my research.
- Thank you to Dr. L Tyasi for your help with statistics, your assistance has helped me gain a better understanding of data management and analysis.
- Department of plant production, soil science and remote sensing for providing me with relevant research materials.

- I would also like to thank Valentine Mashapa, for always providing me with a place to put plant samples and lending me research materials when I needed them.
- I would like to pass my gratitude to SALLnet and TROPAGS teams in Germany for their help and support with crop modeling. In particular, I would like to thank Prof Reymond Rötter, Dr. Brancho Mujica Gennady and Dr. William Nelson for their help with APSIM modeling.
- The anonymous reviewers for giving my paper constructive criticism that helped improve it.
- Special mention to my dear friend Dr. Nompumelelo Thelma Mobe, for introducing me to RVSC and encouraging me to enroll for Ph.D. with the center. Thank you for the motivation at the early stage of my research and towards the end.
- I would like to thank Jimmy Mabina for browsing through the thesis and supporting me during my writing stage.
- None of this would have been possible without the support of my mother Kgabo Emission Mogale and my siblings, Meldah, Betty, John, Manoko, Suzan, Mogau, Maphuti and Phomelelo. These people have been there for me since the begging my studies and gave me love and support throughout. *Kea leboga Dikolobe*.

DEDICATION

This thesis is dedicated in the loving memory of my late best friend and father Nkhwela Samuel Mogale.

This thesis is also dedicated to my mother Kgabo Emission Mogale, thank you for the unconditional love and moral support throughout my studies.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ACRONYMS AND ABBREVIATIONS

A	=	Photosynthetic rate
ANOVA	=	Analysis of Variance
APSIM	=	Agricultural Productions System Simulator
BNF	=	Biological Nitrogen Fixation
Ca	=	Calcium
CEC	=	Cation Exchange Capacity
Ci	=	Sub-stomatal CO_2 concentration
Cu	=	Copper
CSA	=	Climate-Smart Agriculture
^oC	=	Degree Celcius
DAP	=	Days After Planting
E	=	Transpiration rate
FAO	=	Food and Agriculture Organization
gs	=	Stomatal conductance
ha^{-1}	=	Per hectare
HI	=	Harvest index
IPCC	=	Intergovernmental Panel on Climate Change
LAI	=	Leaf Area Index
LER	=	Land Equivalent Ratio
LSD	=	Least Significant Difference
K	=	Potassium
Mg	=	Magnesium
Mn	=	Manganese
ns	=	not significant
P	=	Phosphorus
RCBD	=	Randomized Complete Block Design
Zn	=	Zinc

PUBLICATIONS DURING CANDIDATURE

Peer-reviewed article from the thesis

- **Mogale, T. E.,** Ayisi, K. K., Munjonji, L., and Kifle, Y. G. (2022). Yield Responses of Grain Sorghum and Cowpea in Binary and Sole Cultures under No-Tillage Conditions in Limpopo Province. *Agriculture*, **12**: 733.

Article submitted for publication

- **Mogale, T. E.,** Ayisi, K. K., Munjonji, L., and Kifle, Y. G. Mabitsela K.E. Understanding the impact of intercropping system on CO_2 emissions and soil carbon stocks in Limpopo Province, South Africa. *Submitted to Journal of Soil Science and Plant Nutrition.*

National conferences and presented part of the thesis

- **Mogale, T. E.,** Ayisi, K. K., Munjonji, L., and Kifle, Y. G. (2019). Distribution of photosynthetically active radiation and CO_2 flux in grain sorghum/cowpea intercropping system 35th Annual Conference of the SASAS on 8-9 October 2019, at Riverside Sun in Vanderbijlpark, Gauteng.
- **Mogale, T. E.,** Ayisi, K. K., Munjonji, L., and Kifle, Y. G. (2022). The water use efficiency of dryland grain sorghum cultivars and cowpea grown in sole and binary cultures under different agro-ecological conditions. COMBINED CONGRESS 2022 – Virtual sessions – 25-27 January 2022

Manuscripts under preparation from the thesis

- **Mogale, T. E.,** Ayisi, K. K., Munjonji, L., and Kifle, Y. G. No-till grain sorghum-cowpea physiological responses and growth in sole and binary cultures at two distinct agro-ecological zones.
- **Mogale, T. E.,** Ayisi, K. K., Munjonji, L., and Kifle, Y. G. The effect of grain sorghum-cowpea intercropping on biological nitrogen fixation (BNF) of cowpea in contrasting environments of Limpopo province.
- **Mogale, T. E.,** Ayisi, K. K., Munjonji, L., and Kifle, Y. G. The performance of APSIM in validating biomass and grain yield of grain sorghum and cowpea in intercropping system.

THESIS STRUCTURE

Chapter 1: General Introduction

The general introduction gives a brief information on how climate change affects agricultural production, the role played by agricultural activities towards climate change. The section also gives an overview of grain sorghum and cowpea production under changing climate. It further outlines the problem statement, justification, aim, objectives as well as hypotheses of the study.

Chapter 2: Literature review

The section reviews existing literature on grain sorghum and cowpea focusing specifically on origin, distribution, biology, major uses, nutritive value. The section also covers the role that is played by modern agricultural practices that results in change in climatic conditions and how climate change in return affect crop production and ultimately food security. Furthermore, climate-smart approaches that can be adopted for sustainable food production are discussed as well as ways to enhance soil carbon sequestration. Lastly, the chapter outlines how modeling can be used to predict productivity of the two crops under changing climate.

Chapter 3: Grain sorghum production in Limpopo Province – a review

This chapter outlines the past and current production trends of grain sorghum in South Africa with a special focus on Limpopo Province.

Chapter 4: Growth, physiological responses and productivity of sorghum and cowpea in intercropping system.

Chapter 4 is divided into three sections,

Section 1: Yield responses of grain sorghum and cowpea in intercropping system

Section 2: No-till grain sorghum physiological responses and growth in sole and binary cultures

Section 3: Physiological responses and growth of two cowpea densities in binary and sole cultures under no-till

Chapter 5: The impact of intercropping system on CO_2 emissions and soil carbon stocks

This chapter discusses CO_2 emission rates and soil carbon stocks of grain sorghum and cowpea under an intercropping system across different agro-ecological regions over two seasons.

Chapter 6: The effect of grain sorghum-cowpea intercropping on biological nitrogen fixation (BNF).

Chapter 6 focuses on how an intercropping system affect biological nitrogen fixation using natural abundance method in two distinct agro-ecological zones of Limpopo Province.

Chapter 7: The performance of APSIM in validating biomass and grain yield of grain sorghum and cowpea.

This section illustrates how APSIM model validated the current biomass and grain yield of the component crops. Furthermore, the chapter outline how the information was used to simulate the impact of a changing climate on their productivity in the future.

Chapter 8: General conclusion.

Chapter 8 covers conclusion developed from the study in general from chapter 3-7. Recommendations are also given for future researches.

THESIS ABSTRACT

Sustainable food production has been a major challenge in the era of climate change and a growing population in the twenty-first century. However, climate change scenarios such as extreme temperatures and fluctuations in annual precipitation continue to pose a great threat to agricultural production systems. On the other hand, anthropogenic activities such as conventional farming continue to contribute to climate change through the emission of greenhouse gases while not sustaining agricultural production. The Food and Agriculture Organization of the United Nations (FAO-UN) developed the concept of Climate-Smart Agricultural (CSA) production with the idea of securing food in the face of global change. No-tillage and intercropping systems are among the traditional practices that are advocated as components of climate-smart traditional practices, especially in the semi-arid regions of Africa like the Limpopo Province.

Producing sorghum and cowpeas using CSA practices such as intercropping under no-tillage is envisaged to increase productivity and soil fertility under Limpopo Province's dryland conditions. However, there is still limited information on how grain sorghum-cowpea intercrop will respond in terms of growth, physiological productivity, and carbon dioxide emissions in the system, especially under no-tillage and different growing conditions. Furthermore, more field data is required for predictions of future scenarios using simulating crop models such as the Agricultural Production system sImulator (APSIM). Hence, a no-till Randomized Complete Block Design (RCBD) in a 2 x 4 x 2 factorial arrangement was conducted at two locations (Syferkuil and Ofcolaco) in the Limpopo Province during the 2018/19 and 2020/21 cropping seasons to generate data on sorghum and cowpea growth, physiology, productivity as well as carbon dynamics under planted and simulated intercropping system.

Leaf gaseous exchange and leaf area index (LAI) were measured on fully developed grain sorghum and cowpea leaves in both the binary and sole cultures of sorghum and cowpea. The CO_2 measurements were taken from each plot using a GMP343 CO_2 probe along with an MI70 data logger. Aboveground biomass was collected for each crop from two plants at vegetative, flowering, physiological and harvest maturity and oven-dried at 65 ^oC for 48 hours. In the 2020/21 cropping season, cowpea at Ofcolaco failed to produce grain. Hence, only the grain yield of the 2018/19 cropping season

from Ofcolaco is presented in this thesis. Grains collected for each crop from a 2.7m^2 area were taken to the laboratory to determine grain yield and yield components. Harvest index (HI) and land equivalent ratio (LER) for each crop were also determined. In the laboratory, the total nitrogen (%) and natural abundance of ^{15}N ($\delta^{15}N$‰) were determined using an isotope ratio mass spectrometer with an N analyzer. Growth (biomass) and yield (grain) data obtained from APSIM were compared with data collected from a two-year field experiment at Syferkuil. Multi-variate analysis of variance (ANOVA) model to fit each response variable using the Statistical Analysis System (21 SAS version 9.4). Mean separation was done where the means were different using the least significant difference (LSD) at probability levels of $p \leq 0.05$.

Intercropping system and the density of the companion crop cowpea had a significant ($p \leq 0.05$) effect on the physiological responses of sorghum and cowpea, cowpea yield and yield components at the two experimental sites across seasons. However, grain yield and yield components of sorghum were not affected by intercropping or the density of cowpea. Only cultivars of sorghum were significantly different for grain yield and yield components. At Syferkuil, Enforcer produced the highest grain yield of 4338 kg ha^{-1} in 2018/19, while NS5511 accumulated the highest grain yield of 2120 kg ha^{-1} during the 2020/21 cropping seasons. At Ofcolaco, Enforcer and Avenger were observed to be relatively high-yielding cultivars with a mean grain yield of 2625 kg ha^{-1} and 1191 kg ha^{-1} during the 2018/19 and 2020/21 cropping seasons, respectively. In the 2018/19 and 2020/21 cropping seasons, respectively, cowpea accumulated about 93% and 77% more grain yield in sole compared to binary culture. At Ofcolaco, about 96% more grain yield was obtained in sole compared to binary cultures during the 2018/19 cropping season. Furthermore, cowpea accumulated over 55% and 49% of grain yield when grown at high compared to low population density at Syferkuil and Ofcolaco, respectively. The investigation on the impact of the intercropping system on CO_2 emissions and soil carbon stocks revealed that in 2018/19 at Syferkuil and 2020/21 at Ofcolaco, intercropping systems emitted 11% and 19% less CO_2 respectively than the sole cropping systems. In both diverse agro-ecological sites, low cowpea density consistently resulted in higher CO_2 emissions than high density. The sorghum-cowpea intercropping system significantly influenced the biological nitrogen fixation of cowpea. Intercropping was found to improve the biological nitrogen fixation of cowpea if a density of 74074 plants ha^{-1} is used. The APSIM model was able to

capture the dynamics of biomass and grain yields in the sole and intercropping system under different densities of cowpea.

The findings of this study revealed some useful insights. Firstly, biomass accumulation depended on the cultivar in intercrop as well as the density of cowpea. Secondly, cowpea at a density of 74074 plants ha^{1} was found to be a good crop to intercrop with grain sorghum as it did not show any significant variation in terms of grain yield and yield components of sorghum. The sorghum cultivar, Enforcer and NS5511 were the best performing cultivars in terms of grain yields at Syferkuil and Ofcolaco. Thirdly, the intercropping system under high cowpea density reduced CO_2 emission rates while improving soil nitrogen (N) and carbon stocks. Based on the results of this study, grain sorghum-cowpea intercrop can be adopted as a component of a climate-smart practice to improve crop growth, physiology, as well as productivity compared to sole cropping. However, the grain sorghum cultivar and the density of cowpea should be taken into consideration as they affect the productivity of the two crops. The two seasons data generated from this study was useful in simulating the productivity of intercropping practice using APSIM. However, more field and weather data is required to run long-term simulations on intercropping as a component of the climate-smart method using crop modeling techniques.

Key words: APSIM model, cowpea, CO_2 emissions, intercropping, sorghum

CHAPTER 1: GENERAL INTRODUCTION

Climate change is one of the popular topics that is discussed by different researchers from diverse learning sections. Benhin (2006) defined climate change as the change in the series of weather patterns that may result in increased temperatures and fluctuations in annual precipitation. Human-induced changes are the primary drivers of climatic change, which affects socioeconomic and environmental conditions worldwide (Ramanatha and Xu, 2010). Climate change leads to a decline in food production and ultimately affects food security in many parts of developing countries in Africa and around the world (Bandara and Cai, 2014). Hence, this may pose a threat to the availability of food for the global population.

The world population is growing, which is leading to high expectations in the agricultural sector to provide food for the people (Tilman *et al*., 2011). According to Godfrey *et al*. (2010), the world population will reach 9.5 billion by 2050. To feed such a large number of people, a double in food production is required (FAO, 2016). Grain sorghum and cowpea are among the most important crops in South Africa, together with other crops such as maize, wheat, peanuts, soybeans etc. The crops are produced by both smallholder and commercial farmers for human and livestock consumption (Taylor, 2003). Grain sorghum and cowpea are grain crops cultivated in tropical and subtropical regions of Africa where conditions are not favorable for other crops. The two crops are grown for a variety of reasons under a wide range of environmental conditions. They are highly tolerant to drought conditions and, hence, suitable for semi-arid regions that are susceptible to moisture stress.

However, the production of the two crops is currently constrained due to, among others, changes in weather and climate, which could lead to a decline in food production and a rise in food prices. In addition, increases in ambient and soil temperatures lead to an increased infestation of pests and diseases, which also affect the quality of the crops. Furthermore, modern agricultural practices such as the use of chemical fertilisers and machinery reduce soil quality and increase CO_2 evolution into the atmosphere, which affects sustainable crop productivity and ultimately reduces crop yield and quality.

A climate-smart agricultural approach, which is defined as an integrated approach that focuses on sustainable food production and reduces emissions of greenhouse gases while building resilience to climate change (Singh and Singh, 2017), is required if sustainable crop production is to be achieved in a changing climate and degrading soil environment. Climate change has caused fluctuations in sorghum and cowpea yields due to a lack of knowledge about climate-smart approaches, traditional agricultural practices, and ineffective soil management (Chimonyo *et al*., 2016b).

Climate-smart approaches such as intercropping, crop rotation, cover crops, etc. have been identified as adaptation and mitigation mechanisms for climate change and also to enhance optimum sorghum and cowpea production and soil quality. Such soil management strategies can be employed to enhance grain sorghum and cowpea yields (Jun *et al*., 2014). Grain sorghum farmers have the challenge of poor soil fertility. Hence, intercropping sorghum with cowpea has the potential to enhance biomass production and crop yield due to the symbiotic relationship between cowpea and bacteria that fix atmospheric nitrogen (Egase *et al*., 2016). Furthermore, sorghum/cowpea intercropping will help reduce soil water runoff and soil evaporation through full canopy cover (Zougmore *et al*., 2000; Coll *et al*., 2012). It has been reported that legume/cereal intercropping contributes to the enrichment and protection of soil organic carbon against depletion depending on the agro-ecological region (Odunze *et al*., 2017).

1.1 PROBLEM STATEMENT

The rise in global temperatures and fluctuations in annual rainfall affect soil conditions, resulting in poor crop production (Bryan *et al*., 2009). Commercial farmers rely heavily on modern agricultural practices to optimize production. However, this practice is one of the major contributors to increased greenhouse gas emissions and global climate change (Smith *et al*., 2008). Sorghum and cowpea are important crops grown by farmers in Limpopo province for home consumption as well as for trading in local and distant markets. The production of the two crops has been declining primarily as a result of climate change, unsustainable soil preparation practices, and the unintended challenge of bird damage. The most widely used conventional practice, continuous tillage, destroys soil carbon storage, resulting in poor soil fertility (Odunze *et al*., 2017). There is a dearth of information on the effect of intercropping on soil carbon sequestration in South Africa, particularly in four districts of Limpopo Province, namely, Capricorn, Sekhukhune, Mopani, and Vhembe. Furthermore, information on cultivar productivity, symbiotic activities, and yield performance of sorghum and cowpea, which are highly dependent on agro-ecological conditions, is also limited in the province.

1.2 RATIONALE

Understanding the extent to which climate change variability affects soil quality, soil carbon sequestration, and crop yield in the target production region requires adequate information. Sufficient information about the amount of soil carbon sequestered and the yield of sorghum/cowpea under an intercropping system in target localities of Limpopo Province will help growers with good soil management and sustainable food production. In addition, there is a need to evaluate the effect of sorghum/cowpea intercropping on sorghum yield and soil carbon under diverse agro-ecological conditions in the province. The information generated will enable sorghum and cowpea growers to adapt to changes in climatic conditions while producing an optimum yield. The Agricultural Productions System Simulator (APSIM) model is useful in validating the current biomass and grain yield of the component crops and the information used to simulate the impact of a changing climate on their productivity in the future.

1.3 AIM

The study aimed to generate data that will assist in promoting the practice of grain sorghum-cowpea intercropping systems among farmers in Limpopo Province as a climate-smart agricultural intervention.

1.4 OBJECTIVES

The objectives of the study were to:

i. assess growth, physiological response and yield of grain sorghum and cowpea under an intercropping system in two agro-ecological locations in Limpopo Province;

ii. measure the impact of the intercropping system on CO_2 emissions and soil carbon stocks in different climatic and soil environments of Limpopo Province;
iii. determine the effect of grain sorghum-cowpea intercropping on biological nitrogen fixation (BNF) of cowpea in contrasting environments of Limpopo Province; and
iv. assess the performance of APSIM in validating biomass and grain yield of grain sorghum and cowpea in intercropping system.

1.5 HYPOTHESES

The study was tested under the following null hypotheses:

i. there is no significant difference in growth, physiological response and yield of sorghum cultivars and cowpea under intercropping system in distinct environments in Limpopo Province;
ii. intercropping system has no effect on CO_2 emission rates and soil carbon stocks in different climatic and soil environments of Limpopo Province;
iii. sorghum/cowpea intercropping has no effect on cowpea biological nitrogen fixation under contrasting test locations in Limpopo Province;
iv. there were no challenges with calibrating and validating the performance of APSIM in simulating biomass and grain yield of sorghum/cowpea.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter, the major aspects of grain sorghum and cowpea, such as biology, agronomy, and major uses, are discussed. The chapter further highlights the effect of climate change on the production of grain sorghum and cowpea, and climate-smart approaches such as intercropping systems that can be adopted for sustainable production of grain sorghum and cowpea. Lastly, the chapter outlines how modeling can be used to predict the productivity of the two crops under a changing climate.

2.1.1 Origin and Distribution

Grain sorghum

Grain sorghum (*Sorghum bicolor* (L.) Moench) is an important crop that is grown primarily for its grain in many developing countries in Africa. It is ranked the fifth most important cereal crop in the world after wheat, rice, maize, and barley (FAO, 2005). The crop belongs to the family Poaceae and has more than 7000 varieties grown worldwide (Kangama and Rumei, 2005). Grain sorghum is native to the north-eastern part of Africa, with wild and cultivated species grown in tropical and sub-tropical regions of the world (Dillon *et al*., 2007b). It is further distributed to Central America and South Asia (Kimber, 2000), where it is grown for a variety of reasons.

Cowpea

Cowpea (*Vigna unguiculata* (L.) Walp) is an essential legume crop that is also referred to as the ancient human food source. The crop is believed to have originated from West Africa and spread to East and Central Africa, India, Asia, and South and Central America (Ba *et al*., 2004). Globally, Nigeria is the major producing country, with over 60% of cowpeas produced in west and central Africa (Singh *et al*., 2002).

2.1.2 Production levels of grain sorghum and cowpea

Grain sorghum

Grain sorghum is one of the most important grain crops with a global record of 20 t/ha as reported by Boyer in 1987. Africa and Asia are the leading producers of grain sorghum worldwide, with a production of 904 and 1086 kg ha^{-1}, respectively. However, other countries globally produce a reasonable amount. The United States harvested over 2 million ha in 2009, followed by Europe with about 150 000 ha, and the total produced was 4 355 kg ha^{-1} and 4451 kg ha^{-1}, respectively (FAO, 2011). In Africa, grain sorghum is produced at large quantity by west Africa with the amount of 13703207 t/ha recorded in 2018 while South Africa produced 115000 t/ha (Table 2.1). In South Africa, the major producing areas are Free State, Mpumalanga, North-West, Limpopo, and Gauteng provinces. The crop is grown by all categories of farmers: subsistence, smallholder and commercial farmers. However, the record for subsistence farmers is unknown as they produce for home consumption only. In Limpopo Province, smallholder famers can produce upto 20 000 tonnes of grain sorghum. On the commercial level, Free State is the leading province with an average of 300,000 tonnes harvested on 150 000 ha (DAFF, 2011).

Cowpea

Cowpea is grown on 12.5 million hectares globally and a total of 3 million tonnes of grain is produced (FAO, 2000). Since cowpea is native to Africa, the world's leading producers of cowpea are west and central Africa (Table 2.1), with a total of about 64% of production (Singh *et al*., 1996). Nigeria and Brazil are the world's leading producers of cowpea respectively, followed by other significant producers such as Senegal, Ghana, Mali, and Burkina Faso (Singh *et al*., 2003). In South Africa, there are no production records of cowpea as it is produced by small-holder farmers under dryland conditions. However, the crop is primarily grown in the provinces of Limpopo, Mpumalanga, the North West, and KwaZulu-Natal (Adebowale, 2011).

Table 2.1 Production quantities of Sorghum and cowpea in Africa

Area	Year	Sorghum Qty (t/ha)	Cowpea Qty (t/ha)
West Africa	2018	13703207	6056669
Eastern Africa	2018	7622380	539515
Northern Africa	2018	5804304	111774
Middle Africa	2018	2500161	258558
Southern Africa	2018	152353	5588
South Africa	2018	115000	4871

Source: FAO, 2018.

2.1.3 Grain sorghum production and market in south Africa

South African sorghum farmers are divided into smallholder and commercial based on the size of the land, production methods and market. The major grain sorghum-producing provinces are Mpumalanga, Northwest, Free State, Limpopo, Gauteng, and KwaZulu-Natal (DAFF, 2019). In 2007, Free State was producing more than 50% of the total sorghum production in South Africa, followed by Mpumalanga at 28% (NAMC, 2007). Figure 2.1 shows that Northwest, Limpopo, and Gauteng produced less than 10%. The report on sorghum production in 2019 indicated a decrease in sorghum production in the country over the past decade. In 2019, sorghum production has decreased considerably in the Free State province, from 54% in 2007 to 22% in 2019/20 (Figure 2.1). Although Mpumalanga and Limpopo provinces have shown an increase in production, the overall sorghum production in the country has decreased.

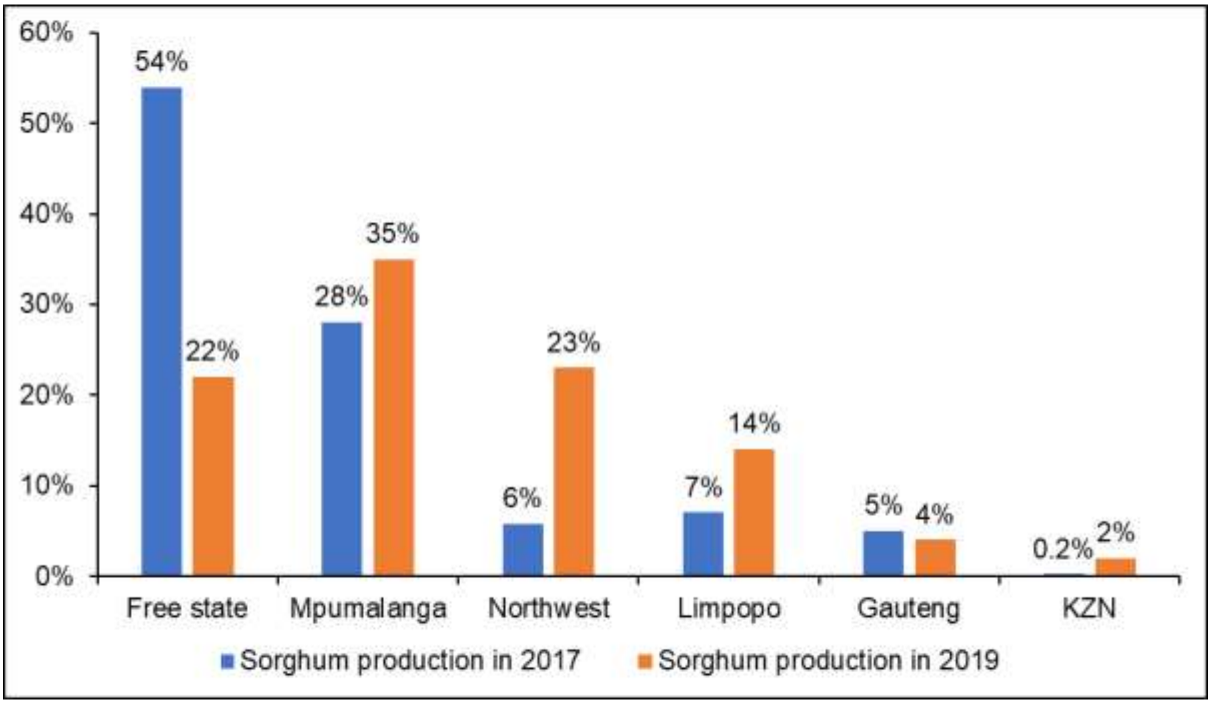

Figure 2.1 Sorghum production by province in 2007 and 2019

Source: National Agricultural Marketing Council (NAMC), 2007; DAFF, 2019)

2.1.4 Morphology of grain sorghum and cowpea

Grain sorghum

Grain sorghum and cowpea are regarded as annual crops. However, under favourable conditions, grain sorghum can be maintained for several seasons. Grain sorghum has a fibrous tap root system that can develop up to 1.5 to 2.4 m (Kimber, 2000), with a slender to stocky stem with a diameter of up to 50 mm (Doggett, 1988). Furthermore, it has leaves that are concentrated near the base or evenly distributed along the stem, depending on the variety. The length of the panicle varies from 75 to 500 mm, with 800 to 3000 kernels. Sorghum seeds are oval-shaped with a yellow or red color and are enclosed with glumes removed during threshing (Doggett, 1988).

Cowpea

Cowpea has a well-developed root system with a growth height of up to 80 cm and up to 2 m for climbing cultivars. The leaves are trifoliate with dark green arranged in alternative patterns. Cowpea has a fine-lipped stem with purple shades. Furthermore, the flowers are arranged in an intermediate fluorescence with peduncles of 5 to 60 cm. The seeds and pods of cowpea vary in shape, color, and size, with up to 20 seeds on each pod (Heuze *et al.*, 2013).

2.1.5 Agronomy of grain sorghum and cowpea

Grain sorghum

In many parts of Africa, grain sorghum planting time is affected by climatic conditions, the length of the growing season as well as cultivar choice. However, the correct planting time for grain sorghum is late October to mid-December. In some parts of Africa, the crop can be planted until late January. Although grain sorghum is generally known to thrive best under harsh conditions, it still requires a well-prepared seed bed with a minimum and maximum temperature of 18 ^oC and 30 ^oC, respectively (FAO, 2015). The correct soil to plant grain sorghum is well-grained, fertile sandy-clay loam soil with a soil pH of 5.0. The general plant population recommended for successful grain sorghum production is 100000 to 160000 plants ha^{-1} at inter and intra-row spacing of 90 cm and 7 cm, respectively. Fertilizer application in grain sorghum should be done according to soil results. However, nitrogen, phosphorus, and potassium are required when the crop shows symptoms of deficiencies (DAFF, 2010).

Cowpea

The correct planting date for cowpea is late November to late December in the areas that receive lower rainfall. Although cowpea can be grown on a wide range of soils, it is recommended that planting should be done on sandy soils for less root penetration with a soil pH of 5.6 to 6.0. For better seed establishment, soil temperatures should be between 8.5 ^{o}C and 20 ^{o}C for leaf growth. However, for optimum growth and development, the temperature should be around 30 ^{o}C with an annual rainfall of 400 to 700 mm. The correct spacing and plant population are determined by the type of cultivar grown as well as its growth habit. However, the crop requires a plant population of 200 000 to 300 000 plants ha^{-1} at inter and intra-row spacing of 70 to 100 cm and 30 to 50 cm, respectively. Like other legumes, cowpea is known to generate its nitrogen through nitrogen fixation. However, superphosphate is recommended at planting to supply P during growth (DAFF, 2011).

2.1.6 Major uses of grain sorghum and cowpea

Grain sorghum

Currently, grain sorghum has a total annual production of 60 million tonnes, with about 35% produced for human consumption (Dicko *et al*., 2006). In many African and Asian countries, grain sorghum is processed into a variety of nutritional traditional foods, including fermented and unfermented bread, dumplings, couscous, porridges, and snacks (Dahlberg *et al*., 2011). The grains are further used in making malted alcoholic and non-alcoholic beverages such as traditional beer. Grain sorghum has been introduced into the market in European countries, but few grain sorghum products are available (Suhenro *et al*., 2000; Carson *et al*., 2000). The crop can also be used for health purposes in many developing countries in Africa, especially in South Africa. According to Ciacci *et al*. (2007), grain sorghum products are safe for patients with celiac disease. Furthermore, gluten-free products have been produced from grain sorghum (Schober *et al*., 2005), which is important for the digestive system.

Grain sorghum is used worldwide as a primary feed for livestock. Stems and leaves are used for animal feeding as a green crop, hay, silage, and pasture (Berenji and Dahlberg, 2004). In Europe, grain sorghum is used to broom corn. The fiber that remains after threshing and cutting off the peduncle is used to manufacture broom-corns and corn brooms (Berenji *et al*., 2011). Sorghum is an important crop in providing sustainable biomass feedstock as it can be both a short-term and long-term solution as a renewable. Sorghum stocks are also used for biofuel production; starch-to-ethanol, sugar-to-ethanol (sweet sorghum), and cellulosic-to-biogas. In the USA, about 15 to 20% of the grain sorghum produced is used for ethanol production (Dahlberg *et al*., 2011).

Cowpea

Cowpea is an important grain legume in many developing countries, tropical and subtropical, due to its high nutritional content. The crop is consumed in different forms. For instance, young fresh leaves, green pods, and green seeds are consumed as vegetables, whereas dry seeds are used to make different foods (Agbogidi and Egho, 2012). In Tanzania, cooked cowpeas are either consumed with rice or in stiff porridge during lunch or dinner (Mamiro *et al*., 2011). Cowpea seeds, either green or dry, can be cooked or canned (Davis *et al*., 1991). According to Bazzano *et al*. (2001), cowpea, like other legumes, is important in stabilizing metabolic diseases such as heart diseases and cancer. In addition, in other African countries like South Africa, cowpea acts as a source of income as the growers sell it to local markets.

Apart from human food, cowpea is also an important fiber provision crop in many developing countries. In West Africa, after harvesting mature cowpea the green haulms are cut and rolled into small bundles containing leaves and vines (Singh *et al*., 2002). The bundles are used as feed supplements during dry seasons. Like other legumes, cowpea has a symbiotic relationship with bacteria that fix atmospheric nitrogen. Hence, it can be used to supply nitrogen to other component crops such as maize and grain sorghum in a rotation or intercropping system. Cowpea is used to improve soil fertility as well as structure in many rural areas due to the rapid decomposition of its roots which produces higher nitrogen residues (Valenzuela and Smith, 2002).

2.1.7 Nutritive value of grain sorghum and cowpea

Grain sorghum

Sorghum and cowpea are two grain crops that have common nutrients such as carbohydrates, protein, and fat. For instance, sorghum grain is composed of about 75% starch followed by up to 17% protein as well as over 160 mg/g of amino acids in red seeds and about 126 mg/g in white seeds (Linko *et al*., 2005). According to Cardoso *et al*. (2015), sorghum grains make excellent sources of nutrients as well as bioactive compounds such as 3–deoxyanthocyanidins, tannins, and polycosanols, which assist with non-communicable animal diseases.

Cowpea

In the case of cowpea, the grain is highly nutritious with a protein content of 22 to 30%, dietary fiber, minerals, vitamins, and several phytochemicals (Sreerama *et al*., 2012). Cowpea supplements cereal grains such as grain sorghum by increasing the quantity and quality of proteins and vitamins (OECD, 2016). In addition, in many African countries, it is used to provide lysine, which is the most limiting nutrient in cereal crops (Iqbal *et al*., 2006). Furthermore, the protein in cowpea is highly digestible and provides nitrogen balance and net protein retention (Rangel *et al*., 2004). In South Africa, the two crops are consumed together as one meal as they contain different nutritional values. Therefore, growing these two crops together on one piece of land may not only enhance the soil but also help minimize the cost of production inputs.

2.2 EFFECT OF CLIMATE CHANGE ON GRAIN SORGHUM AND COWPEA PRODUCTION

Climate change is one of the most discussed issues in the twenty-first century that affects socio-economic and economic status globally. It is defined as the long period of weather conditions that affect crop productivity (Elum *et al*., 2017). Although climate change is a global challenge, severe impacts have been experienced by developing countries such as South Africa (FAO, 2016). These severe conditions have affected livelihoods as well as food security. Grain sorghum and cowpea are among the most important crops in South Africa, together with other crops such as maize and wheat. The crops are produced by smallholder and commercial farmers for human and animal consumption (Taylor, 2003). However, the production of the two crops is currently constrained due to, among others, changes in weather and climate, which could lead to a decline in food production and a rise in food prices.

2.2.1 Temperature

Temperature is one of the climate variables that affect crop productivity and, ultimately, food security. Global temperatures have since 1970 increased by about 0.8 ^{o}C, which has affected mostly poor countries (Collins, 2011). South Africa is one of the developing countries that has been affected by the rise in annual temperatures. Blignaut *et al*. (2009) have reported that South Africa has been approximately 2% hotter between 1997 and 2006, which has drastically affected the production of grain sorghum and cowpea. About 80% of farmers in West Africa and 95% in South Africa believe temperatures have increased over the last two decades (Bryan *et al*., 2009; Callo-Concha, 2018). The evidence is perceived as a decline in crop productivity in and around Africa. Hence, the study was conducted to introduce production practices that will enable growers to produce grain sorghum and cowpea at an optimal level under fluctuating temperatures.

2.2.2 Rainfall

Apart from variation in global temperatures, rainfall is another climatic factor that affects crop growth and development globally. Drought and floods are two extreme weather conditions that affect the livelihoods of farmers in the semi-arid regions of Africa (Stringer *et al*., 2009; Muller 2009). These events result in total crop failure and hence threaten food security. Although grain sorghum and cowpea thrive well under drought conditions, soil moisture is still required for optimum growth and yield. In South Africa, most farmers grow grain sorghum and cowpea on dry land. However, with the changing climate, a drastic decrease in the yield of the two crops has been observed. According to Bryan *et al*. (2009) and Rakgase and Norris, (2015), 97% of farmers in South Africa have observed changes in annual rainfall, which has affected the overall crop production. For the sustainable production of grain sorghum and cowpea in South Africa, farmers should adopt climate-smart techniques.

2.3 CLIMATE-SMART APPROACHES FOR SUSTAINABLE GRAIN SORGHUM AND COWPEA PRODUCTION.

Modern agricultural practices such as the excessive use of chemical fertilisers and machinery reduce the soil quality and increase CO_2 emissions into the atmosphere. They affect sustainable crop productivity and ultimately reduce crop yield and quality. A climate-smart agricultural approach (CSA), which is defined as an integrated approach that focuses on sustainable food production and reduces emissions of greenhouse gases while building resilience to climate change (Singh and Singh, 2017), is required if sustainable crop production is to be achieved in a changing climate and degrading soil environment. The primary goals of CSA are to increase agricultural productivity to increase income, food security, and development; to increase adaptive capacity and resilience to climate change; and, finally, to reduce greenhouse gas emissions while increasing soil carbon sequestration (Harvey *et al*., 2014; Brandt *et al*., 2015). Climate change has caused fluctuations in sorghum and cowpea yields due to a lack of knowledge about climate-smart approaches, traditional agricultural practices, and ineffective soil management (Chimonyo *et al*., 2016b).

2.3.1 No-till system

Conventional tillage is the most frequently used practice in agriculture due to its time efficiency and not labor intensive. The practice involves turning up the soil surface using heavy machinery. The use of tillage leaves the soil bare, vulnerable to erosion and increases the emission of greenhouse gases (Swanepoel *et al*., 2015). Hence, for sustainable food production, while improving soil fertility, there's a need to adopt agricultural practices with less disturbance to the soil. Minimum soil disturbance is one of the key principles of conservation agriculture that can be considered for sustainable agriculture in the changing climate. The no-till system is recommended in many countries with poor soil fertility as it improves organic matter content as well as the physical structure of the soil. Furthermore, the practice reduces emissions of greenhouse gases, which is one of the goals of climate-smart practice (Derpsch *et al*., 2014).

For successful crop growth and productivity, growers need to sustain soil fertility and conserve moisture. No-tillage focuses on minimum or little soil disturbance when preparing the soil for crop production (Machado *et al*., 2003). Several studies have been conducted under the no-till system (Baumhardt and Jones, 2002). However, not much has been done on how intercropping systems are influenced by no-till systems across different locations over the season. Furthermore, little attention has been given to how climate change effects, such as the emission of greenhouse gases, are influenced by the no-till system. Tesfay *et al*. (2020) indicated that conservation practices like tillage system can improve crop productivity through improved soil health. Hence, the study was conducted to investigate how a no-till system can be used as a climate-smart practice for sustainable grain sorghum and cowpea production in an intercropping system.

2.3.2 Intercropping system

Intercropping is one of the traditional agricultural practices regarded as an alternative for climate change mitigation. The system is defined as the concurrent growing of two crop species on the same piece of land at the same time (Hauggaard-Nielsen *et al*., 2008). It is a highly productive traditional farming method that reduces climate-driven crop failure (Hu *et al*., 2017). It is commonly known for its efficient utilization of natural resources such as land while intensifying crop growth and productivity (Ning *et al*., 2017). Intercropping is known worldwide and has been adopted to eradicate different soil, crop, and social challenges. For instance, intercropping can reduce CO_2 emissions while enhancing carbon sequestration and crop productivity (Hu *et al*., 2017). Farmers in Latin America grow legumes alongside maize or potatoes, whereas Nigerian farmers grow 80% of their cowpeas in an intercropping system (Francis, 1986). In Africa, where most soils have poor fertility and soil nutrient limitations, intercropping cereals with legumes has been the most common practice (Mao *et al*., 2015). This is due to a symbiotic relationship between legume crops and Rhizobia that enables the fixation of atmospheric nitrogen. Intercropping with legumes enhances nutrient availability, crop growth and nutrient use efficiency. It also reduces nitrogen leaching, the use of inorganic fertilizers, agrobiodiversity, soil fertility, and, ultimately, crop yield (von Cossel *et al*., 2017; Latati *et al*., 2017).

There are different types of intercropping systems which vary in spatial and temporal patterns (Figure 2.2). Mixed cropping seeds are mixed in an available space without the arrangement of rows. In alternate row intercropping, two or more crop species are planted alternatively on the same piece of land. The other type of intercropping is within-row, where crops are planted simultaneously within the same row at different seeding ratios. Lastly, strip intercropping is defined as the cultivation of two or more plant species in several alternating rows (Lithourgidis *et al*., 2011). The type of intercropping used in the study is row-intercropping. In South Africa, the most common intercropping practiced by farmers is mixed intercropping. Hence, intercropping is an important cropping system that can enhance food security and air quality through less contribution to air pollution in South Africa, particularly in Limpopo Province. The study focused on promoting intercropping to local growers in Limpopo Province for sustainable crop production while reducing emissions of greenhouse gases.

Figure 2.2 Different types of intercropping systems

Source: Lithourgidis *et al*. (2011)

2.4 EFFECT OF GRAIN SORGHUM AND COWPEA INTERCROPPING SYSTEM ON:

2.4.1 Yield and yield components

The intercropping system is an important crop production system that can be used to improve the productivity of grain sorghum and cowpea, especially for small-scale farmers with low input. Cereal-legume intercrop is the common intercropping practiced. There is a yield advantage in intercropping compared to sole cropping systems due to the efficient utilization of growth resources such as water, light, and nutrients (Tsubo *et al*., 2001). The land equivalent ratio is one component that is widely known for measuring the productivity of intercropping systems by comparing yields of sole with binary plots. Many researchers have reported higher productivity in intercrops as compared to the sole. This has been a regular practice among many farmers in the semi-arid regions of Africa (Hayder *et al*., 2003; Mohammed *et al*., 2008; Eskandari and Ghanbari, 2010).

2.4.2 Leaf gaseous exchange and light interception

Crop morphology is one of the most debated topics when different species are intercropped together. The most discussed issues are the exchange of leaf gases and water retention. Intercropping increases water retention through increased root density and arrangements of different crop species. Furthermore, full canopy cover by crops results in reduced soil evaporation (Ofori *et al*., 2014). Chimonyo *et al*. (2016b) and Zougmore *et al*. (2000) reported that intercropping grain sorghum with cowpea has the potential to reduce runoff by about 30% and improve water management, especially in rainfed areas. In addition, the water captured in an intercropping system is exchanged for CO_2, which will be helpful in biomass production. One of the major factors to consider when intercropping grain sorghum and cowpea is plant density. According to Makoi *et al*. (2010), higher cowpea density when intercropped with grain sorghum affects photosynthetic activities such as stomatal conductance, photosynthetic rate etc. Intercropping system improves photosynthetic rate (A), transpiration rate (E), stomatal conductance (gs) and sub-stomatal CO_2 concentration of maize compared to sole cropping system (Lima Filho, 2000). Gathering more information on the leaf gaseous responses of other cereal crops like grain sorghum undre different environment will assist with better recommendations in Limpopo Province.

The leaf is the most important plant organ, distributing resources such as light to other plant structures and serving as a good indicator of plant health. According to Poorter *et al*. (2009), plants respond to changes in environmental conditions such as temperature (light) by changing their leaf morphology, which will temper with the allocation of resources. Hence, other leaf traits such as LAI will be affected. Photosynthetically active radiation (PAR) is the amount of radiation that is available for plant photosynthesis. Its ultimate importance is the role it plays in biomass accumulation, which contributes to grain yield. The rate of photosynthesis and conversion into biomass accumulation depends on the amount of light that is captured by plant canopies (intercepted PAR) and canopy size per unit leaf area (Leaf Area Index) (Lambers *et al*., 2008). Planting different crop species in an intercropping system result in an increase in LAI and IPAR, resulting in a high photosynthetic rate and higher biomass production (Bilalis *et al*., 2010; Salau *et al*., 2014). Grain sorghum and cowpea have different leaf structures and shapes. Hence, intercropping the two crops is important to smallholder farmers of semi-arid regions as they have high complementary use of resources such as light and water.

2.4.3 Soil CO_2 emissions and carbon stocks

The emission of greenhouse gases (GHG) due to anthropogenic activities increases the concentration of carbon dioxide in the atmosphere (Wang *et al*., 2010). Hence, higher levels of GHGs in the atmosphere lead to a change in climatic conditions which affect food production; hence, food insecurity. Soil carbon sequestration is the process whereby carbon from the atmosphere is fixed by plants and organic residues and stored in the soil (Kane, 2015). The process is about the removal of carbon dioxide from the atmosphere through plant photosynthesis, its transfer to plant biomass, and from plant biomass to the soil, where it is stored as soil organic carbon in the labile (Macleod *et al*., 2019).

Carbon plays a role in soil organic matter. It can be added into the soil through plant and animal residues and deposited onto the soil surface (Kleinen *et al*., 2016). It is a key factor in soil fertility, although it is dependent on soil organisms. In addition, the duration of soil organic carbon storage is determined by soil (texture and structure), rainfall, temperature, cropping system, and soil management (Cheeseman *et al*., 2016). For instance, the higher decomposition by soil micro-organisms causes carbon dioxide to be emitted back into the atmosphere (Gardi and Jefry, 2009; Rumpel *et al*., 2012). However, the amount of carbon available in the soil is determined by the difference between carbon added to the soil and carbon lost into the atmosphere. Soil management practices such as conventional tillage and continuous cultivation play a role in carbon loss (Six *et al*., 2002).

Crop production practices such as extensive use of tillage and monoculture have a major effect on soil organic carbon stocks (Han *et al*., 2009). To reduce the emission of soil carbon into the atmosphere, sustainable production practices have to be adopted. Gan *et al*. (2011b) and Gan *et al*. (2014) reported that conservation agriculture such as intercropping systems under reduced tillage proved to have low carbon emissions as compared to monoculture in semi-arid regions. Hence, this study was done with one of the several objectives to promote the use of CA practices such as intercropping to improve soil organic carbon. Furthermore, no-tillage system decreases CO_2 in a long term (38 to 40 years) measurements due to impeoved soil agagregate stability (Ruis *et al*., 2022). No-tillage system decrease soil CO_2 emission rates and increased soil carbon stocks compared to convetional tillage (Nyambo *et al*., 2020). These will assist farmers in Limpopo Province with improved soil fertility and hence sustainable crop production while dealing with the effects of climate change. There are different methods and tecchniques to measure CO_2 emission from the soil. Among the methods, Ruis *et al*. (2022), using a LiCOR 8100 A (LiCOR, Lincoln, NE) automated gas analyzer placed on a 20 cm ring inserted (2.54 cm depth) into the soil on the shoulder of the main crop row. Munjonji *et al*. (2021) used the CO_2 chambers method which involve isntalling in the field according to the USDA-ARS GRACEnet Project Protocols.

2.4.4 Biological nitrogen fixation

Low crop productivity in the smallholder farming sector is due to declining soil fertility as a result of continuous cropping. Enhancing crop productivity through the use of chemical fertilizers is disadvantageous due to high input costs and the negative effect on the environment (Erisman *et al*., 2008). Legumes can provide natural N due to their relationship with rhizobia. Rhizobia fix atmospheric nitrogen into biologically useful forms within root nodules (Sprent, 2009), the process is called biological nitrogen fixation (BNF). It is a process by which nitrogenase converts atmospheric nitrogen into ammonia (Dupont *et al*., 2012). According to the procedure of Shearer and Kohl (1986), N_2 fixation is calculated as the difference between δ15N of the non-fixing plant (grain sorghum) and the δ15N of N_2 fixing planting (cowpea) as formulated below:

$$\delta^{15}N_{legume} = [(R_{legume}/R_{standard}) -1] \times 1000$$

where; $\delta^{15}N_{legume}$ is the value of the $\delta^{15}N$ of the N_2 fixing plant (cowpea), R_{legume} is the sample isotope ratio ($^{15}N/^{14}N$), $R_{standard}$ is $^{15}N/^{14}N$ for atmospheric N_2 (0.0036765)

$$\%NDFA = (\delta^{15}N_{referenceplant} - \delta^{15}N_{legume})/(\delta^{15}N_{referenceplant} - \beta)$$

where: $\delta^{15}N_{referenceplant}$ is the value of the $\delta^{15}N$ of the N taken up from the soil, obtained in leaves of the spontaneous plants used as the non-fixing reference (sorghum), $\delta^{15}N_{legume}$ is the value of the $\delta^{15}N$ of the N_2 fixing plant (cowpea), β is the value of the isotopic discrimination of ^{15}N made by the plants during the BNF process
NDFA is nitrogen derived from the air.

The process plays a major role in ecology and agronomy as it accounts for 65% of the nitrogen used in crop production (Figueiredo *et al*., 2013). Legumes are the most important in enriching the pools of soil N for non-N-fixing crops such as grain sorghum (Jensen *et al*., 2012). In addition, BNF supplies nitrogen to legume growth and grain production under a wide range of environmental and soil conditions in an intercropping system. The use of legumes in intercropping will assist with maintaining and improving soil fertility while improving crop growth and yield (Sanginga and Woomer, 2009). In the context of climate change, the adoption of a cereal-legume intercropping system will reduce the use of N fertilisers as nitrogen can be provided to cereal crops through BNF. Hence, less NO_2 and CO_2 will be emitted into the atmosphere (Brito *et al*., 2009). Therefore, the process of BNF may have economic viability and sustainability for grain sorghum production in many African areas where the crop is consumed in larger quantities.

2.5 MODELING GRAIN SORGHUM AND COWPEA IN AN INTERCROPPING SYSTEM

Agricultural simulation models have a significant role in addressing climate change challenges developing mitigation and adaptation strategies. Furthermore, studies have reported that agricultural simulation models play a role in providing information about cropping practices and crop improvement strategies to address food security (Hochman *et al*., 2009b; Cooper *et al*., 2009; Confalonieri *et al*., 2010; Gaydo *et al*., 2012a). These models are the key simulators of crop physiological processes, productivity, water and nutrient uptake, carbon assimilation as well as biomass (Holzworth *et al*., 2014).

The Agricultural Production System Simulator (APSIM) is one of the crop models that has been extensively used to simulate and make predictions of crop growth and productivity, taking into consideration climate change scenarios. APSIM is a model used across the world to assess different cropping systems by incorporating weather, crop, and soil data into the structure (Figure 2.3). It is a cropping system simulation model that is designed to predict economic products for different crops. Hence, it can be used to predict the growth and yield of crops by focusing on climate change, soil and crop management (Keating *et al*., 2003). The model incorporates a generic crop model that utilises library routines for simulating growth and development processes (Wang *et al*., 2002).

APSIM has an important role in addressing challenges such as food security and climate change adaptation and mitigation (Holzworth *et al*., 2014). Several studies have been conducted where APSIM has been used to simulate; atmospheric CO_2 (Asseng *et al*., 2004), soil water balance (Bouman and van Laar, 2006), N_2 fixation and fertility trials (Gaydon *et al*., 2012), and intercropping systems (Chimonyo *et al*., 2016a). From the literature, APSIM has been a useful model to predict the growth and productivity of many crops and their mitigation as well as adaptation strategies to climate change. Hence, using APSIM in this study was useful in simulating the response of grain sorghum-cowpea under intercropping systems of climate risks in South Africa, especially in Limpopo Province where the use of crop models to predict future climate is limited.

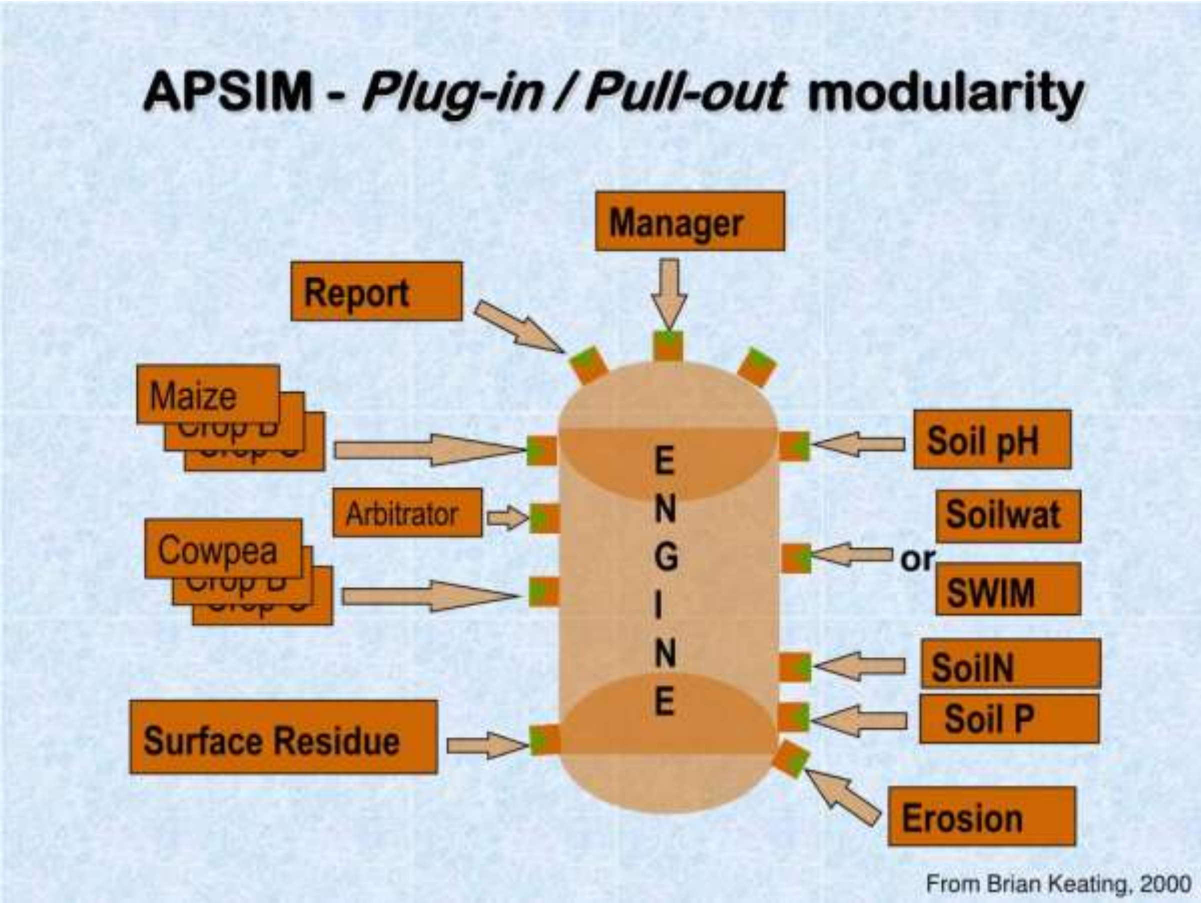

Figure 2.3 APSIM schematic diagram

Source: Holzworth *et al*. (2006)

CHAPTER 3: GROWTH, YIELD AND PHYSIOLOGICAL RESPONSES OF GRAIN SORGHUM AND COWPEA UNDER INTERCROPPING SYSTEM ACROSS TWO AGRO-ECOLOGICAL

3.1 YIELD RESPONSES OF GRAIN SORGHUM AND COWPEA IN BINARY AND SOLE CULTURES UNDER NO-TILLAGE CONDITIONS IN LIMPOPO PROVINCE

Published: *Agriculture*, **12**: 733, DOI Number:

Abstract

Climate change is severely disrupting ecosystem services and crop productivity in many smallholder farming systems in South Africa, particularly the semi-arid region of Limpopo Province, with a consequent reduction, resulting in lower crop growth and yields. Many Agricultural Scientists are emphasizing the need for critical analysis of conservation agricultural practice in a holistic interactive manner through crop modeling as a way to improve cropland productivity, amid climate change. However, obtaining accurate data for improved crop modeling in many instances has been a major limitation. A no-tillage intercrop experiment involving grain sorghum and cowpea was laid out in a randomised complete block design (RCBD) with four replications over two seasons in two distinct agro-ecological zones, Syferkuil and Ofcolaco in Limpopo province. The main objective was to assess the productivity of four sorghum cultivars (Avenger, Enforcer, Titan and NS5511) intercropped with cowpea (betch witch) under two cowpea densities (31037 plants ha^{-1} and 74074 plants ha^{-1})- and contribute to improved crop model analysis. Leaf area index of grain sorghum was higher in sole compared to binary cultures. However, the results revealed that the cropping system did not have a significant effect on grain yield and yield components of grain sorghum cultivars. Enforcer obtained the highest grain yield of 4338 kg ha^{-1} in 2018/19 whereas NS5511 accumulated the highest grain yield of 2120 kg ha^{-1} during 2020/21 cropping seasons at Syferkuil. At Ofcolaco, Enforcer and Avenger were high yielding cultivars with the means of 2625 kg ha^{-1} and 1191 kg ha^{-1} during the 2018/19 and 2020/21 cropping season, respectively. Cowpea results revealed that in 2018/19 cowpea accumulated about 93% more grain yield in sole compared to binary cultures. In 2020/21 77% more grain yield was accumulated in sole compared to binary cultures. At Ofcolaco about 96% more grain yield was obtained in sole compared to binary cultures during the 2018/19 cropping season. Furthermore, cowpea accumulated over 55% and 49% of grain yield when grown in high compared to low population density at syferkuil and Ofcolaco respectively. The total LERs exceeded 1.0 at the two locations across seasons, ranging from 1.3 to 1.9. From the result, grain sorghum hindered grain yield of cowpea due to the less efficient utilization of resources at Syferkuil and Ofcolaco. However, cowpea grain yield in binary cultures improved with increased population density. Hence, for the adoption of the sorghum-cowpea intercropping system as a climate-smart practice for sustainable production in the Limpopo province other management practices such as planting time should be considered.

Keywords: climate-smart agriculture, grain yield, yield components, intercropping system, land equivalent ratio.

3.1.1 Introduction

Grain sorghum and cowpea are two of the most important grain crops grown in South Africa, particularly in Limpopo Province, where they are stapled foods for many subsistence farmers (Taylor, 2003). When conditions are favorable, smallholder farmers can produce up to 20000 tha^{-1} of grain sorghum (DAFF, 2011). Cowpeas are also grown in the province for domestic consumption, with the excess sold at the local market to generate revenue. Temperature extremes and precipitation fluctuations have long hampered grain sorghum production in Southern Africa (Touch *et al*., 2016). Furthermore, anthropogenic activities such as conventional agriculture, overuse of chemical fertilizers, and continuous cultivation of the same crop on the same plot of land have contributed approximately 12% of the greenhouse gases emitted into the atmosphere globally (Rockstorm *et al*., 2009; Stocker *et al*., 2013). These practices' negative impact has also contributed to severe land degradation (Burt *et al*., 2016; Olsson *et al*., 2019).

Agriculture must become more productive and diverse to cope with climate change and increased natural resource constraints (Singh and Singh, 2017). Producing more food with fewer resources while preserving and improving farmers' livelihoods is a global challenge. Adopting climate-smart agricultural practices such as intercropping, and conservation tillage can boost crop productivity and alleviate food insecurity in many Limpopo province areas (Sri-vastava *et al*., 2016). Intercropping is defined as the simultaneous cultivation of two crops on the same plot of land (Hauggaard-Nielsen *et al*., 2008), whereas a no-tillage system is a practice of preparing the soil with minimal soil disturbance (Derpsch *et al*., 2014). The two systems are widely used around the world due to their efficient use of resources such as land and water, as well as their ability to improve soil fertility and crop intensification (Ning *et al*., 2017).

The most common system used in South Africa is maize-legume intercropping. However, with average maize production threatened by climate change, sorghum has been projected as one of the most viable substitute crops due to its ability to withstand harsh conditions in South Africa. As a result, sustainable grain sorghum management and crop utilization as a maize substitute can secure food for the general populace while mitigating climate change scenarios (Rippke *et al*., 2016). Intercropping grain sorghum with cowpea improves soil fertility due to nitrogen fixation by the legume crop.

Crop models can be used to assess the productivity of traditional agronomic practices such as intercropping systems in a changing climate. However, in South Africa, the availability of data required to run crop model simulations remains a challenge (Kephe *et al*., 2020). The main goal was to evaluate the productivity of four sorghum cultivars (Avenger, Enforcer, Titan, and NS5511) intercropped with cowpea (betch witch) under two cowpea densities and to generate data that can aid in climate-smart practices and crop model analysis.

3.1.2 Materials and methods

3.1.2.1 Study area

A field experiment was carried out in two distinct agro-ecological regions of Limpopo province during the 2018–19 and 2020–21 cropping seasons (Figure 3.1). The first location was the University of Limpopo Experimental Farm in Syferkuil, which was located at 23° 50' 02.7" S and 29° 41' 25.5" E. The area receives 350 to 500 mm of rainfall per year, with average maximum and minimum temperatures of 15 ^{o}C and 30 ^{o}C, respectively. The second location was Itemeleng Ba-Makhutjwa Primary Cooperative at Farmers Field at Ofcolaco, which was located at 24° 06' 38.3" S and 30° 23' 11.8" E near Tzaneen. Ofcolaco receives approximately 650 to 700 mm of rainfall per year, with an average maximum and minimum temperatures of 18 ^{o}C and 35 ^{o}C, respectively. The two locations also have different soil types: sandy-clay at Syferkuil and clay-loam at Ofcolaco (Department of Agricultural Development, 1991). The experimental sites were both previously used to plant soybeans, followed by two years of fallow under no-till dryland conditions.

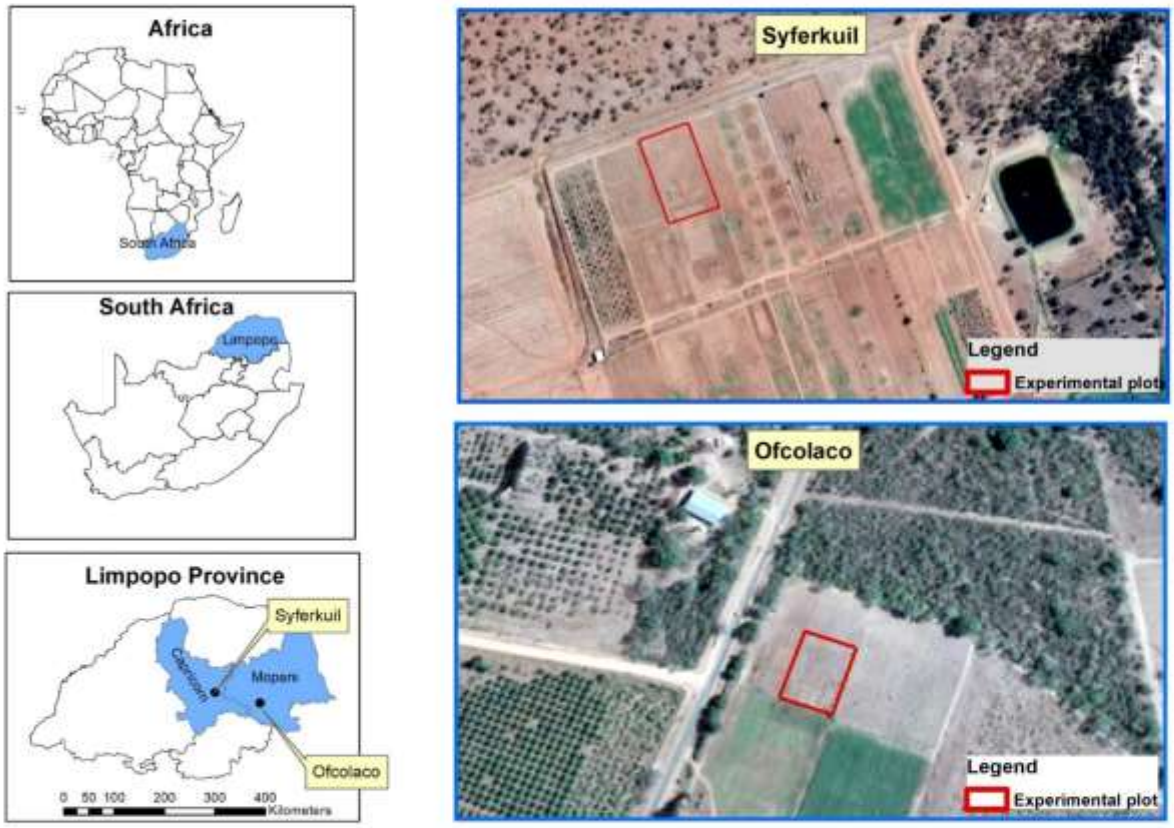

Figure 3.1 The map of agro-ecological regions where the field experiments were conducted during the 2018/19 and 2020/21 cropping seasons.

3.1.2.2 Soil samples

Soil samples were collected before planting at the depth of 0-30 cm and 30-60 cm using a random sampling method at the two experimental sites. A total of four composite samples per sampling depth from each location, representing the experimental blocks were collected and analysed in the laboratory for chemical and physical properties (Table 3.1). The methods used to analyse the soil properties were chosen based on accuracy. The samples were sieved to pass through a 2 mm sieve and analysed for chemical properties. Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), manganese (Mn) and copper (Cu) were following the procedure of the Mehlich-III multi-nutrient extraction method. Soil pH was determined in potassium chloride (KCl) (van Reeuwijk, 2002), and soil bulk density using a metal ring at each soil depth following the procedure of (Prikner *et al*., 2004). Available mineral nitrogen (N) was determined using the colorimetric method for ammonium and nitrate. The bray-1 method was used to determine available phosphorus (P), cation exchange capacity (CEC) following the procedure of Rayment and Higginson (1992).

Walkley and Black method were used to determine organic carbon (org.C). Soil particle size was determined using the hydrometer method (Anderson and Igram, 1993). Before planting Syferkuil soil had higher K, Ca and Mg macronutrients and low Phosphorus P compared to the soil from Ofcolaco. However, Ofcolaco soil had higher micronutrients Zn, Mn and Cu compared to Syferkuil soil. The results further indicated that soil from Ofcolaco has high organic carbon of 1.38% compared to Syferkuil which had about 0.6% organic carbon.

Table 3.1 Pre-plant soil chemical and physical properties from Syferkuil and Ofcolaco

Soil properties	**Syferkuil**	**Ofcolaco**
P (mg/kg)	22.00	53.75
K (mg/kg)	433.00	234.00
Ca (mg/kg)	1119.75	917.25
Mg (mg/kg)	558.50	152.25
Exch. Acidity (cmol/L)	0.03	0.04
Total cations (cmol/L)	11.32	6.47
Acid sat. (%)	0.00	0.75
pH (KCL)	6.35	6.06
Zn (mg/kg)	1.48	5.48
Mn (mg/kg)	17.50	48.25
Cu (mg/kg)	4.08	5.13
org. C (%)	0.60	1.38
N (%)	0.05	0.05
Clay (%)	30.00	23.25
Fine silt (%)	7.50	8.25
Coarse silt and sand (%)	65.50	72.25
Texture class	Sandy clay loam	Clay loam

3.1.2.3 Field design and management

Prior to planting, the land at both locations was prepared by first reducing the size of weeds using a motorised slasher, followed by the application of Roundup, a non-selective, systematic, broad-spectrum glyphosate-based post-emergence herbicide one month after slashing. Round-up was applied at 250 ml in 10 litres of water. The trial was planted 10 days after herbicide application as a randomised complete block design (RCBD) in a factorial arrangement with replications under a no-tillage condition. The experimental treatments comprised four grain sorghum cultivars namely Avenger, Enforcer, Titan and NS5511 and two cowpea (var. Betch Witch) densities (37037 planta ha^{-1} and 74074 plants ha^{-1}). Sorghum and cowpea were planted in both sole and binary cultures. Grain sorghum density was maintained at 37037 plants ha^{-1} for each cultivar. Each experimental unit was 3.0 m x 3.6 m consisting of four rows of sorghum and four rows of cowpea in the intercropped treatment. For grain sorghum, seeds were planted at inter and intra-row spacing of 0.9 m and 0.3 m, respectively. Cowpea was planted at an inter-row spacing of 0.9 m and intra-row of 0.3 and 0.15 m to obtain the treatment densities of 37037 and 74074 plants ha^{-1} respectively. The spacing between sorghum and cowpea in the intercropped treatment was thus, 0.45 m (Figure 3.2).

The trials were planted on the 17th of January 2019 and the 20th of November 2020 at Syferkuil, whereas at Ofcolaco, the planting dates were 23rd March 2019 and the 21st November 2020. Each experimental unit received phosphorus in a form of superphosphate (10.5% P) at 20 kg P ha^{-1}, based on pre-plant soil fertility analysis. Nitrogen was applied as Limestone Ammonium Nitrate (LAN) (28% N) at a rate of 100 kg N ha^{-1} in a split application of 50 kg N ha^{-1} each at planting and knee height of grain sorghum. All fertilisers were banded along the row. Standard crop management practices including thinning, weeding, and pest control for both crops were monitored and addressed when necessary throughout the cropping season. Aphids and stalk borer infestation in cowpea and grain sorghum were controlled using Cypermethrin 200cm. Hundred and twenty (120) ml of Cypermethrin was diluted with 64L of water. The damage on birds' attack on sorghum grains from flowering to physiological maturity was prevented by covering sorghum heads using a protective translucent nylon mesh net at the onset of the milk stage.

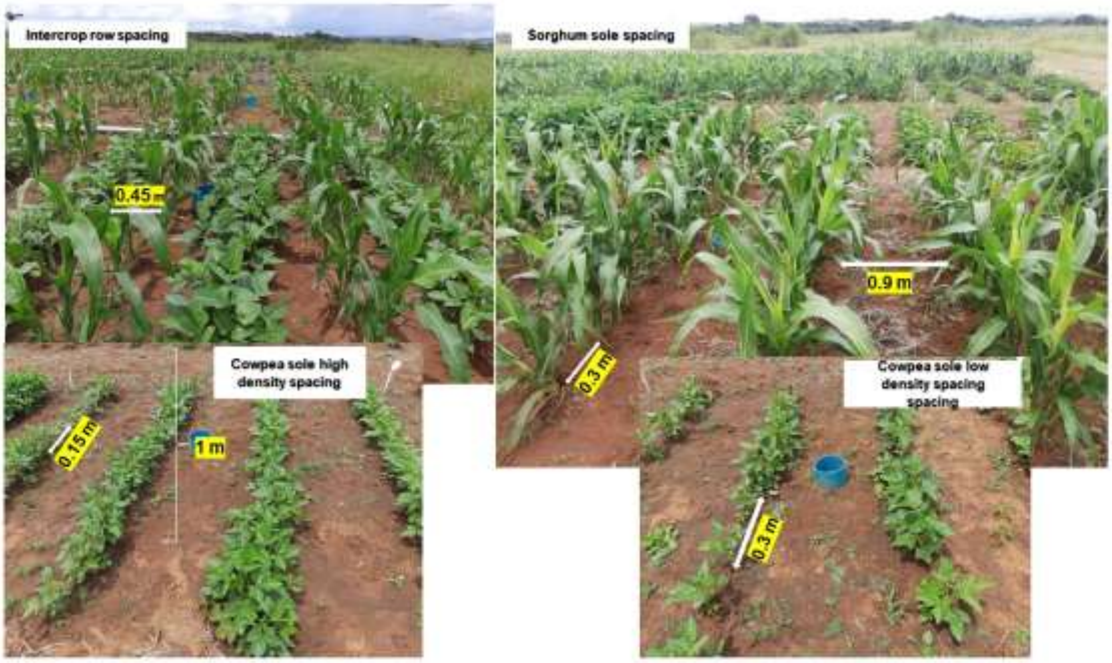

Figure 3.2 Binary and sole row arrangements.

3.1.2.4 Weather conditions

Two automatic weather stations near or at the experimental sites were used to provide daily weather data (Figure 3.3). At the University of Limpopo experimental farm (Syferkuil), the weather station was located at the farm whereas, at Ofcolaco, a rain gauge placed at the site and an automatic weather station situated 27.9 km from the experimental site were used to access daily weather data during the period of experimentation.

Figure 3.3 The weather stations where climate data was collected during growing seasons.

3.1.2.5 Data collection

Leaf Area Index (LAI) data was collected from two weeks after emergence per experimental unit and continued every two weeks until physiological maturity. The data was collected using AccuPAR LAI Ceptometer LP-80 (Decagon Devices, Inc Washington State) on middle rows of binary and sole cultures of grain sorghum and cowpea between 10H00 am and 1H00 pm. LAI on individual fully expanded flag leaves of three plants within an experimental unit was measured at 3 minutes interval. In the 2020/21 cropping season, cowpea at Ofcolaco failed to produce grain. Hence, only the grain yield of the 2018/19 cropping season from Ofcolaco is presented in this paper. At harvesting, 10 plants with their heads were sampled from two middle rows within an area of 2.7 m^2 to determine biomass and grain yield. All cowpea plants from a 2.7 m^2 area were harvested with pods to determine grain yield and biomass. Cowpea leaves that dropped to the ground were retrieved on a continuous basis after flowering and added to the final biomass at harvest. Biomass was oven-dried in the laboratory at 65^oC for 72 hours and weighed using a weighing balance to get the weight of dry matter. The grain from the harvested area was weighed in the laboratory to determine grain yield and yield components. Grain yield was determined by the weight grains per plot and converting to kg ha^{-1}. Three grain sorghum from the harvested heads were sampled from 10 heads harvested to determine the head weight and head length. The

3 plants were threshed separately to determine seed weight per head as well as shelled head weight. 1000 seed weight was determined by counting and weighing 1000 grain sorghum seeds. Cowpea pod weight was obtained by weighing pods collected per plot in 2.7 m^2 and 100 seed weight was determined by counting as well as weighing 100 seeds of cowpea. Harvest index (HI) and land equivalent ratio (LER) for each crop were calculated using the following formulas:

$$HI\ (\%) = \frac{Grain\ yield}{stover\ yield + grain\ yield} * 100 \qquad \text{……………………..equation 1}$$

$$LER = \frac{YSbinary}{YSsole} + \frac{YCbinary}{YCsole} \text{…………………….…………….equation 2}$$

Where:

YSbinary is the yield of sorghum in intercropping, YSsole is the yield of sorghum in sole culture, YCbinary is the yield of cowpea in intercropping and YCsole is the yield of cowpea in sole culture.

3.1.2.6 Data analysis

After checking the relevant model assumptions including normality, independence and constant variance, we have used univariate multi-factor analysis of variance (ANOVA) model to fit each response variable using the Statistical Analysis System (21 SAS version 9.4). In grain sorghum, the four cultivars were regarded as factor 1 and the cropping system as factor 2. In the case of cowpea, the cropping system was factor 1 while density was factor 2. For LAI, sampling day (time), cultivars and cropping system were tested for interaction for grain sorghum. The LAI interaction of cowpea was tested among sampling day, cropping system and density. The interaction of yield and yield components, as well as the harvest index of grain sorghum, was tested between cultivars and the cropping system. In cowpea, the interaction was tested between cropping systems and density. Mean separation was done where the means were different using the least significant difference (LSD) at probability levels of $p \leq 0.05$. Land equivalent ratio (LER) was used to assess the productivity and effectiveness of the intercropping system.

3.1.3 Results

3.1.3.1 Weather conditions during growing seasons

Syferkuil had daily average minimum and maximum temperatures of 12 ^oC and 27 ^oC respectively with a total rainfall of 349 mm in 2018/19 and 292 mm in the 2020/21 growing period (Figure 3.4). Rains of about 40 mm and 10 mm were received during the planting period at Syferkuil in the 2018/19 (January) and 2020/21 (November) cropping seasons.

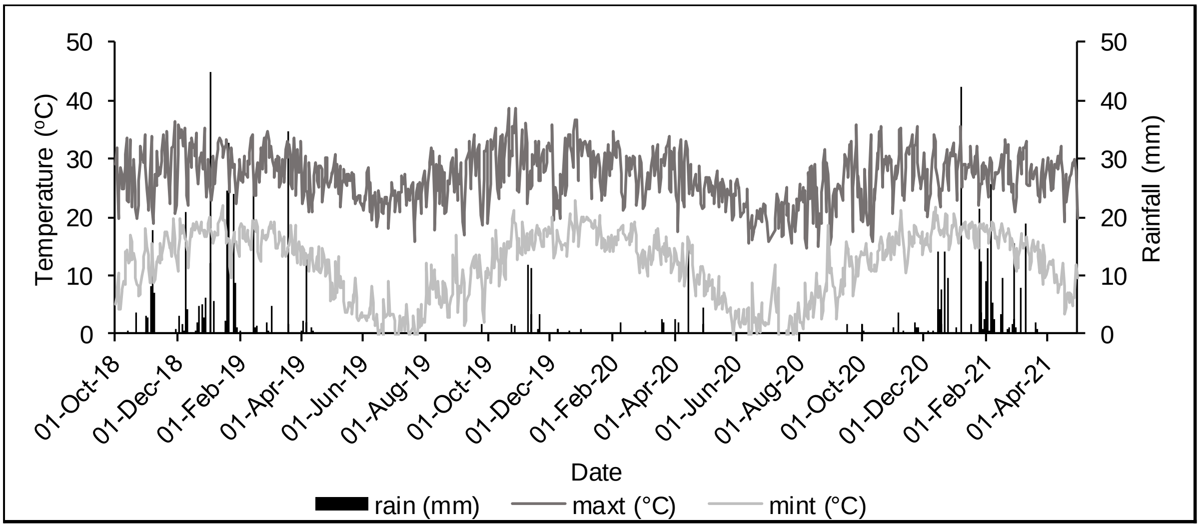

Figure 3.4 Syferkuil daily rainfall, maximum and minimum temperature during 2018/19 and 2020/21 cropping seasons.

Source: Agricultural Research Council (ARC) Weather station at study locations.

At Ofcolaco, the maximum and minimum temperatures across the two seasons were 31 ^oC and 18 ^oC respectively with a total rainfall of 261 mm in 2018/19 and 608 mm in 2020/21. During planting months Ofcolaco received rainfall of 5 mm in 201819 and 38 mm in 2020/21. The highest rainfall (about 130 mm) in 2018/19 was received in December when minimum and maximum temperatures were 22 ^oC and 35 ^oC respectively. These were higher compared to the other months. However, in 2020/21 the highest rainfall was received in December when temperatures were lower compared to other months (Figure 3.5).

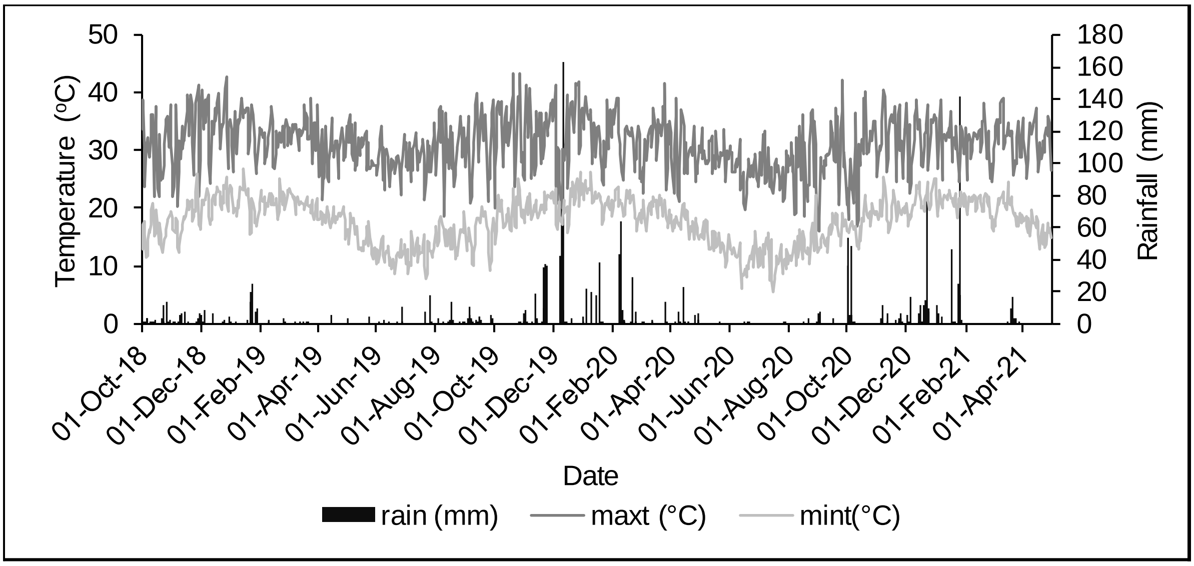

Figure 3.5 Ofcolaco daily rainfall, maximum and minimum temperature during 2018/19 and 2020/21 cropping seasons.

Source: Agricultural Research Council (ARC) Weather station at study locations.

3.1.3.2 Grain yield and yield components of sorghum and cowpea

The cropping system and density of the companion cowpea crop did not affect the grain yield of sorghum cultivars at the test sites over two seasons. Grain sorghum cultivars, on the other hand, significantly ($p \leq 0.05$) influenced grain yield over the two cropping seasons at Syferkuil and Ofcolaco (Figures 3.6 & 3.7). The results revealed that cultivars Enforcer and NS5511 outperformed Avenger and Titan with an average grain yield of 4153 kg ha^{-1} during the 2018/19 cropping season, while Avenger and Titan produced an average yield of 2607 kg ha^{-1} (Figure 3.6). According to the results, 85.86 kg ha^{-1} more grain yield was harvested in 2018/19 at this location than in 2020/21. The cultivar NS5511 with the yield of 2120 kg ha^{-1} outperformed the cultivars Enforcer, Avenger, and Titan, which had mean yields of 1942 kg ha^{-1}, 1652 kg ha^{-1}, and 1561 kg ha^{-1}, respectively (Figure 3.6).

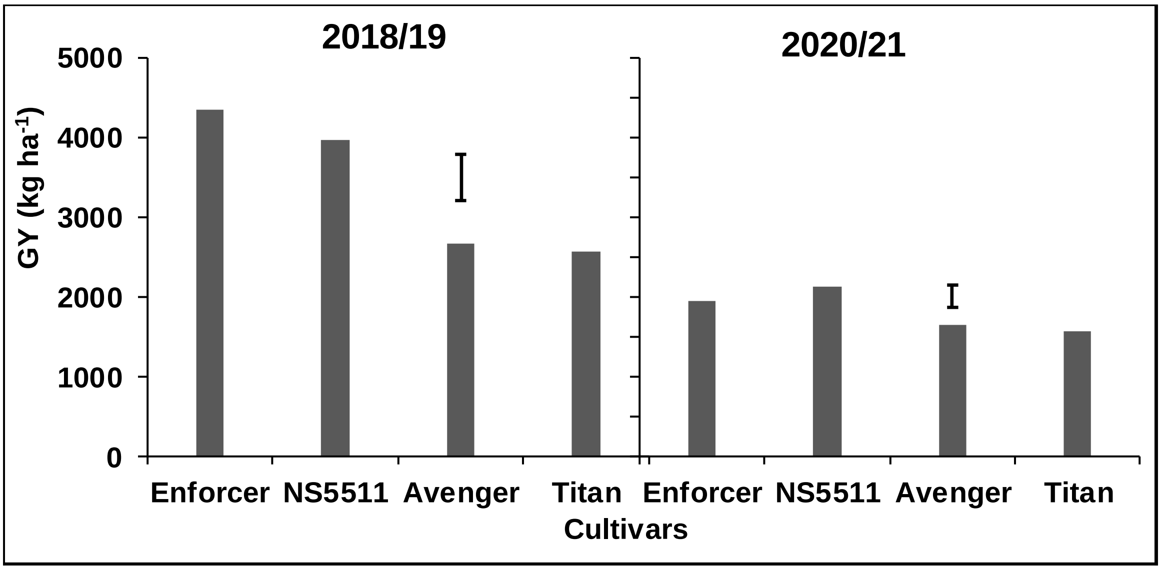

Figure 3.6 Grain yield of four sorghum cultivars evaluated at Syferkuil during 2018/19 and 2020/21 cropping seasons. Vertical bars represent LSD value ($p \leq 0.05$) for mean separation.

The grain yield of the sorghum cultivars at Ofcolaco was inconsistent across seasons (Figure 3.7). Enforcer and Titan, for example, produced higher grain yields than NS5511 and Avenger in the 2018/19 cropping seasons, averaging 2562 kg ha^{-1} and 1584 kg ha^{-1}, respectively. However, in 2020/21, NS5511, Avenger, and Enforcer outperformed Titan, which produced a yield of 910 kg ha^{-1}.

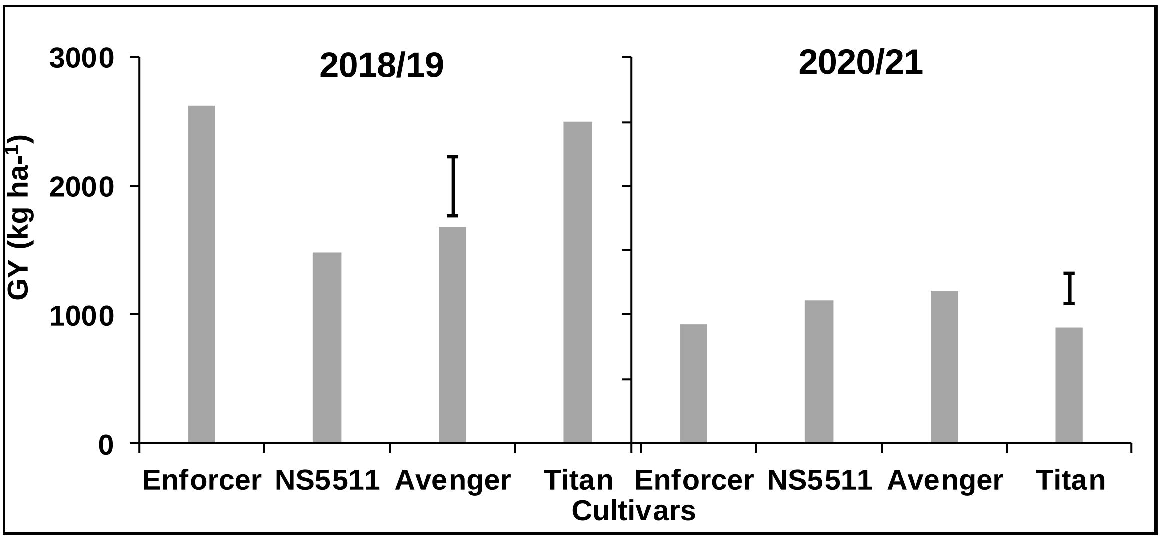

Figure 3.7 Grain yield (GY) of four grain sorghum cultivars evaluated at Ofcolaco during 2018/19 and 2020/21 cropping seasons. Vertical bars represent LSD value ($p \leq 0.05$) for mean separation.

Harvest index (HI) based on grain production differed significantly (p ≤ 0.05) between grain sorghum cultivars at the two locations and cropping seasons. Across the two cropping seasons and two locations, Enforcer consistently had the highest harvest index compared to the other cultivars (Figure 3.8). NS5511 had the second highest harvest index at Syferkuil compared to Avenger and Titan during the 2018/19 cropping season, but the HI were similar in the other seasons and locations.

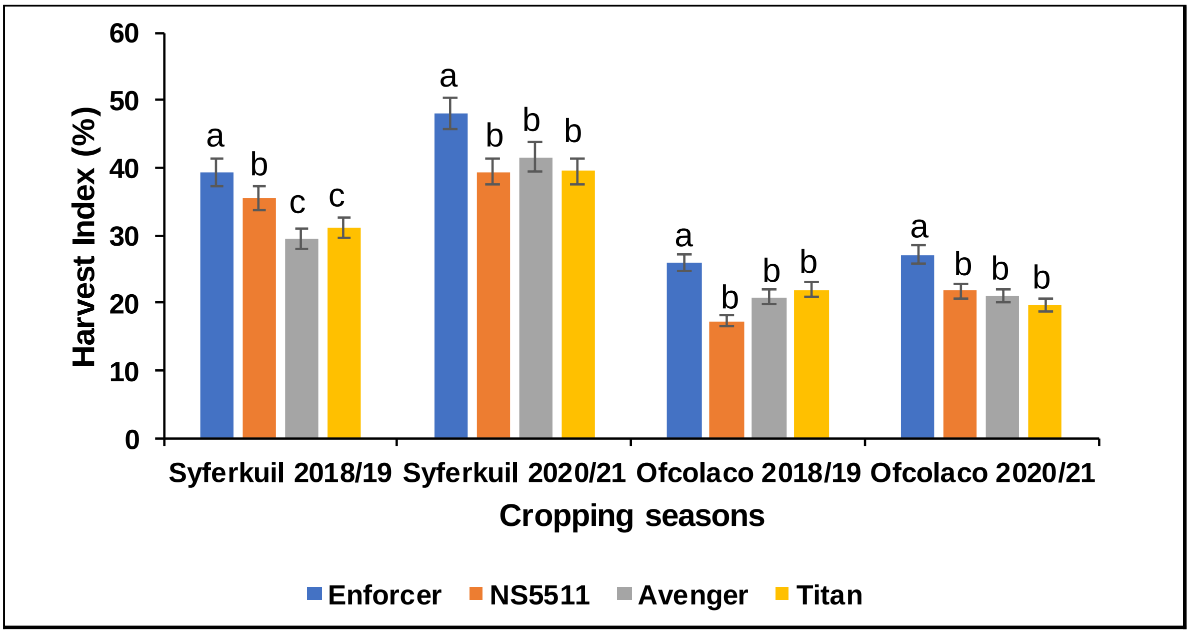

Figure 3.8 Harvest index of four grain sorghum cultivars at the two agro-ecological regions across different cropping seasons.

Regarding grain sorghum yield components, a significant variation (p ≤ 0.05) was observed among the grain sorghum cultivars at Syferkuil during the two cropping seasons except for 1000 seed weight and seed weight per head, which did not differ during the 2020/21 cropping season (Table 3.2). The cultivar Enforcer was generally superior in most of the yield components compared to the other cultivars during the 2018/19 cropping season at this location, except for shelled head weight. The cultivar NS5511 had a relatively higher 1000-seed weight and seed weight per head compared to Avenger and Titan. The cultivar Avenger had a lower seed weight per head and harvest index compared to the cultivar Titan, regardless of having a longer head length, shelled head weight, and head weight compared to the other cultivars in the 2018/19 cropping season. In the 2020/21 cropping season, all the cultivars had a high head length and harvest index compared to cultivar NS5511 (Table 3.2). The results further revealed that cultivar Avenger produced fewer seeds per head compared to all other cultivars but had a relatively higher head length and shelled head weight. The mean head length and shelled head weight were 29.09 cm and 18.82 g, respectively.

Table 3.2 Yield components of four grain sorghum cultivars evaluated at Syferkuil during 2018/19 and 2020/21 cropping season.

			Syferkuil 2018/19		
Cultivars	Head length (cm)	Head weight (g head^{-1})	Shelled head weight (g head^{-1})	1000-seed weight (g)	Seed weight head (g head^{-1})
Enforcer	27.54^{a}	109.13^{a}	47.01^{ab}	28.17^{a}	61.21^{a}
NS5511	25.07^{b}	92.39^{b}	43.06^{ab}	23.88^{b}	49.03^{b}
Avenger	26.08^{ab}	77.19^{bc}	49.65^{a}	21.76^{c}	27.49^{c}
Titan	25.34^{b}	71.76^{c}	39.93^{b}	27.82^{a}	31.80^{c}
Grand mean	26	87.62	44.91	25.41	42.38
LSD (0.05)	1.79	16.09	8.93	1.51	156.3
			Syferkuil 2020/21		
Enforcer	28.59^{a}	108.97^{ab}	14.47^{b}	39.41	90.13
NS5511	26.54^{b}	112.15^{a}	16.55^{ab}	43.02	90.83
Avenger	29.09^{a}	98.35^{b}	18.82^{a}	38.61	82.39
Titan	28.67^{a}	99.31^{b}	17.45^{a}	41.03	81.95
Grand mean	28.22	104.7	16.82	40.52	86.33
LSD (0.05)	1.22	11.6	2.93	ns	ns

Means followed by the same letter are not significantly different based on LSD ($p \leq 0.05$).

At Ofcolaco, the results indicated that all yield components significantly differed among the grain sorghum cultivars during the two cropping seasons, except head length, which did not vary in 2020/21 (Table 3.3). The cultivar Avenger was superior in many of the yield components measured compared to all other cultivars except 1000 seed weight and harvest index during the 2018/19 cropping season. Furthermore, the seed weight per head of Avenger and NS5511 (48.15 g head^{-1} and 40.10 g head^{-1}) was higher than the grand mean of 30.47 g head^{-1}. However, the two cultivars (Avenger and NS5511) had lower HI compared to the grand mean. The results further indicated that Enforcer and Titan obtained a higher average HI of 23.94% compared to Avenger and NS5511, with an average of 19.13%. However, the two cultivars (Avenger and NS5511) obtained about 63.79% more seed weight head^{-1} compared to Enforcer and

Titan. In the 2020/21 cropping season, the results showed that although there was no statistical variation among the cultivars, the cultivar Avenger had the tendency to produce a higher head length. Although there was no statistically significant difference between cultivars Avenger and NS5511, Avenger had higher head weight and seed weight per head. The cultivar (Avenger) also had a high shelled head weight of 14.26 g head^{-1} and a higher 1000 seed weight of 6.29 g compared to all the other cultivars.

Table 3.3 Yield components of four grain sorghum cultivars evaluated at Ofcolaco during 2018/19 and 2020/21 cropping season.

Cultivars	Head length (cm)	Head weight (g head^{-1})	Shelled head weight (g head^{-1})	1000-seed weight (g)	Seed weight head (g head^{-1})
			Ofcolaco 2018/19		
Enforcer	25.61^{ab}	28.33^{c}	7.43^{b}	35.69^{c}	17.71^{b}
NS5511	21.91^{b}	50.04^{b}	6.68^{b}	45.76^{a}	40.10^{a}
Avenger	30.95^{a}	70.03^{a}	12.91^{a}	43.59^{ab}	48.15^{a}
Titan	29.59^{a}	24.69^{c}	8.08^{b}	39.98^{bc}	15.91^{b}
Grand mean	27.02	43.27	8.78	41.26	30.47
LSD (0.05)	8.81	11.99	2.23	5.68	9.82
			Ofcolaco 2020/21		
Enforcer	30.1	28.37^{b}	7.40^{b}	4.09^{b}	24.29^{b}
NS5511	30.34	40.36^{a}	9.87^{b}	4.55^{b}	35.80^{a}
Avenger	30.98	44.53^{a}	14.26^{a}	6.29^{a}	38.24^{a}
Titan	30.91	32.37^{b}	9.88^{b}	4.47^{b}	27.91^{b}
Grand mean	30.58	36.41	10.35	4.85	30.81
LSD (0.05)	2.02	7.63	1.31	30.2	6.62

Means followed by the same letter are not significantly different based on LSD ($p \leq 0.05$).

During the 2018/19 cropping season, cowpea grain yield was 63 percent higher under high density versus low density at Syferkuil (Figure 3.9). However, grain yield was 32% higher under high density compared to low density in the 2020/21 cropping season.

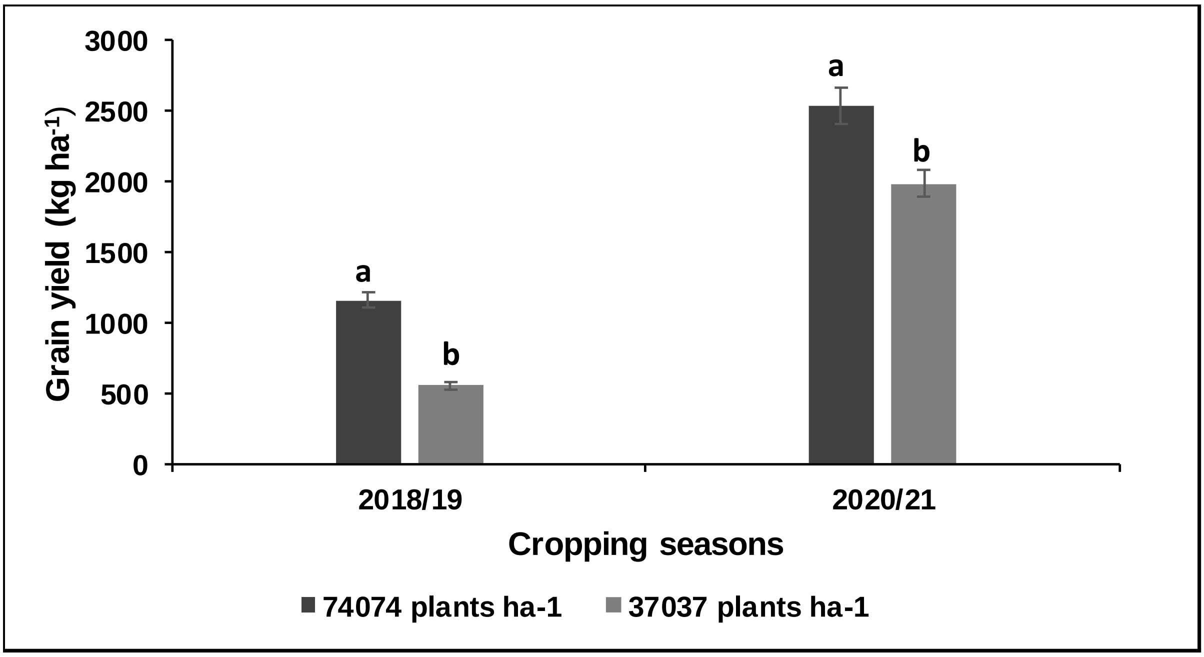

Figure 3.9 Grain yield of cowpea under two densities of cowpea grown at Syferkuil during contrasting seasons. Different letters indicate that the means were different at P ≤ 0.05.

In sole compared to binary culture, cowpea produced a higher grain yield in sole with a mean of 1534 kg ha^{-1} and 992 kg ha^{-1} in high and low density, respectively, during the 2018/19 cropping season (Figure 3.10). Although in binary cultures there was no statistical difference between treatments, the grain yield of cowpea was higher when intercropped with Titan, followed by NS5511, with a grain yield of 852 kg ha^{-1} and 718 kg ha^{-1} respectively. In the 2020/21 cropping season, grain yield was significantly affected by the cropping system. Similar to the 2018/19 cropping season, the results indicated that cowpea attained a higher grain yield when grown in sole compared to binary culture, with a mean of 5045 kg ha^{-1} in high density sole and 3411 kg ha^{-1} in low density sole (Figure 3.10).

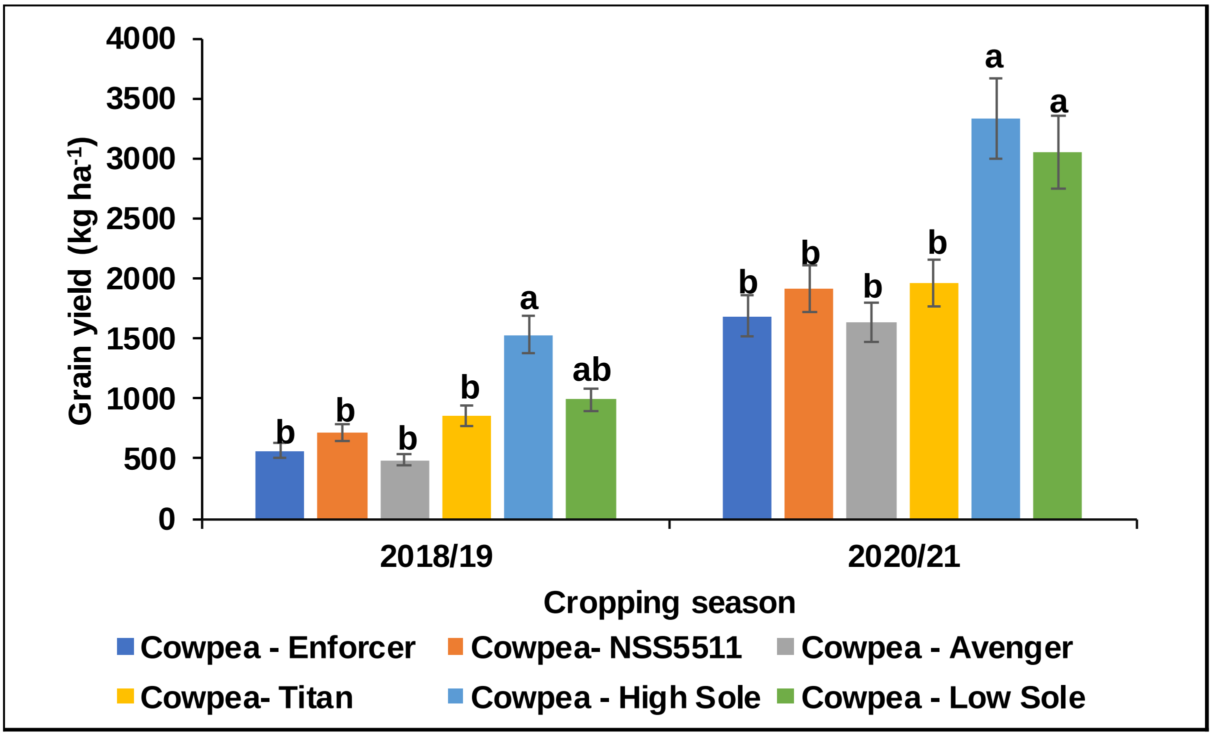

Figure 3.10 Grain yield of cowpea under in binary and sole cultures grown at Syferkuil during two contrasting seasons. Different letters indicate that the means were different at P ≤ 0.05

Grain yield among cowpea treatments was higher under high cowpea density compared to lower density with the means of 3175 kg ha^{-1} and 1233 kg ha^{-1} respectively at Ofcolaco during the 2018/19 cropping season (Figure 3.11).

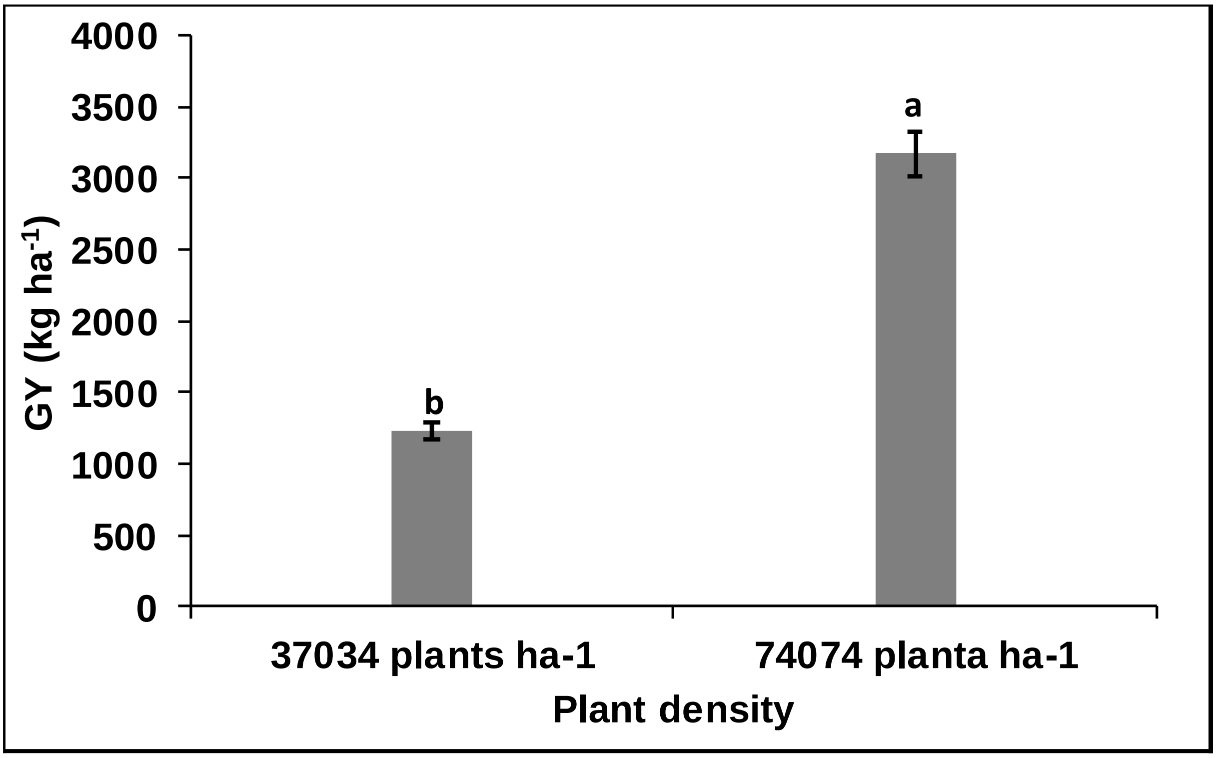

Figure 3.11 Grain yield of cowpea under two densities of cowpea grown at Ofcolaco during the 2018/19 cropping season. Different letters indicate that the means were different at $P \leq 0.05$.

The results from Ofcolaco revealed that, in binary cultures, cowpea attained the highest yield of 1701 kg ha^{-1} when intercropped with Avenger followed by intercrop with Titan which produced 1508 kg ha^{-1} (Figure 3.12). Although intercrop with Enforcer attained the lowest grain yield compared to all treatments in binary and sole cultures, there was a higher harvest index obtained by the same treatment compared to binary cultures.

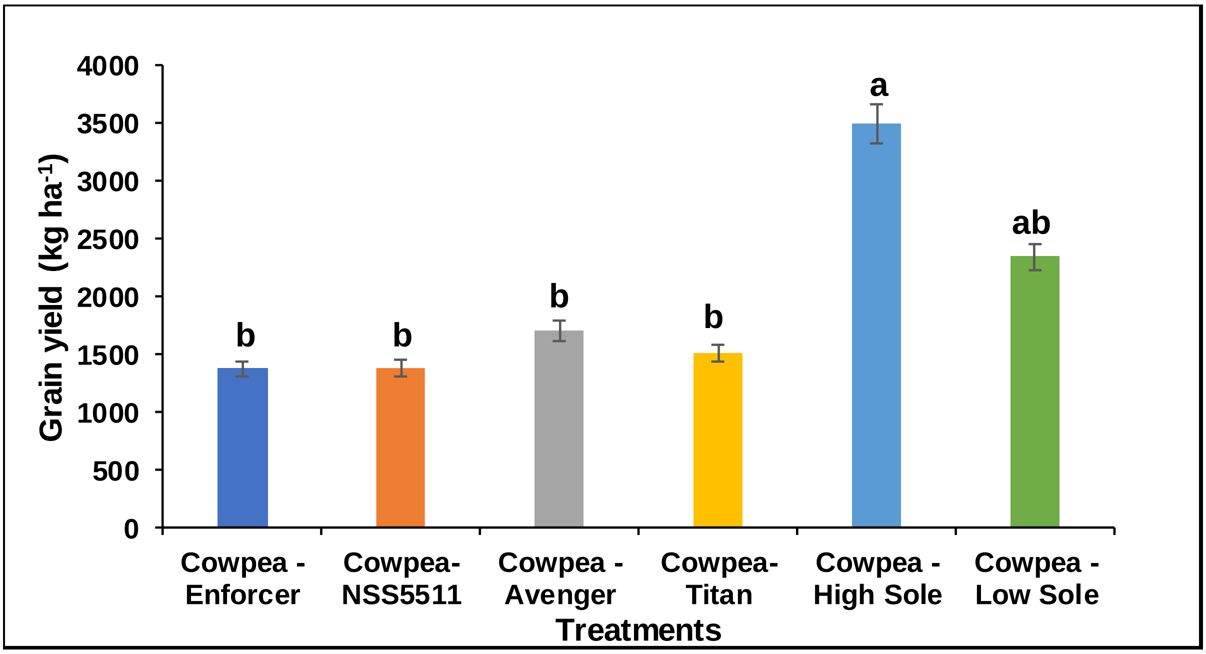

Figure 3.12 Grain yield of cowpea under in binary and sole cultures grown at Ofcolaco during 2018/19 cropping season. Different letters indicate that the means were different at $P \leq 0.05$.

There was no significant variation ($p \leq 0.05$) in the cowpea harvest index according to the cropping system at Syferkuil and Ofcolaco during the two cropping seasons. Sole cowpea under high density had a higher harvest index compared to the other cowpea treatments during the 2018/19 and 2020/21 cropping seasons at the two locations (Figure 3.13). The cowpea intercrop with Avenger had the lowest harvest index during the 2018/19 cropping season at Syferkuil. Furthermore, cowpea intercrop with Enforcer and Titan had a higher harvest index compared to sole cowpea in low density culture during the same season. At Ofcolaco and Syferkuil during the 2018/19 and 2020/21 cropping seasons, respectively, binary cultures were not statistically different (Figure 3.13).

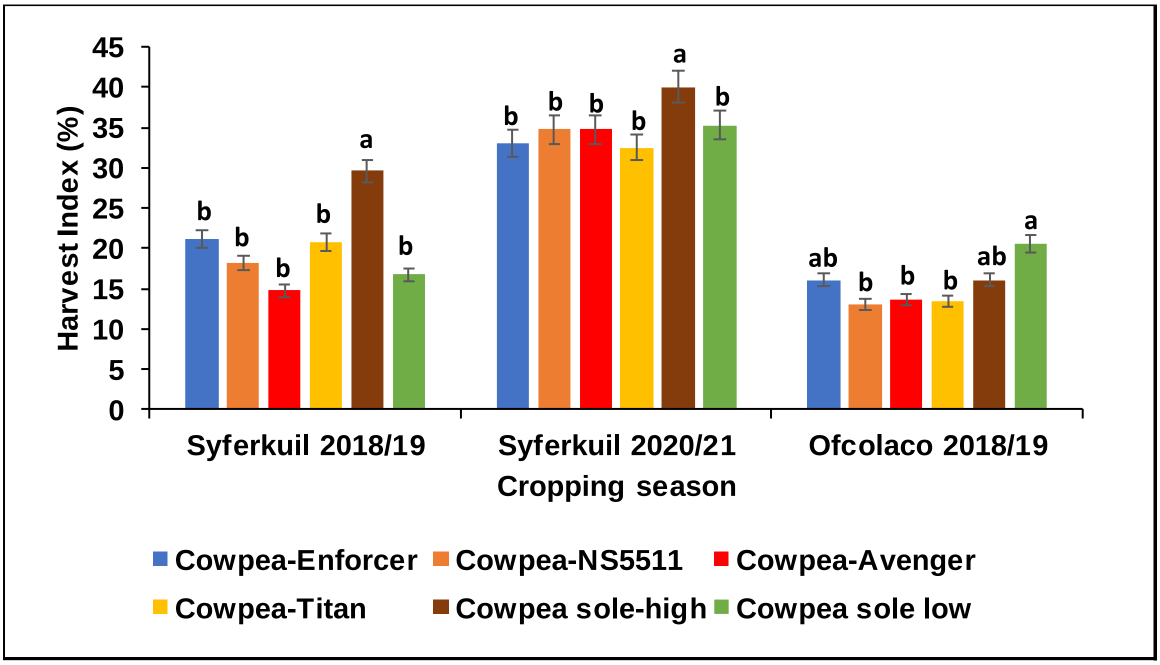

Figure 3.13 Harvest index of cowpea in binary and sole cultures at Syferkuil and Ofcolaco during 2018/19 and 2020/21 cropping seasons.

Assessing the yield components, the weight of 100 seeds was not significantly different between binary and sole cultures of cowpea at Syferkuil during the 2018/19 cropping season. However, significant variation ($p \leq 0.05$) was found for this yield component in the 2020/21 cropping season. Pod weight per plot was influenced by the cropping system in both seasons at this location (Table 3.4). The weight of 100 seeds was not significantly affected by the cropping system at Ofcolaco among cowpea treatments in binary and sole cultures during the 2018/19 cropping season. However, pod weight per plot was significantly ($p \leq 0.05$) affected by the intercropping system for cowpea treatments. The cowpea sole under high density resulted in a high pod weight per plot compared to all other treatments (Table 3.4).

Table 3.4 Yield components of cowpea in binary and sole cultures evaluated at Syferkuil and Ofcolaco during the 2018/19 and 2020/21 cropping season.

	Syferkuil 2018/19		Syferkuil 2020/21		Ofcolaco 2018/19	
Treatments	100-seed weight	pod weight per plot	100-seed weight	pod weight per plot	100-seed weight	pod weight per plot
Cowpea - Enforcer	16.17	139.73^{c}	15.54^{b}	336.56^{b}	14.71	364.10^{b}
Cowpea - NSS5511	16.24	167.23^{c}	14.51^{c}	384.06^{b}	14.68	355.97^{b}
Cowpea - Avenger	16.17	114.72^{c}	14.65^{c}	321.87^{b}	14.29	440.97^{b}
Cowpea - Titan	16.78	199.10^{bc}	15.53^{b}	383.44^{b}	14.88	307.22^{b}
Cowpea - High Sole	16.22	325.51^{a}	15.54^{b}	681.02^{a}	14.96	778.94^{a}
Cowpea - Low Sole	16.39	285.19^{ab}	16.61^{a}	398.36^{b}	14.74	715.51^{a}
Grand mean	16.33	205.25	15.39	417.55	14.71	493.79
LSD (0.05)	0.86	79.31	0.69	99.31	ns	170.16

Means followed by the same letter are not significantly different based on LSD ($p \leq 0.05$).

3.1.3.3 Partial and total land equivalent ratio (LER) of sorghum and cowpea

The partial land equivalent ratio of cowpea ranged from 0.4 to 0.7 at Syferkuil during the 2018/19 and 2020/21 cropping seasons, respectively (Table 3.5). The partial of grain sorghum at Syferkuil was between 0.7 and 1.3 in the 2018/19 and 2020/21 cropping seasons. At Ofcolaco, the partial land equivalent ratio was between 0.4 and 0.6 for cowpea and 0.8-1.4 for grain sorghum in the 2018/19 and 2020/21 cropping seasons. The total LER was above 1.0 in all grain sorghum and cowpea intercrop treatments. At Syferkuil, Enforcer had a higher LER when intercropped with low cowpea density compared to high cowpea density, with a mean of 1.8 and 1.3, respectively, during the 2018/19 season. The Avenger had a total LER of 1.6 and 1.7 under low and high density, respectively. However, Titan obtained 1.5 and 1.6 total LER in low and high density, respectively. The results also indicated that Avenger and NS5511 intercropped with cowpea high density had a total LER of 1.7, whereas NS5511 and Titan intercropped with low density had a total LER of 1.6 in the 2018/19 cropping season. In the 2020/21 cropping season, Titan intercrop with cowpea under low and high density had a total LER of 1.8 and 1.9, respectively. Enforcer intercrop with cowpea low density had the lowest total LER of 1.3 compared to all treatments.

At Ofcolaco, total LER ranged from 1.4 to 1.9, with the highest observed in NS5511 intercrop with cowpea high density (Table 3.5).

Table 3.5 Total land equivalent ratio of grain sorghum and cowpea at Syferkuil and Ofcolaco during 2018/19 and 2020/21 cropping seasons.

Treatments	Syferkuil 2018/19	Syferkuil 2020/21	Ofcolaco 2018/19
Enforcer+Cowpea-low	1.7	1.3	1.7
Enforcer+Cowpea-high	1.3	1.4	1.2
NSS5511+Cowpea-low	1.5	1.6	1.9
NSS5511+Cowpea-high	1.7	1.6	1.3
Avenger+Cowpea-low	1.6	1.5	1.6
Avenger+Cowpea-high	1.7	1.7	1.5
Titan+Cowpea-low	1.6	1.8	1.5
Titan+Cowpea-high	1.5	1.8	1.6

Low = 37037 p ha^{-1}, High = 74074 p ha^{-1}

3.1.3.3 Leaf area index of sorghum and cowpea in binary and sole cultures

At Syferkuil, the leaf area index (LAI) was significantly different ($p \leq 0.05$) among grain sorghum cultivars at Syferkuil during the 2018/19 and 2020/21 cropping seasons (Figure 3.14). NS5511 had a higher LAI compared to the other sorghum cultivars followed by Enforcer during the 2018/19 cropping season. However, Enforcer was superior compared to the other cultivars in the 2020/21 growing season.

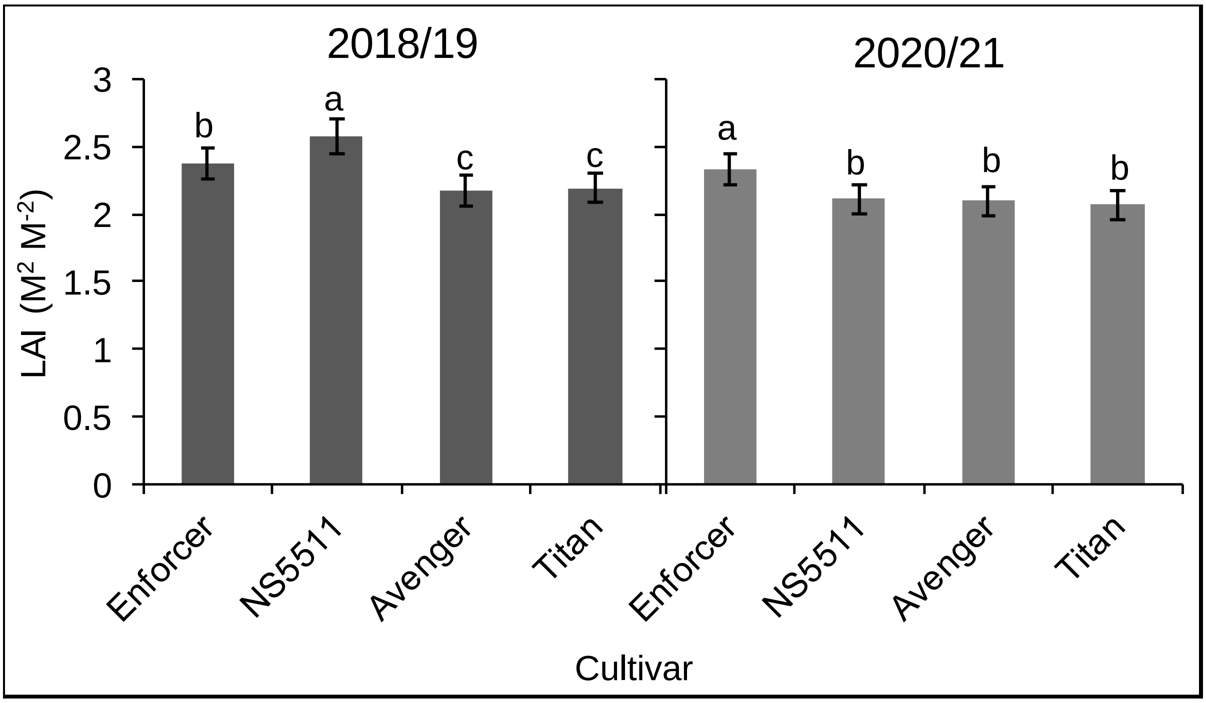

Figure 3.14 Leaf area index of four grain sorghum cultivars evaluated at Syferkuil during 2018/19 and 2020/21 cropping seasons.

There was no variation among grain sorghum cultivars for LAI at Ofcolaco during the 2018/19 cropping season. However, in 2020/21 there was a significant variation in LAI among the cultivars (Figure 3.15). The results revealed that NS5511 and Avenger were higher than Enforcer and Titan during the 2020/21 cropping season.

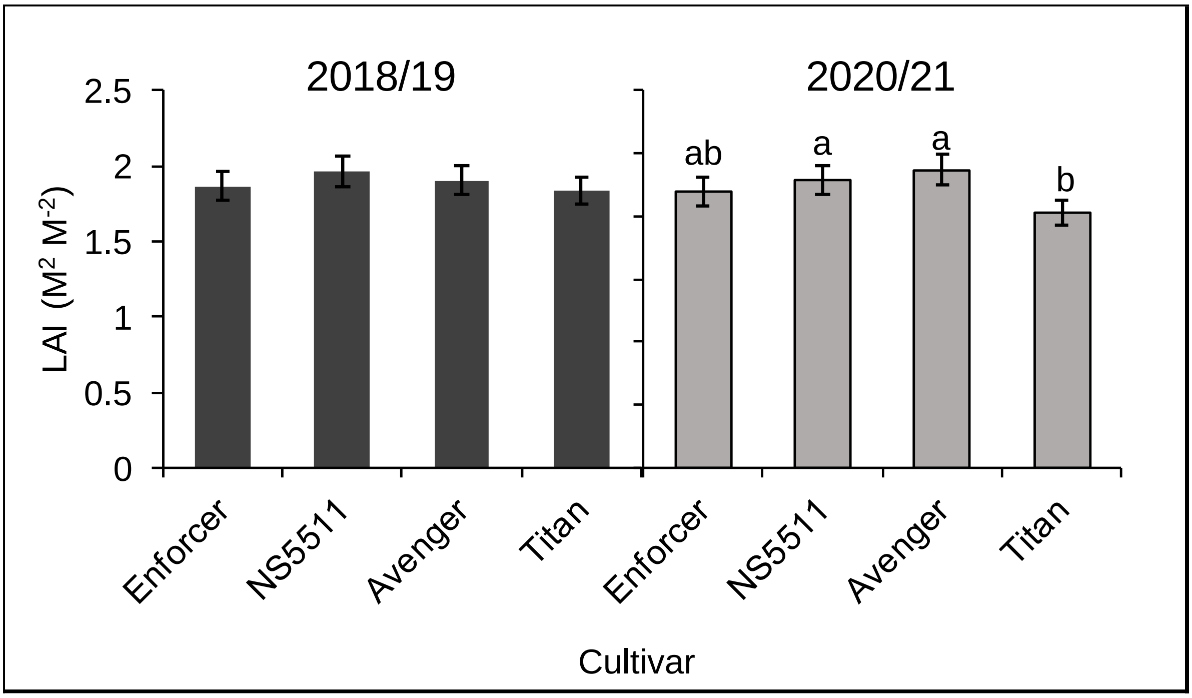

Figure 3.15 Leaf area index of four grain sorghum cultivars at Ofcolaco during 2018/19 and 2020/21 cropping seasons.

There was a significant interaction effect between the cropping system and sampling day of cowpea at Syferkuil during the 2018/19 and 2020/21 cropping seasons. The results indicated that, in the 2018/19 cropping season, cowpea treatments had higher LAI at 63DAP, excluding cowpea sole under high density. Cowpea sole high density started at a higher rate and remained steady until 83DAP (Figure 3.16). During the 2020-21 cropping season, cowpea treatments started at a low rate and increased until 67DAP, then decreased until 104DAP (Figure 3.16).

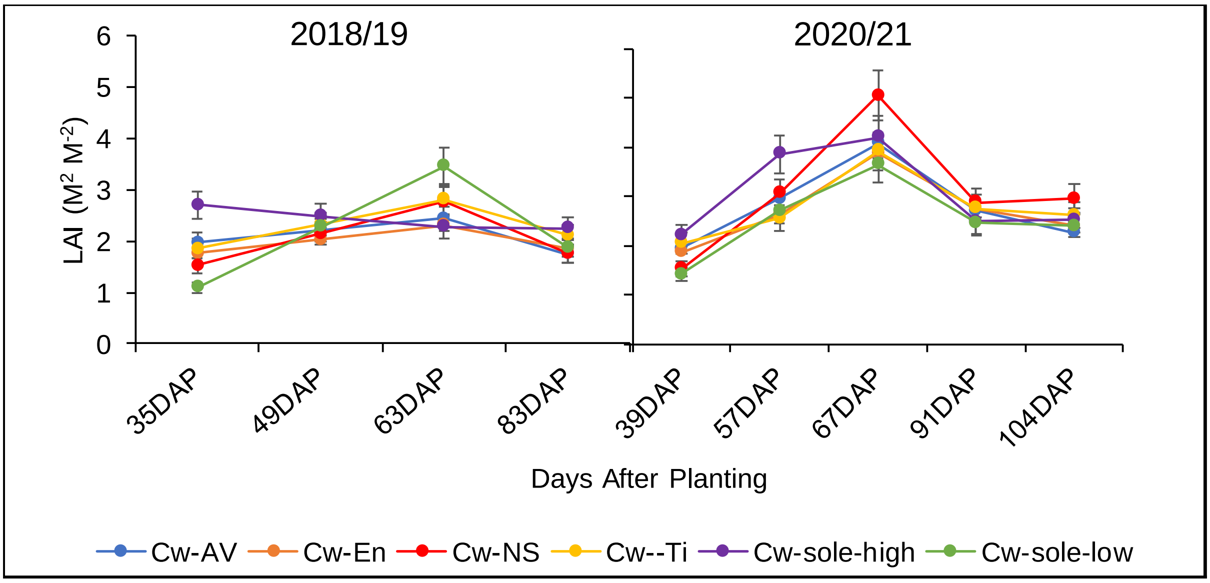

Figure 3.16 Leaf area index of cowpea treatments in binary and sole cultures at Syferkuil during 2018/19 and 2020/21 cropping seasons.

The results from Ofcolaco were similar to that of Syferkuil, with significant interaction occurring between the cropping system and sampling day during the two cropping seasons. Cowpea treatments had a similar trend during the 2018/19 growing season, with the highest LAI between 49DAP and 83DAP (Figure 3.17). However, in the 2020–21 cropping season, cowpea treatments had fluctuating LAI across the sampling day.

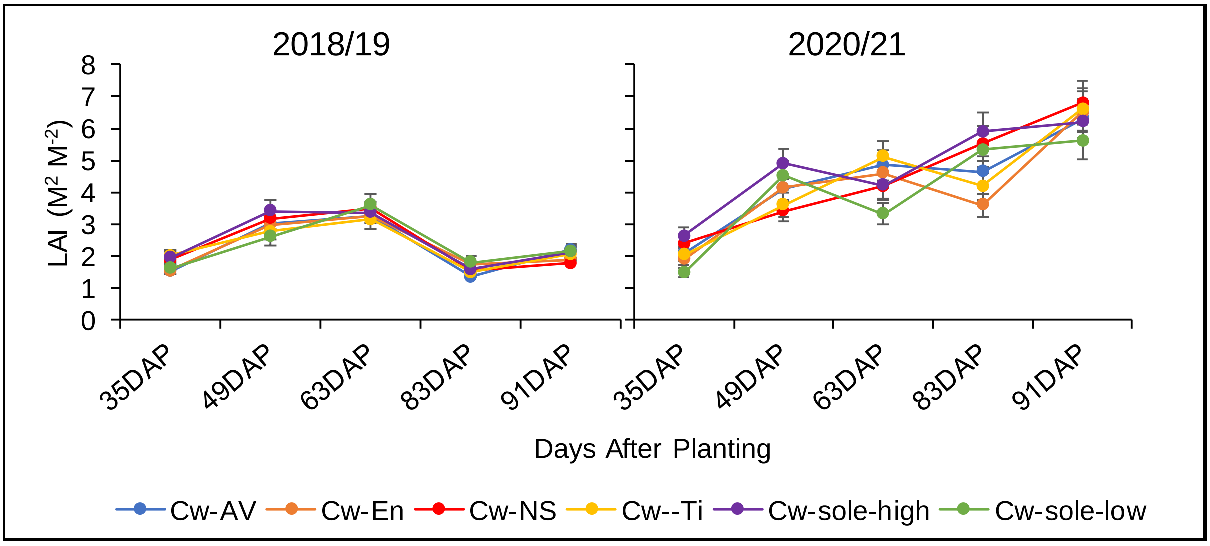

Figure 3.17 Leaf area index of cowpea treatments in binary and sole cultures at Ofcolaco during 2018/19 and 2020/21 cropping seasons.

3.1.4 Discussion

The variation in temperatures and rainfall received during the cropping seasons influenced the agronomic performance of grain sorghum cultivars at the two locations.

Ofcolaco was generally warmer than Syferkuil during the 2018/19 and 2020/21 cropping seasons, which may have resulted in variation in crop performance and grain yield. Other studies reported that the differences in grain yield of sorghum were due to distinct agro-ecological regions which varied across seasons (Gasura *et al*., 2015 and Assefaw, 2007). From our study, grain sorghum generally performed better in 2018/19 compared to the 2020/21 cropping seasons and vice versa for cowpea. The cropping system and the density of the companion crop cowpea did not influence the grain yield of sorghum cultivars at the two test locations across different seasons. The results were contrary to what other study observed (Somu *et al.*, 2020). The authors reported that sorghum was significantly influenced by the treatment combination in the sorghum-legume intercrop. Grain sorghum cultivars showed a significant variation in terms of grain yield due to the adaptive mechanism of the crop, which varied with cultivar, location, and season. Similar results were reported elsewhere (Ghani *et al*., 2015; Nida *et al*., 2016; Hadebe *et al*., 2017).

The density of cowpea and the cropping system significantly influenced grain yield and yield components of cowpea under the two agro-ecological regions and across the cropping seasons. The findings were in line with another study where the author reported that the yield of cowpea was highly influenced by crop density (Chimonyo *et al*., 2016). However, cowpea density did not improve in the pearl millet-cowpea intercrop (Nielson *et al*, 2018). In this study, cowpea produced a higher grain yield when grown under high density (74074 plants ha^{-1}) either in binary or sole compared to low density (37037 plants ha^{-1}). Increased density probably allowed more cowpea plants to compete for light and water in binary cultures through improved root density and, ultimately, high yield accumulation. Similar results were reported by other studies (Makoi *et al*., 2010; Moriri *et al*., 2010; Masvaya *et al*., 2017). In the sole, cowpea produced more grain yield in the sole compared to the binary culture at Syferkuil and Ofcolaco during the 2018/19 and 2020/21 cropping seasons. This is mainly due to increased canopy size (LAI), which is important for monitoring crop growth and accumulation of grain yield (Kamara *et al*., 2017).

The results also revealed that cowpea performed better at Syferkuil when intercropped with Titan compared to when intercropped with other grain sorghum cultivars. However, at Ofcolaco, cowpea yielded higher when intercropped with Avenger, although the results were based on one season of data. High interspecific competition between crops is required for the efficient utilization of growth resources (Takim, 2012). However, the efficient utilization of those resources must be greater than the interspecific competition (Zhang and Li, 2003). In this study, there was high competition for light between grain sorghum cultivars and cowpea intercrop at Syferkuil, as shown by the variation in LAI which hindered cowpea yield accumulation under low density when intercropped with Enforcer and NS5511. However, at Ofcolaco, there was complementarity between cowpea and the two grain sorghum cultivars (Avenger and Titan) in the binary system.

Yield components are important variables used to determine the yield potential of crops in response to different agro-ecological regions (Kozak and Madry, 2006). In this study, yield components varied from one location to another and across seasons. For instance, at Syferkuil, Enforcer and NS5511 obtained the highest seed weight per head compared to Avenger and Titan, ultimately resulting in a higher grain yield during the two cropping seasons. Therefore, under the growing conditions of Syferkuil, the seed weight per head can be used to recommend cultivars Enforcer and NS5511 for high grain yield production. At Ofcolaco, Enforcer and Titan were superior cultivars in 2018/19, whereas in the 2020/21 cropping season, NS5511 and Avenger obtained higher grain yields. These indicate that the adaptation of grain sorghum cultivars at Ofcolaco is highly dependent on the growing conditions of a particular season. During the two cropping seasons, NS5511 and Avenger had higher seed weight per head compared to Enforcer and Titan. Hence, head weight and seed weight per head can be used by breeders as selection criteria for the recommendation of cultivars to local growers (El-Aref *et al*., 2019). The higher grain yield of cowpea was explained by the pod weight per plot, which was consistent throughout the cropping seasons at the two test locations.

The leaf area index of a crop canopy is an important parameter that can be used to predict growth and yield (Xinyou *et al*., 2003). At Syferkuil, the leaf area index of grain sorghum was significantly affected by the cropping system as well as the cultivar. During the two cropping seasons, Enforcer and NS5511, which ultimately accumulated more grain yield, had a higher leaf area index compared to the other cultivars. At Ofcolaco, the leaf area index was significantly influenced by the growing period during

2018/19, whereas in 2020/21, the binary had more leaf area index compared to sole cultures. This further explains the variation in grain yield among grain sorghum cultivars at Ofcolaco. The leaf area index of cowpea was influenced by the cropping system, DAP, as well as cropping seasons. The LAI was higher at 40 and 63 DAP depending on the cowpea treatment. The capturing of light by canopies at late flowering to mid pod formation stages is important for optimum grain accumulation (Kamara *et al*, 2017; El-Aref *et al*, 2019).

LER was used in this study to measure the grain sorghum and cowpea intercrop efficiency relative to sole cropping. According to the results, the total LERs were found to vary with the growing seasons and treatments for grain sorghum and cowpea. However, the total LER values calculated were all greater than 1.0 in the test locations and across different seasons, indicating a high yield advantage in the binary cultures and more efficient productivity compared to the sole cultures. Several studies have reported LER values greater than 1.0 in sorghum-cowpea (Oseni, 2010), sorghum-cowpea (Gebremichael *et al*., 2019), sorghum-soybean (Musa *et al*., 2021) and maize-cowpea (Dahmardeh *et al*., 2010). The results further indicated that the LER was influenced by the density of cowpea as well as the grain sorghum cultivar in intercrop at each experimental site. LER variation due to mixture in various planting patterns was also reported elsewhere (Yesuf, 2003; Yu *et al*., 2015; Nelson *et al*., 2018). The high LER observed in this study was due to the efficient utilization of resources such as light, water, and nitrogen between grain sorghum cultivars and cowpea (Reddy, 2000). The goal of growers, as well as breeders, is a high grain yield, which depends on other yield variables. Hence, the relationship between yield and yield components is important, whether it be positive or negative. According to the results, the strength of the correlation between grain yield and yield components varied with cultivar, intercropping system, and cropping season as well as the agro-ecological region.

3.1.5 Conclusion

In conclusion, grain sorghum cultivars were not affected by either the cropping system or the density of a companion crop cowpea. Enforcer and NS5511 produced higher grain yield at the two test locations compared to Avenger and Titan. The productivity of cowpea was influenced by the cropping system as well as the crop density. Cowpea performed better in terms of grain yield in sole compared to binary cultures. However, the yield of cowpea improved in binary cultures when the density was 74074 planta ha^{-1}. The Head weight of sorghum and pod weight of cowpea can be used as selection criteria for a recommendation of cultivars to grow at Syferkuil and Ofcolaco. Based on the results of this study grain sorghum–cowpea intercrop can be adopted as a climate-smart practice to improve yield compared to mono-cropping. However, the density of cowpea and grain sorghum cultivars should be taken into consideration as they affect the productivity of the two crops. The data generated from this study could be useful in simulating the productivity of intercropping practice as a climate-smart method using crop modeling techniques.

3.2 PHYSIOLOGICAL RESPONSES AND GROWTH OF NO-TILL GRAIN SORGHUM IN SOLE AND BINARY CULTURES WITH COWPEA IN TWO DISTINCT AGRO-ECOLOGICAL ZONES

Abstract

Intercropping is one of the ancient cropping systems that has been identified as a climate-smart strategy to enhance crop physiological processes, resource use efficiency and growth under marginal growth environments. A no-till field experiment was laid out in a randomised complete block design (RCBD) with four replications in two distinct agro-ecological zones, Syferkuil and Ofcolaco to assess leaf gaseous exchange and its impact on biomass accumulation of binary and sole grain sorghum cultivars. Crop height and stem diameter data were collected from the vegetative stage until physiological maturity. Transpiration efficiency was also calculated using the final biomass and evapotranspiration of the growing season. The results revealed that 2018/19 was a better season for leaf gaseous parameters and biomass accumulation compared to the 2020/21 cropping season. Furthermore, Ofcolaco had a better conversion of photosynthates to biomass as compared to Syferkuil. The results further indicated that an increase in sub-stomatal CO_2 concentration (ci) led to a decrease in photosynthetic rate (A), transpiration rate (E) and stomatal conductance (gs) which was consistent throughout agro-ecological zones and across cropping seasons. From Syferkuil's 2018/19 results, the grain sorghum cultivar with the highest biomass when intercropped with low cowpea density was Enfocer, with a mean of 6022 kg ha^{-1}. This was followed by NS5511 with a biomass yield of over 5500 kg ha^{-1} in binary and sole cultures. Titan, intercropped with low cowpea density produced the lowest biomass yield compared to all other treatments. During the 2018/19 cropping season at Ofcolaco, sole Titan accumulated the highest biomass followed by NS5511 and Titan intercropped with cowpea at a low density. The biomass yields were 10013.00 kg ha^{-1}, 9558 kg ha^{-1} and 9170 kg ha^{-1}, respectively. NS5511 accumulated the lowest biomass of 5630 kg ha^{-1} when intercropped with a higher cowpea density of 74074 plants ha^{-1} compared to when intercropped with a low cowpea density of 37037 plants ha^{-1} and sole culture. Higher biomass at Ofcolaco was due to a higher photosynthetic rate as well as warm temperatures experienced by grain sorghum during the growth period. From the data generated, photosynthetic activities of grain sorghum play a huge role in biomass accumulation. In addition, leaf gaseous exchange was improved

in the binary culture compared to the sole, depending on environmental conditions as well as the cultivar grown. Therefore, the findings of the study revealed that intercropping systems can be adopted as a climate mitigation and adaptation strategy for improved grain sorghum growth and development.

Key words: climate change; intercropping; leaf gaseous exchange; biomass

3.2.1 Introduction

Intercropping is a highly productive farming practice defined as the concurrent cultivation of two or more crops on the same piece of land (Hu *et al*., 2017). The practice is adopted in many regions across the globe due to its efficient use of resources such as land, water, nutrients, and light (Zhang and Li 2003; Ning *et al*., 2017). Mao *et al*., (2015) reported that cereal-legume intercropping optimizes the utilization of resources in areas where they are limited. Several studies have reported improved photosynthetic activities in binary compared to sole cultures, which ultimately led to higher biomass accumulation and grain yield (Huang *et al*., 2015; Zhang *et al*., 2012; Yin *et al*., 2016; Hu *et al*., 2016; Wang *et al*., 2015). Plant physiological characteristics, including photosynthesis, are the basis of crop growth and development and influence crop productivity (Jiao *et al*., 2017). Establishing the photosynthetic response of crops is therefore important in intercropping systems for sustainable crop production, especially in dry areas such as the Limpopo Province of South Africa.

Grain sorghum is among the most consumed staple cereal crops in Limpopo Province. Farmers in the province have a challenge of poor soil fertility, which affects soil moisture that is required for optimum growth. Adoption of intercropping under a no-till system can improve soil physical and biological properties (Machado *et al*., 2003; Scalise *et al*. 2017). Improvements in soil conditions because of intercropping and no-till systems will result in better physiological responses compared to sole cropping, especially in dry areas of Limpopo Province where farmers depend on rainfall (Filho, 2000). Intercropping increases water retention through increased root density and arrangements of different crop species. Furthermore, full canopy cover by crops results in reduced soil evaporation (Ofori *et al*., 2014). Chimonyo *et al*., (2016b) and

Zougmore *et al*., (2000) reported that grain sorghum intercrop has the potential to reduce runoff by about 30% and improve field water management, especially in rainfed areas. In addition, the water captured in an intercropping system is exchanged through photosynthetic activities, which is helpful in biomass production.

According to Makoi *et al*. (2010), when grain sorghum is intercropped with high-density cowpea, photosynthetic activities such as stomatal conductance and photosynthetic rate are significantly impacted. Extensive information on leaf gaseous exchange, transpiration efficiency, as well as their effects on biomass accumulation and grain yield under grain sorghum intercrop is required for better crop growth management. The ability of grain sorghum or cowpea to utilize resources efficiently for biomass accumulation depends on photosynthetic capacity per unit leaf area in a cropping system (Lambers *et al*., 2008). To understand aspects of crop growth and productivity, it is important to have a clear knowledge of how gases and water are exchanged in an intercropping system. Understanding these parameters in an intercrop system, especially in dry areas is important to monitor the productivity of grain sorghum/cowpea intercrop as well as efficient utilization of resources. The study was conducted to assess the physiological responses and biomass accumulation of grain sorghum cultivars in sole and intercropping systems.

3.2.2 Materials and methods

The study sites, soil sampling, experimental set-up and management, are the same as described in section 3.1.2. in chapter 3.

3.2.2.1 Data collection

Field data was collected from two weeks after emergence per experimental unit and continued every two weeks until physiological maturity. Data was collected on the middle rows of binary and sole cultures of grain sorghum. Sub-stomatal CO_2 concentration (ci), photosynthetic rate (A), stomatal conductance (gs) and transpiration rate (E) were measured using the LCi-SD Ultra-compact photosynthesis machine (ADC BioScientific Ltd, United Kingdom) between 09H00 am and 12H00 pm on fully developed fresh binary and sole grain sorghum leaves. Aboveground biomass was collected from 2 plants at vegetative, flowering and physiological maturity. At harvesting, 10 plants were sampled from two middle rows at an area of 2.7 m^2 to determine the final aboveground biomass. Biomass was taken to the laboratory and oven-dried at 65 ^{o}C for 48 hours and weighed to determine dry biomass.

3.2.2.2 Statistical analysis

After checking the relevant model assumptions including normality, independence and constant variance, a multivariate analysis of variance (ANOVA) model was used to fit each response variable using the Statistical Analysis System (21 SAS version 9.4). Mean separation was done where the means were different using the least significant difference (LSD) at probability levels of $p \leq 0.05$. The linear regression was used to determine the relationship between biomass and growth stages.

3.2.3 Results

3.2.3.1 Weather conditions during the growing season

The details of the weather conditions during the growing season are similar to those presented in chapter 3 section 3.1.

3.2.3.2 Mean square of leaf gaseous parameters during 2018/19 and 2020/21 cropping seasons at Syferkuil.

There was a highly significant variation in A, E and gs among the grain sorghum cultivars at Syferkuil during the 2018/19 cropping season (Table 3.6). However, ci was not different among grain sorghum cultivars. The results further revealed that the cropping system did not have a significant effect on the physiological response of grain sorghum cultivars. In contrast, A, E,gs and ci were highly significant across the sampling day. For A and E, there was no significant interaction between cultivars and cropping systems. However, for gs and ci, there was a significant interaction between cultivars and cropping systems. Furthermore, there was no significant interaction between system and sampling day as well as cultivar, system, and sampling day for grain sorghum evaluated at Syferkuil during the 2018/19 cropping season. The results from the 2020/21 cropping season indicated that grain sorghum cultivars did not affect the variables A, E and gs at Syferkuil but significantly influenced ci (Table 3.6). The results also indicated that E, gs and ci were not affected by the cropping system, but A was. The interaction effect of cultivars and cropping systems was not significant on the variables measured except ci. However, a significant interaction effect of cultivars and data collection day on the physiological variables was significant. The interaction effect of the three variables, cultivar, cropping system, and sampling day was also significant on the physiological variables, with the exception of E and gs.

Table 3.6 Means squares of physiological traits of grain sorghum cultivars at Syferkuil during 2018/19 and 2020/21 cropping season.

Source	DF	A ($\mu molm^{-2}\ s^{-1}$)	E ($mmolm^{-2}\ s^{-1}$)	gs ($molm^{-2}\ s^{-1}$)	ci ($mol\ m^{-2}\ s^{-1}$)
		Syferkuil 2018/19			
Cultivar (C)	3	4810.38***	76.52***	1.14**	15816.91^{ns}
System (S)	1	122.43^{ns}	2.64^{ns}	0.05^{ns}	38659.53^{ns}
Sampling Day (DAP)	6	26749.41***	544.18***	3.09***	241712.58***
Cultivar*System	3	548.45^{ns}	13.12^{ns}	0.68*	48642.29*
Cultivar*DAP	18	1384.72*	16.45^{ns}	0.56**	42220.55**
System*DAP	6	717.46^{ns}	16.60^{ns}	0.44^{ns}	31494.14^{ns}
Cultivar*System*DAP	18	815.93^{ns}	13.42^{ns}	0.45^{ns}	29402.76^{ns}
		Syferkuil 2020/21			
Cultivar (C)	3	12.63^{ns}	0.18^{ns}	0.0001^{ns}	15716.56***
System (S)	1	59.29**	0.75^{ns}	0.0018^{ns}	81.40^{ns}
Sampling Day (DAP)	5	670.33***	28.20***	0.07***	305669.53***
Cultivar*System	3	12.57^{ns}	0.06^{ns}	0.0009^{ns}	12458.27***
Cultivar*DAP	15	46.95***	0.74*	0.0009*	12702.02***
System*DAP	5	55.97***	0.31^{ns}	0.0005^{ns}	3229.12^{ns}
Cultivar*System*DAP	15	41.48***	0.33^{ns}	0.0004^{ns}	16007.48***

***Significant at $p \leq 0.05$; ** significant at $p < 0.01$; *** significant at $p < 0.001$; ns represent nonsignificant. A = photosynthetic rate, E = transpiration rate, gs = stomatal conductance, ci = sub-stomatal CO_2 concentration.**

3.2.3.3 Effect of sampling day on leaf gaseous exchange of grain sorghum cultivars during the 2018/19 growing period at Syferkuil.

There was significant variation among grain sorghum cultivars across sampling days on A, gs and ci at Syferkuil during the 2018/19 cropping season. Photosynthetic rate (A) among the cultivars fluctuated from 35 DAP to 119 DAP. All the cultivars started at a lower rate and reached the first peak at 49 DAP and dropped at 83 DAP (Figure 3.18). At the first peak, Titan had the highest A compared to other cultivars, and Avenger, the lowest. The second highest peak was reached at 91 DAP where Enforcer, NS5511 and were superior compared to Avenger. Stomatal conductance also showed a fluctuating trend for all cultivars (Figure 3.18). Enforcer was higher at 49 DAP compared to other cultivars. At 91 DAP all cultivars were also at a higher rate compared to the previous sampling day (83 DAP) and decreased until 119 DAP. The results revealed that the ci increased with the decrease in A and gs (Figure 3.18). For instance, at 35 DAP, 83 DAP and 105 DAP were A and gs were lower, and ci was at a higher rate for all the cultivars.

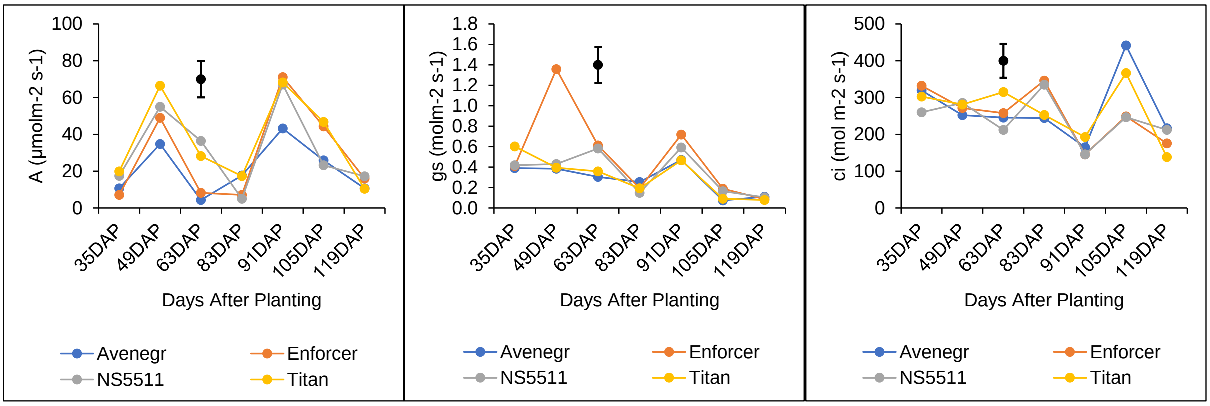

Figure 3.18 Photosynthetic rate (A), stomatal conductance (gs) and sub-stomatal CO_2 concentration (ci) of four grain sorghum cultivars during the 2018/19 growing period at Syferkuil. The error bars on each graph represent LSD at $p \leq 0.05$.

3.2.3.4 Leaf gaseous exchange variation among grain sorghum cultivars during 2018/19 cropping season.

Although the cropping system did not influence the measured physiological traits of grain sorghum, cultivar variation was observed for E, A and gs during the 2018/19 cropping season (Figure 3.19). Titan was the superior cultivar in terms of A compared to other cultivars followed by NS551 with a mean of 35.75 μmolm^{-2} s^{-1} and 31.64 μmolm^{-2} s^{-1} respectively. Avenger recorded A of 21.05 μmolm^{-2} s^{-1} in comparison to all cultivars. The results in Figure 4.19 showed that Enforcer had higher gs and E values of 0.51 molm^{-2} s^{-1} and 7.86 mmolm^{-2} s^{-1}, respectively than all other grain sorghum cultivars.

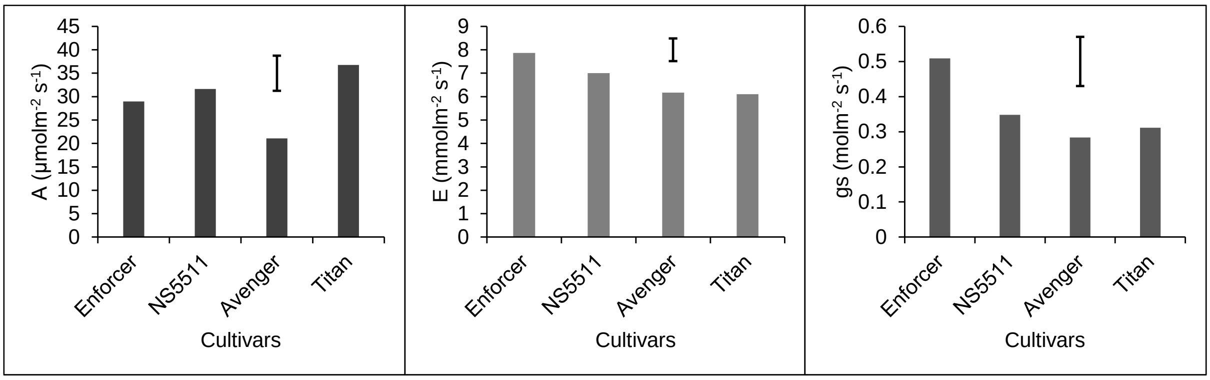

Figure 3.19 Photosynthetic rate (A), transpiration rate (E) and stomatal conductance (gs) of four grain sorghum cultivars at Syferkuil during 2018/19. The error bars on each graph represent LSD at $p \leq 0.05$.

3.2.3.5 Effect of cropping system on leaf gaseous parameters at Syferkuil during 2020/21 cropping season.

The results from the 2020/21 cropping season indicated A and ci were significantly affected by cultivar, data sampling date as well as cropping system. Grain sorghum cultivars in binary and sole cultures had similar trends at Syferkuil during the 2020/21 cropping season (Figure 3.20). In binary culture, Enforcer was superior at 35 DAP compared to other cultivars which had a fairly similar A. Cultivars dropped at 57 DAP and started to increase after until 117 DAP. At 91 DAP Avenger was superior in terms of A compared to other cultivars. In sole culture, cultivars started at a high rate (35 DAP) where Enforcer was superior and Titan was lower compared to all the cultivars. The cultivars dropped at 57 DAP and pick again at 67 DAP. Enforcer dropped at 91 DAP whereas other cultivars continued to increase. At 104 DAP Avenger and Enforcer increased until 117 DAP, however, NS5511 and Titan were decreasing. The sub-stomatal CO_2 concentration (ci) was influenced by the rate of photosynthesis (A). When A increased, ci decreased and this was consistent with cultivar, cropping system and DAP. As indicated in figure 4.20 ci in binary cultures started at a low rate at 39 DAP, reached its highest peak at 57 DAP and started to drop until 117 DAP. Titan and Avenger were superior cultivars in terms of ci at 57 DAP however, from 67 DAP until 117 DAP Enforcer and NS551 were superior cultivars. In sole cultures, Enforcer, NS5511 and Titan were higher compared to Avenger at 57 DAP. However, at 67 DAP Avenger was at its highest peak when the other cultivars decreased. At 104 DAP Avenger, Enforcer and NS5511 had equal ci which was higher than Titan.

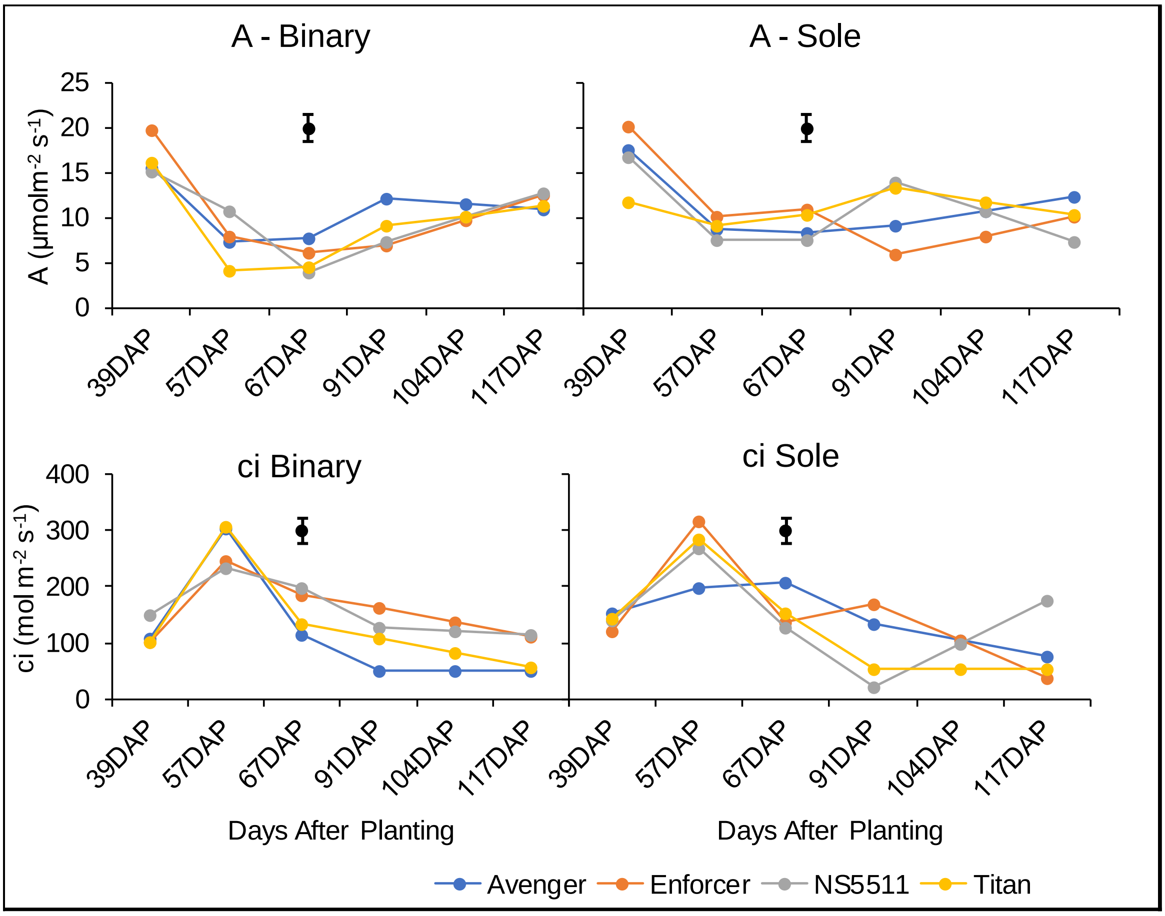

Figure 3.20 Photosynthetic rate (A) and sub-stomatal CO_2 concentration (ci) of four grain sorghum cultivars in binary and sole cultures during the 2020/21 growing period at Syferkuil. The error bars on each graph represent LSD at $p \leq 0.05$.

Transpiration rate (E) and stomatal conductance (gs) were not affected by the cropping system. However, the variation was observed among the cultivars and across DAP. The results revealed that E and gs started at higher rates and decreased from 57 DAP until 67 DAP. The cultivars peaked from 91 DAP until 117 DAP for both E and gs (Figure 3.21).

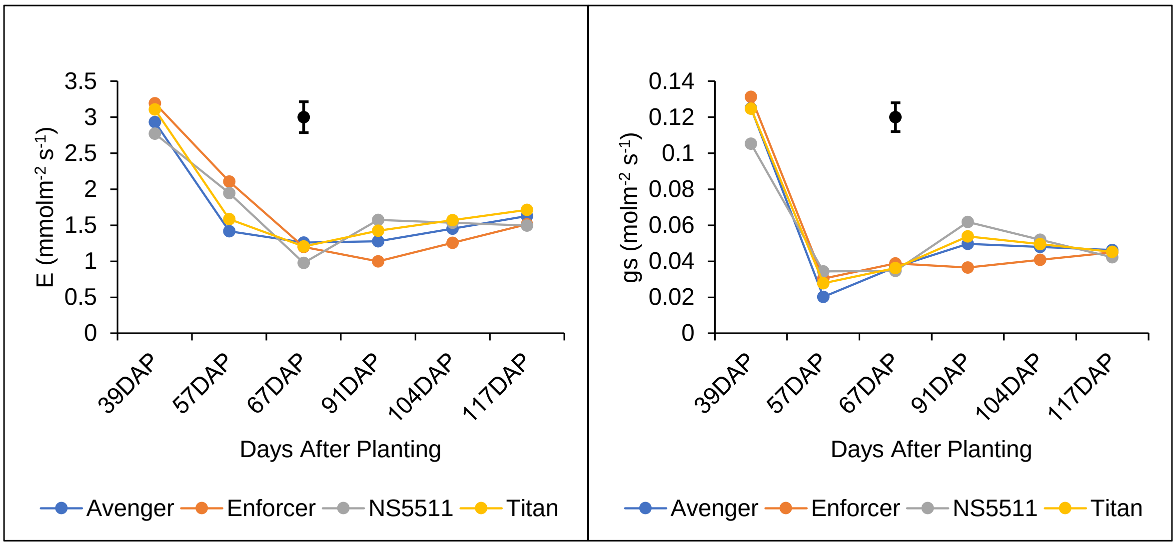

Figure 3.21 Transpiration rate (E) and stomatal conductance (gs) of grain sorghum cultivars during 2020/21 growing period at Syferkuil. The error bars on each graph represent LSD at $p \leq 0.05$

3.2.3.6 Biomass accumulation of four grain sorghum cultivars during 2018/19 and 2020/21 cropping season at Syferkuil

Biomass accumulation at Syferkuil showed an increasing trend during the two cropping seasons of 2018/19 and 2020/21. All cultivars had r^2 of 0.9 during the two cropping seasons (Figure 3.22). During the 2018/19 season, NS5511 accumulated higher biomass of 4741.10 kg ha^{-1} and 5609.20 kg ha^{-1} after flowering and harvest maturity respectively, followed by Enforcer with biomass of 3977.60 kg ha^{-1} and 5165.70 kg ha^{-1}. Avenger and Titan had lower biomass accumulation compared to Enforcer and NS551. During the 2020/21 cropping season, NS5511, Titan and Avenger had higher biomass compared to Enforcer with average means of 2479.48 kg ha^{-1}, 2297.50 kg ha^{-1}, 2208.32 kg ha^{-1} and1979.15 kg ha^{-1}.

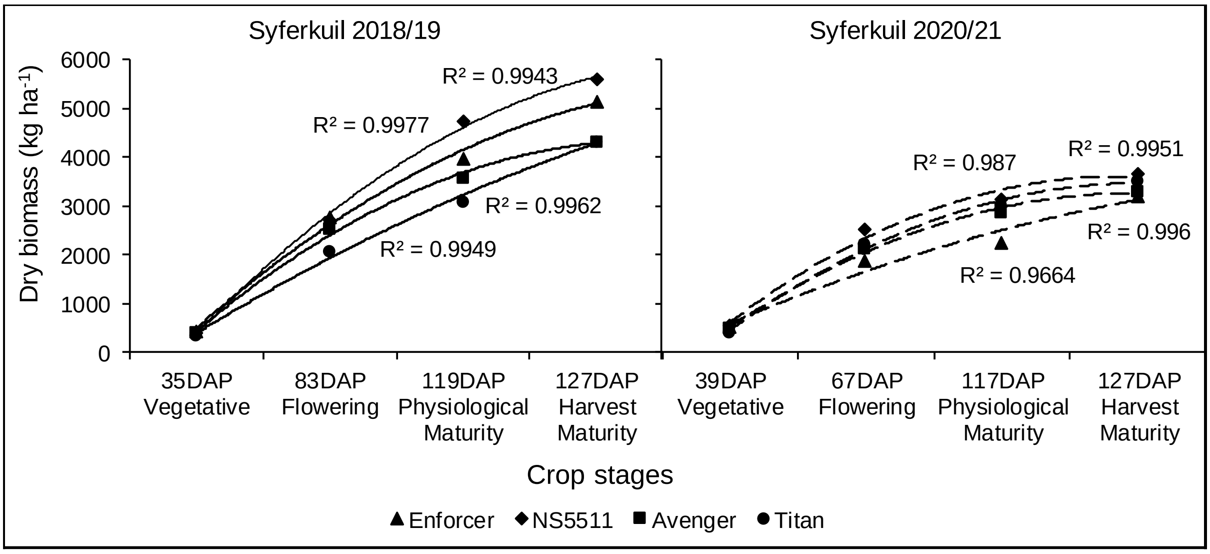

Figure 3.22 Dry biomass accumulation during the growing period of four grain sorghum cultivars at Syferkuil in the 2018/19 and 2020/21 cropping seasons.

3.2.3.7 Mean square of leaf gaseous parameters during the 2018/19 and 2020/21 cropping seasons at Ofcolaco.

At Ofcolaco E, gs and ci were not significantly different among grain sorghum cultivars during 2018/19 cropping season. The rate of photosynthesis was significantly different ($P \leq 0.001$) among grain sorghum cultivars. Furthermore, the variables showed a significant variation ($P \leq 0.01$) for the system and as well as sampling day. However, there was no significant interaction between cultivars and the system for gs and ci. According to the results, there was highly significant interaction ($P < 0.001$) between cultivars and sampling day as well as system and sampling day for A and E. During the 2020/21 cropping season, E and gs were not significantly different among grain sorghum cultivars at Ofcolaco. However, A and ci were highly different ($P \leq 0.001$) among grain sorghum cultivars. The results further indicated that cropping season did not affect all variables excluding ci. However, all variables were significantly different ($P \leq 0.001$) during the growing period. There was no significant interaction between cultivars and cropping system as well as between system and sampling day for E and gs. However, all variables indicated a significant interaction among cultivars, cropping system and sampling day excluding gs (Table 3.7).

Table 3.7 Means squares for physiological traits of grain sorghum cultivars at Ofcolaco during 2018/19 and 2020/21 cropping season.

		Ofcolaco 2018/19			
Source	DF	A	E	gs	ci
Cultivar (C)	3	3466.32***	15.09^{ns}	0.05^{ns}	8732.37^{ns}
System (S)	1	9346.66***	194.05***	1.08***	75822.45*
Sampling Day (DAP)	6	28667.50***	872.63***	3.02***	517960.28***
Cultivar*System	3	7862.27***	48.34***	0.05^{ns}	15017.16^{ns}
Cultivar*DAP	18	4174.67***	26.34***	0.11^{ns}	33095.16**
System*DAP	6	4145.70***	61.31***	0.19*	33120.62^{ns}
Cultivar*System*DAP	18	4836.75***	9.17^{ns}	0.16**	42949.85***
		Ofcolaco 2020/21			
Cultivar (C)	3	95.24***	0.40^{ns}	0.0003^{ns}	12438.85**
System (S)	1	2.71^{ns}	0.25^{ns}	0.00009^{ns}	22724.15**
Sampling Day (DAP)	5	311.26***	8.17***	0.0120***	45782.02***
Cultivar*System	3	34.82*	0.21^{ns}	0.0006^{ns}	8767.37*
Cultivar*DAP	15	125.76***	3.18***	0.0007^{ns}	26487.62***
System*DAP	5	105.88***	0.96^{ns}	0.0004^{ns}	35770.75***
Cultivar*System*DAP	15	43.71***	1.26**	0.0004^{ns}	9329.61***

***Significant at $p \leq 0.05$; ** significant at $p < 0.01$; *** significant at $p < 0.001$; ns represent nonsignificant. A = photosynthetic rate, E = transpiration rate, gs = stomatal conductance, ci = sub-stomatal CO_2 concentration.**

3.2.3.8 The effect of cropping system on leaf gaseous exchange of four grain sorghum cultivars at Ofcolaco during the 2018/19 and 2020/21 growing period.

The results revealed that A, gs and ci varied significantly ($P \leq 0.01$) in terms of cultivar, cropping system as well as DAP during 2018/19 cropping season at Ofcolaco (Figure 3.23). The photosynthetic rate in binary culture started at a high rate and reached a peak at 91 DAP and then dropped until 117 DAP. Avenger and NS5511 were superior at 35 DAP compared to Enforcer and Titan. Cultivars dropped from 49 DAP and increased at 83 DAP. The results indicated that Titan was higher at 91 DAP compared to all other cultivars in a binary culture. In sole system Avenger and Enforcer started at higher rate compared to NS5511 and Titan. All cultivars dropped at 63 DAP and Avenger, Enforcer and Titan increased at 83 DAP NS5511 decreased. However, at 105 DAP NS5511 had higher A compared to all other cultivars in sole cultures.

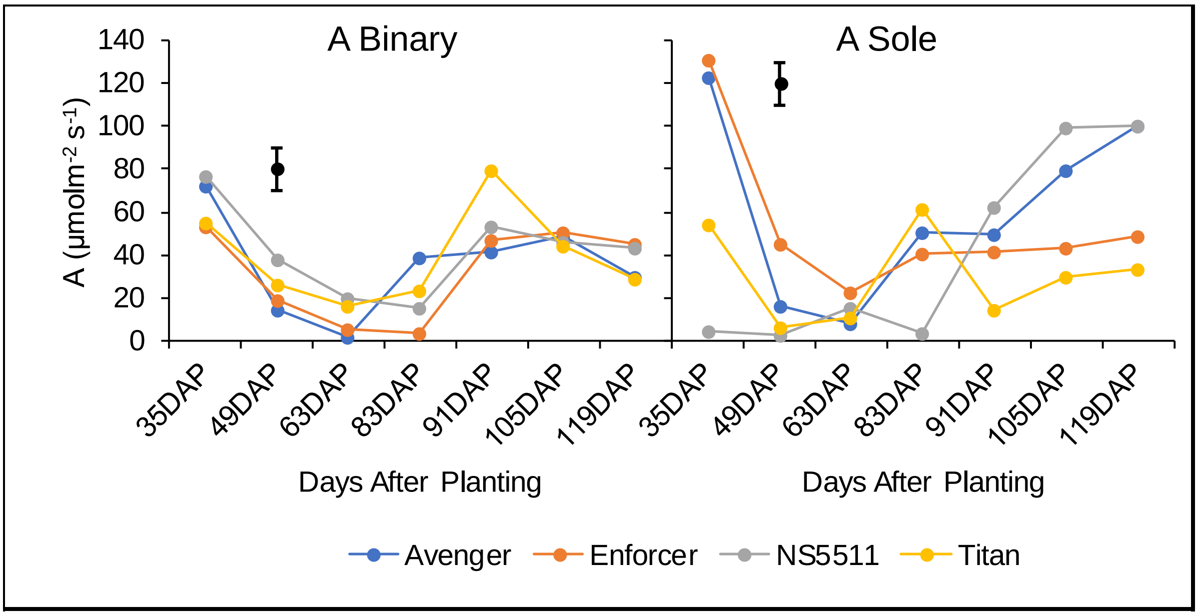

Figure 3.23 Photosynthetic rate (A) of four grain sorghum cultivars in binary and sole cultures during the 2018/19 growing period at Ofcolaco. The error bars on each graph represent LSD at $p \leq 0.05$.

Stomatal conductance was also different in sole and binary cultures of grain sorghum cultivars during 2018/19 cropping season at Ofcolaco. In binary cultures, cultivars had decreasing trend until 83 DAP and reached the highest peak at 91 DAP then decreased until 119 DAP. At 49 DAP Titan and Enforcer had high gs compared to NS5511 and Avenger. However, between 63 DAP and 83 DAP cultivars had similar gs. At 91 DAP, NS5511 had higher gs compared to all other cultivars followed by Avenger. In sole cultures, Titan had lower gs at 35 DAP compared to other cultivars. However, at 91 DAP Titan was higher in terms of gs compared to all other cultivars (Figure 3.24).

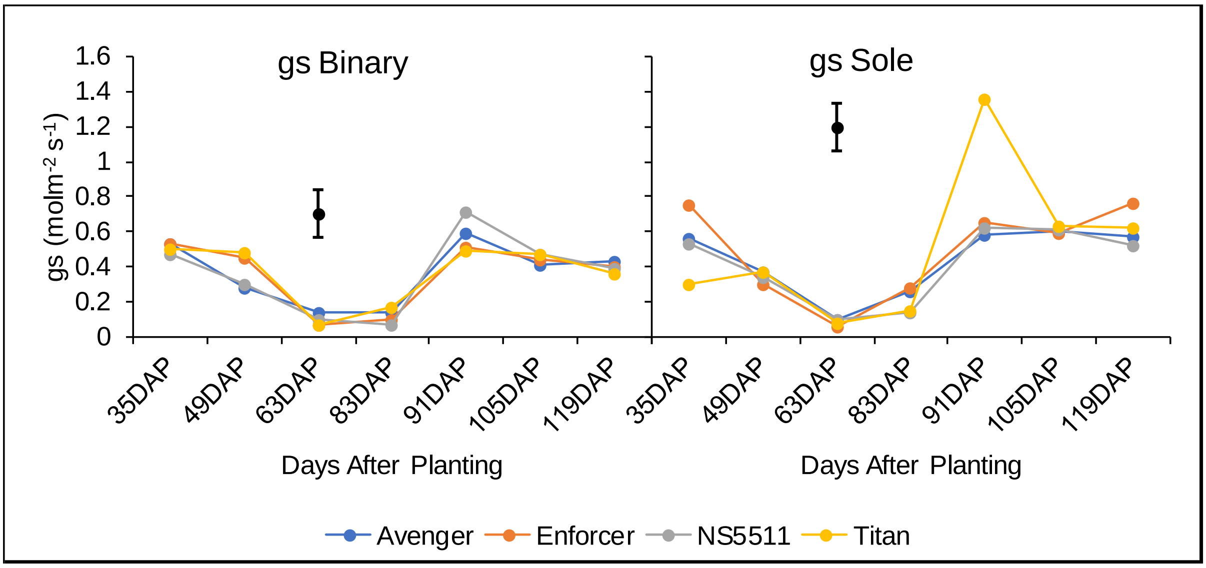

Figure 3.24 Stomatal conductance (gs) of four grain sorghum cultivars in binary and sole cultures during 2018/19 growing period at Ofcolaco. The error bars on each graph represent LSD at $p \leq 0.05$.

The sub-stomatal CO_2 concentration (ci) in binary and sole cultures had different trends for all the cultivars. In binary cultures, cultivars started at lower rate but increased from 49 DAP to 83 DAP and then dropped until 119 DAP (Figure 3.25). Enforcer and NS5511 were higher at 49 DAP and 63 DAP respectively. However, at 83 DAP NS5511 dropped while other cultivars were increasing. The results in sole cultures revealed that ci was increasing from 35 DAP to 49 DAP for Avenger and NS5511 while Enforcer and Titan were decreasing. At 83 DAP, Avenger and NS5511 increased again.

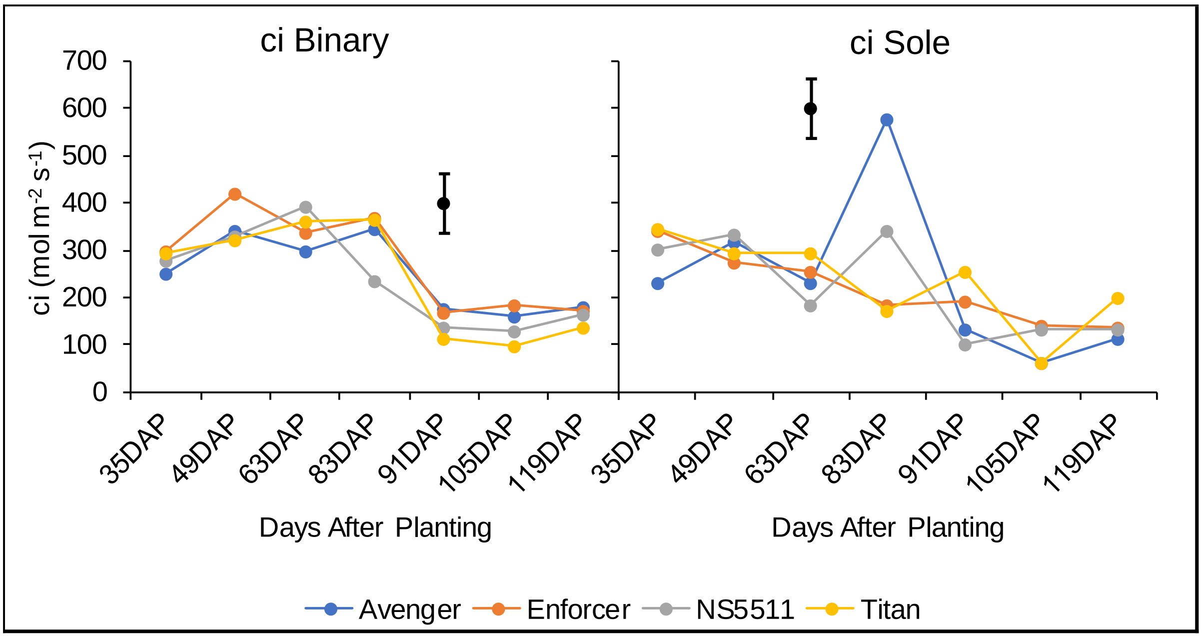

Figure 3.25 Sub-stomatal CO_2 concentration (ci) of four grain sorghum cultivars in binary and sole cultures during the 2018/19 growing period at Ofcolaco. The error bars on each graph represent LSD at $p \leq 0.05$.

The results from 2020/21 cropping season revealed that A, E and ci were significantly affected by cultivar, cropping system as well as DAP. Stomatal conductance was not significantly different for all the three factors. As shown in figure 3.26 cultivars responded differently in cropping system across the growing season in terms of A. Avenger had higher A compared to all the cultivars at 39 DAP however, it decreased from 57 DAP until 117 DAP. Enforcer, NS5511 and Titan had low A at 39 DAP and increased until 67 DAP. At 91 DAP, all cultivars were at the lowest rate compared to other DAP. In sole cultures all cultivars started at high rate and decreased until 67 DAP. Enforcer had lower A compared to other grain sorghum cultivars from 39 DAP to 67 DAP. The cultivar started to increase at 91 DAP was higher while other cultivars were decreasing. Furthermore, Avenger, NS5511 and Enforcer were higher at 104 DAP while Titan was lower.

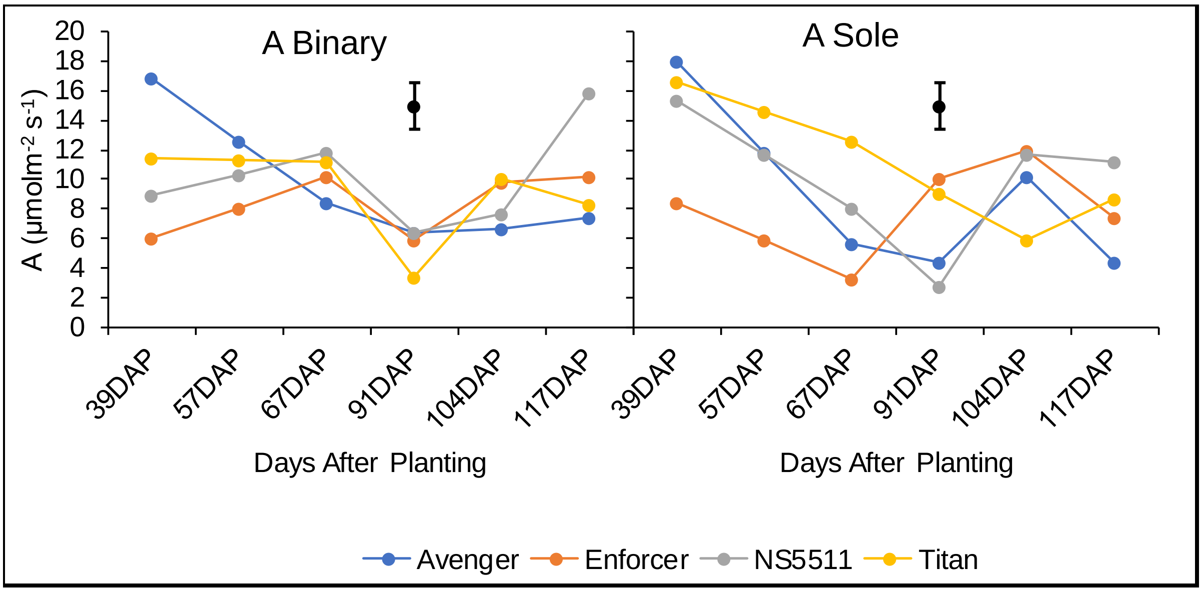

Figure 3.26 Photosynthetic rate (A) of four grain sorghum cultivars in binary and sole cultures during 2020/21 growing period at Ofcolaco. The error bars on each graph represent LSD at $p \leq 0.05$

The rate of transpiration (E) from binary cultures was similar for cultivars from 39 DAP to 67 DAP with Avenger and Titan superior compared to NS5511 and Enforcer. At 91 DAP Titan was lower than other grain sorghum cultivars. However, at 104 DAP Avenger, Enforcer and Titan had the same E while NS5511 had lower E compared to other cultivars (Figure 3.27). The results from sole cultures indicated that Avenger, Enforcer and NS5511 were at decreasing rate from 29 DAP to 67 DAP. However, Titan increased from 39 DAP to 67 DAP. Enforcer was at higher rate at 91 DAP while Titan was lower at 104 DAP.

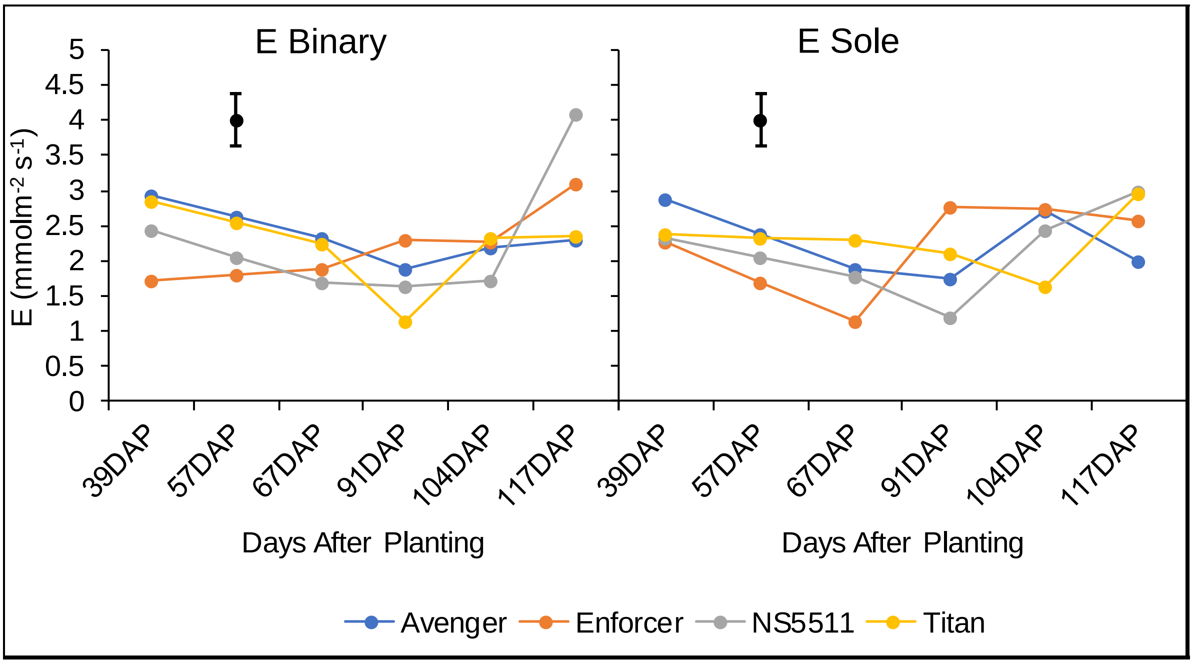

Figure 3.27 Transpiration rate (E) of four grain sorghum cultivars in binary and sole cultures during 2020/21 growing period at Ofcolaco. The error bars on each graph represent LSD at $p \leq 0.05$.

Grain sorghum cultivars indicated a variation in response to ci in binary and sole cultures at Ofcolaco during 2020/21 cropping season (Figure 3.28). in binary cultures, Enforcer and Titan was at increasing rate from 39 DAP to 67 DAP then decreased from 91 DAP to 104 DAP. However, Avenger and NS551 were at decreasing rate from 39 DAP to 67 DAP then increase at 91 DAP. The results further indicated that NS5511 and Titan were at increasing rate from 39 DAP to 67 DAP in sole cultures. Avenger and Enforcer were at decreasing rate from 39 DAP to 67 DAP. The results further revealed that Enforcer had lower E at 91 DAP and 104 DAP while other three cultivars were higher at 91 DAP and decreased at 104 DAP.

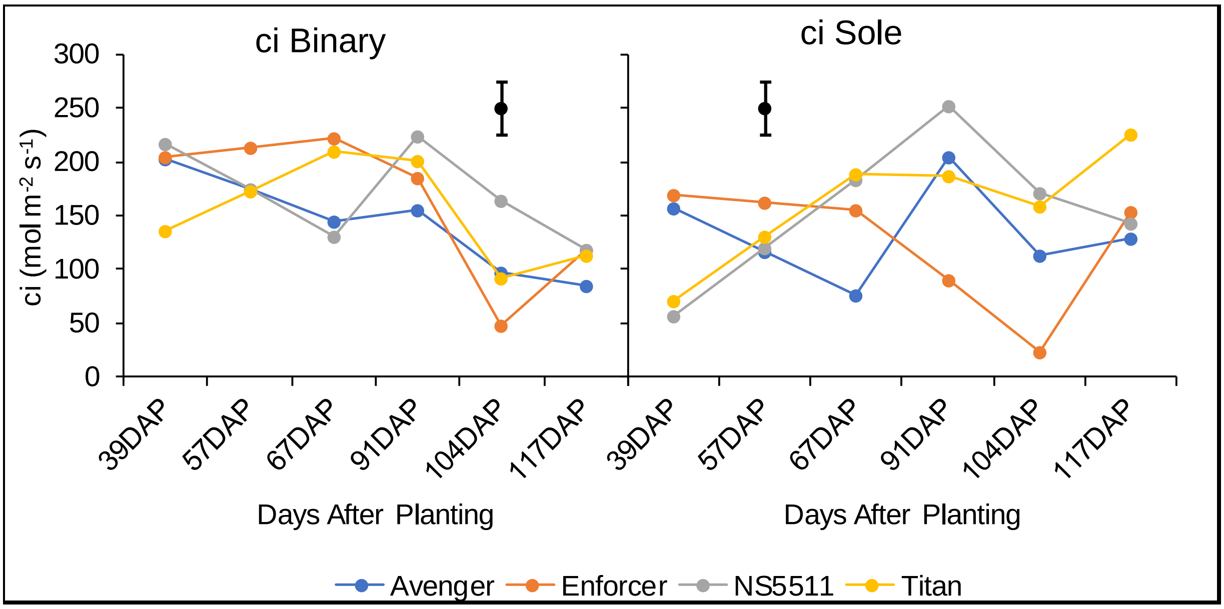

Figure 3.28 Sub-stomatal CO_2 concentration (ci) of four grain sorghum cultivars in binary and sole cultures during 2020/21 growing period at Ofcolaco. The error bars on each graph represent LSD at $p \leq 0.05$.

3.2.3.9 Biomass accumulation of four grain sorghum cultivars during 2018/19 and 2020/21 cropping season at Ofcolaco

Like Syferkuil, biomass from Ofcolaco showed increasing trend during the two cropping seasons of 2018/19 and 2020/21 with the R^2 of 0.9 (Figure 3.29). During 2018/19 cropping season, biomass showed no much variation among the cultivars. However, at physiological and harvest maturity Titan accumulated higher biomass compared to all cultivars. In 2020/21 cropping season, Enforcer and Titan had lower biomass compared to NS5511 and Avenger. However, at harvest maturity Avenger had higher biomass compared to all other cultivars.

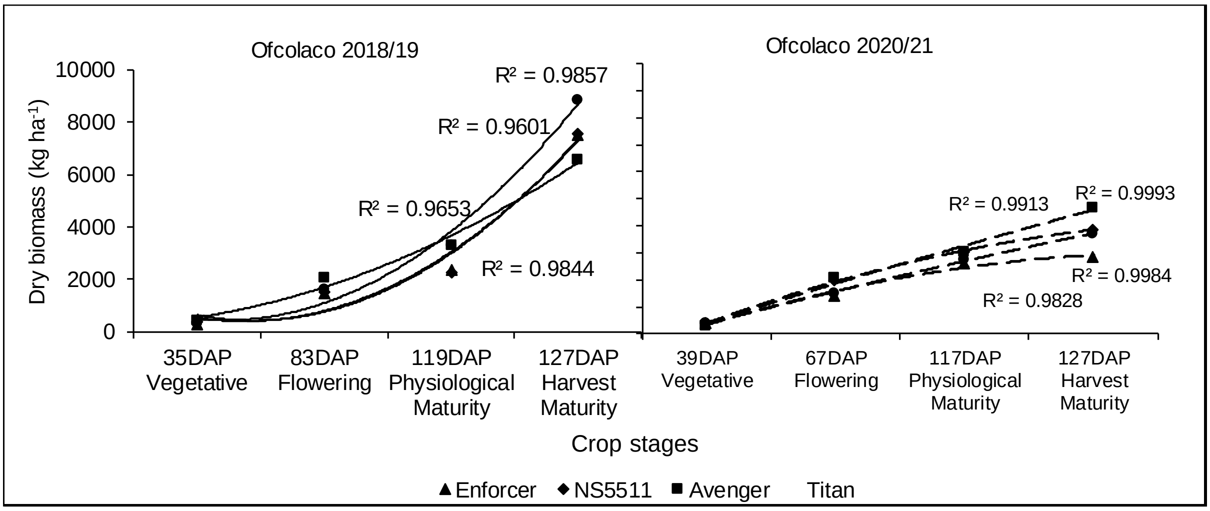

Figure 3.29 Dry biomass accumulation during the growing period of four grain sorghum cultivars at Ofcolaco in the 2018/19 and 2020/21 cropping seasons.

3.2.4 Discussion

Cropping system, cultivar variation and sampling day significantly influenced A, E, gs and ci of grain sorghum cultivars in two distinct agro-ecological regions of Limpopo Province. Pinheiro and Filho (2000) reported variation among leaf gaseous parameters in binary and sole cultures diurnally. However, Franco *et al*. (2018) found no variation among leaf gaseous parameters. The four grain sorghum cultivars used in this study indicated variation in response to interspecific interactions with the companion crop (cowpea), which depends on environmental conditions and cropping season (Hauggard-Nielsen *et al*., 2011). The results revealed that the density of the companion crop (cowpea) did not have an effect on the leaf gaseous activities of grain sorghum at different locations across seasons. This indicates that the variation in physiological responses among grain sorghum cultivars was not as a result of the number of legume crops in binary cultures.

The results from Syferkuil and Ofcolaco indicated an increase in ci resulted in a decrease in A, E and gs regardless of the cropping system, cultivar or DAP. Liu *et al*. (2010) reported that a decrease in ci indicates that the photosynthetic activities of the crop decreased due to stomatal limitations. Hence, low gs, E and A observed in the study with an increase in ci. Grain sorghum cultivars from Ofcolaco enhanced ci in binary compared to sole culture. Higher A, E and gs of grain sorghum observed at Ofcolaco resulted in improved photosynthesis of grain sorghum canopies (Schroeden-Moreno and Jano 2008; Li *et al*., 2020; Yan *et al*., 2020). Temperature is one of the climate variables that affect the photosynthetic activities of crops (Franco *et al*., 2018). Ofcolaco generally has higher temperatures compared to Syferkuil (Figure 3.4 & 3.5). Therefore, higher photosynthetic activity reported at Ofcolaco was due to warmer temperatures received during crop growth. Wang *et al*. (2018) described dry matter accumulation as a basis for crop growth, which ultimately relates to crop productivity. The results of the study revealed that biomass accumulation varied among the cultivars, environmental conditions, and cropping season. Higher biomass was accumulated in 2018/19 compared to 2020/21 cropping season. Similar results indicating variation in biomass accumulation across seasons were reported by other authors, Gong *et al*. (2020), Hu *et al*. (2016) and Yin *et al*. (2015).

NS5511 and Enforcer were the superior cultivars in terms of biomass accumulation at Syferkuil during the 2018/19 cropping season compared to all other cultivars. However, Titan which accumulated the lowest biomass compared to other cultivars had the highest A throughout the growing period. The findings are in contrast to what Gaju *et al*. (2016) found. They reported that a higher photosynthetic rate results in 90% of the biomass accumulated by the crop. This indicates that Titan was unable to translate the photosynthesis products into biomass. In 2020/21 cropping season, Enforcer accumulated lower biomass at Syferkuil compared to all other cultivars while NS5511 was still the superior cultivar. The biomass accumulation of grain sorghum from this study was highly influenced by photosynthetic capacity, which depends on environmental conditions. This was observed with generally lower biomass that was accumulated by grain sorghum cultivars at Syferkuil due to low photosynthetic activity compared to Ofcolaco. The results of the study revealed some useful insights about the rate of photosynthesis and biomass accumulation. For instance, grain sorghum cultivars such as NS5511 and Enforcer with lower A accumulated higher biomass compared to cultivars with higher A. This means that the organic matter that was synthethized by NS5511 and Enforcer canopies was able to translate into biomass accumulation (Yin *et al.*, 2017).

3.2.5 Conclusion

The physiological response of grain sorghum cultivars in intercropping systems varies from one agro-ecological zone to another and across the seasons. Hence, the study reported variations in leaf gaseous activities of grain sorghum cultivars at the two locations and seasons. Enforcer and NS5511 were superior cultivars in terms of biomass accumulation than with 24% more than Avenger and Titan at Syferkuil during the two cropping seasons. At Ofcolaco, the cultivars had variation in biomass accumulation during the 2018/19 and 2020/21 cropping seasons. For extensive recommendations, photosynthetic activities and the effects of biomass and grain yield accumulations should be investigated along with local landraces grown by local farmers of Limpopo Province. Furthermore, yield components should also be evaluated to serve as selection criteria when recommending these cultivars to local growers. Between the two study locations, biomass productivity at Ofcolaco was found to be higher compared to Syferkuil.

3.3 PHYSIOLOGICAL RESPONSES AND GROWTH OF TWO COWPEA DENSITIES IN BINARY AND SOLE CULTURES UNDER NO-TILL SYSTEM.

Abstract

The physiological responses of cowpea in intercropping system have not been investigated across different location of Limpopo Province. Two field trials were conducted at two different agro-ecological regions during the 2018/19 and 2020/21 cropping season to assess growth and physiological response of two cowpea densities in intercropping system. The experiments were laid out in randomized complete block design (RCBD) replicated 4 times. LCi Ultra-compact photosynthesis was used to collect data biweekly until physiological maturity. Ten (10) Plants were harvested at harvesting on 2.7 m^2 area to dry at 65 ^oC and weighed using weighing balance. All data collected was subjected to analysis of variance using statistical analysis software system 9.4 followed by mean separation using least significant difference at $p \leq 0.05$.The response of cowpea in terms of leaf gaseous parameters and biomass accumulation varied with cropping system, density, growing stages as well as agro-ecological conditions. In this study, the results indicated that increase in ci resulted in decreased photosynthetic rate (A), transpiration rate (E) and stomatal conductance (gs) depending on agro-ecological conditions of a cropping season. Cowpea sole high density (Sole-high) had the highest A of 19.4 $\mu molm^{-2} s^{-1}$ compared to all treatments at 91 sampling day. Cowpea obtained higher biomass in sole compared to binary cultures Furthermore, under high density cowpea was able to attain higher biomass compared to low density. Furthermore, increased plant density enhanced photosynthetic rate (A) which led to higher grain yield and dry matter accumulation depending on environmental conditions. Ofcolaco experienced higher temperatures compared to Syferkuil and that may have resulted in improved photosynthetic activities of cowpea and high translation of photoassimilates into dry matter accumulation.

Key words: Biomass, intercropping, leaf gaseous exchange, plant density

3.3.1 Introduction

Cowpea is an important grain legume crop that serves as source of proteins in many developing countries like South Africa. Dube and Fanadzo (2013) stated that cowpea mainly thrives well under poor soil fertility due to its symbiotic relationship with bacteria that can fix atmospheric nitrogen. Hence, cowpea can contribute about 28 kg of N in the soil when grown with cereal in a rotation or intercropping system (Chikowo *et al*., 2004). It is planted as sole or as an intercrop with cereal crops such as maize and grain sorghum (Singh *et al*., 2003; Moriri *et al*., 2010). With the high demand for food and feed for livestock due to growing population, sustainable production of staple crops such as cowpea is required to close the gap of demand while mitigating or adjusting to climate change scenarios. In 2016 FAO developed a systematic approach that enhances crop growth and production while reducing the emission of greenhouse gases-climate smart agricultural production (CSA). Intercropping system is one of CSA practices is defined as cultivation of two crops at the same time on the same piece of land (Wu and Wu, 2014). It is a traditional crop production practice that widely used across the globe in both scientific and socio-economic aspects (Lima Filho, 2000; Sibhatu *et al*., 2015; Herve *et al*., 2017; Mnzhebele *et al*., 2020).

Improved soil conditions as a result of intercropping and no-till system will ultimately cause better physiological responses compared to sole cropping especially in dry areas of Limpopo Province where farmers depend on rainfall (Lima Filho, 2000). Intercropping increases water retention through increased root density and arrangements of different crop species. Furthermore, full canopy cover by crops results in reduced soil evaporation (Ofori *et al*., 2014). Chimonyo *et al*. (2016b) and Zougmore *et al*. (2000) reported that intercropping grain sorghum with cowpea has the potential to reduce runoff by about 30% and improve water management especially in rainfed areas. In addition, the water captured in an intercropping system is exchanged for CO_2 which will be helpful in biomass production.

One of the major factors to consider when intercropping grain sorghum and cowpea is plant density. According to Makoi *et al*. (2010), higher cowpea density when intercropped with grain sorghum affect photosynthetic activities such as stomatal conductance, photosynthetic rate etc. Extensive Information on leaf gaseous exchange and the impact on biomass accumulation of cowpea is required for better crop growth management. The efficiency and effectiveness of intercropping system to cowpea growth and physiology must be investigated for a specific agro-ecological region. This will help with clear understanding of the system and how it contributes to the sustainable production of a crop. Leaf gaseous activities are important components of cowpea that affect growth and biomass accumulation. Hence, the study was conducted to determine leaf gaseous activities of cowpea in binary and sole cultures under two densities, and to determine the effect of leaf gaseous exchange on biomass accumulation of cowpea across different agro-ecological regions of Limpopo Province.

3.3.2 Materials and methods

The study sites, soil sampling, experimental set-up and management, are the same as described in section 3.1.2. in chapter 3.

3.3.2.1 Data collection

Leaf gaseous exchange data was collected on middle rows of binary and sole cultures of cowpea. Sub-stomatal CO_2 concentration (ci), photosynthetic rate (A), stomatal conductance (gs) and transpiration rate (E) were measured using LCi-SD Ultra compact photosynthesis machine (ADC BioScientific Ltd, United Kingdom) between 09H00 am and 12H00 pm on fully developed fresh binary and sole grain sorghum leaves. Biomass was collected from each experimental unit from an area of 1 m^2 at vegetative (DM-V), flowering (DM-F), physiological maturity (DM-PM) and harvesting (DM-H). The samples were taken to the lab and oven-dried at 65 ^oC for 72 hours. The weight of dry mass was obtained by weight samples using a weighing balance.

3.3.2.2 Statistical analysis

Leaf gaseous exchange and biomass data was subjected to a 5 x 2 factorial block analysis of variance (ANOVA) using statistical analysis software system 9.4 University of Limpopo Version. The cowpea cropping system was defined as factor 1 and factor 2 was the cowpea density. The cropping system, density as well the sampling date were used to test for interaction Least significant difference was used where the treatments were significantly different at $p \leq 0.05$. The data from each location and season were analysed separately.

3.3.3 Results

3.3.3.1 Leaf gaseous exchange of cowpea

The cropping system had a significant effect on sub-stomatal CO_2 concentration (ci) and transpiration rate (E) in sole and binary cultures of cowpea at Syferkuil during the 2018/19 cropping season (Table 3.8). However, stomatal conductance (gs) and photosynthetic rate (A) of cowpea in sole and binary cultures were not affected by the cropping system. The density of cowpea did not have significant effect on ci, E, gs and A of cowpea during the same cropping season at Syferkuil. The results revealed a highly significant variation among cowpea treatments in sole and binary cultures for ci, E, gs and A. The interaction between cropping system (S) and density (D) did not show significant variation for ci, E, gs and A of cowpea. In contrast, cropping system (S) interaction with (DAP) had a significant effect on ci, E ad A excluding gs. However, gs was significantly affected by the interaction between density (D) and sampling day (DAP) whereas ci, E and A were not significantly different. The interaction of cropping system (S), density (D) as well as sampling day (DAP) did not have significant effect on ci, E, gs and A.

In the 2020/21 cropping season, there was a significant variation for E and A of cowpea in binary ad sole cultures. In terms of density, only A showed a significant variation among cowpea treatments. However, sampling day showed highly significant variation during the growing period. According to the results, cropping system x density interaction had a significant variation for E. Furthermore, cropping system x sampling day interaction had an effect on E, gs as well as A. the results further revealed that density x sampling day interaction did not affect ci and gs, however, the differences were observed on E and A of cowpea treatments. Cropping system density and days after plating interaction had an effect on ci whereas E, gs and A were not significantly affected by the interactions among the three factors (Table 3.8).

Table 3.8 Means square for leaf gaseous exchange of cowpea treatments in sole and binary cultures from Syferkuil during 2018/19 and 2020/21 cropping seasons.

Source	2018/19				
	DF	ci (mol m^{-2} s^{-1})	E (mmolm^{-2} s^{-1})	gs (molm^{-2} s^{-1})	A (µmolm^{-2} s^{-1})
System (S)	5	33840.5*	35.0**	0.1	1830.1
Density (D)	1	9168.1	9.3	0.1	1413.3
Sampling Day (DAP)	3	173011.7***	655.4***	1.6***	21401.5***
System*Density	3	7659.1	21.7	0.1	369.6
System*DAP	15	36108.0***	19.8*	0.1	2477.5**
Density*DAP	3	1780.9	20.2	0.2*	205.6
System*Density*DAP	9	12042.5	9.5	0.03	1497.1
	2020/21				
System (S)	5	6517.7	0.47*	0.0004	115.38***
Density (D)	1	8526.9	0.06	0.0000245	91.46****
Sampling Day (DAP)	4	337155.1***	32.95***	0.047***	701.21***
System*Density	3	5665	0.48*	0.00012636	0.00024
System*DAP	20	7843.7	0.78***	0.00051*	93.94***
Density*DAP	4	8992.5	0.79**	0.00018236	82.80***
System*Density*DAP	12	12080.7*	0.000023	0.00010236	0.000014

Means squares with * = significant different at 5%, * = significantly different at 1%. ci = sub-stomatal CO_2 concentration, E = transpiration rate, gs = stomatal conductance, A = photosynthetic rate.**

The interaction between the cropping system and sampling day (S x DAP) revealed a significant variation for ci, E and A of cowpea treatments during the 2018/19 cropping season at Syferkuil. Figure 4.30 indicate that cowpea treatments in sole and binary cultures had similar ci, E and A respectively at 35DAP. At 49DAP cowpea intercrop with avenger, cowpea in sole culture under high and low density had increasing ci whereas cowpea intercrop with enforcer, NS5511 and titan had decreasing ci. Ci of cowpea treatments dropped at 63DAP and increase again at 83DAP. The rate of transpiration (E) was high at 49DAP for cowpea sole under low density, cowpea intercrop with enforcer, titan and avenger. Cowpea in sole under high density and intercrop with NS5511 had decrease in E at 49DAP. All cowpea treatments reached highest peak in terms of E at 63DAP then decreased at 83DAP. Cowpea treatments in binary cultures had higher A at 49DAP compared to sole cultures (Figure 3.30). However, cowpea sole low density and cowpea intercrop with avenger increased while other treatments decreased. The treatments decreased at 83DAP.

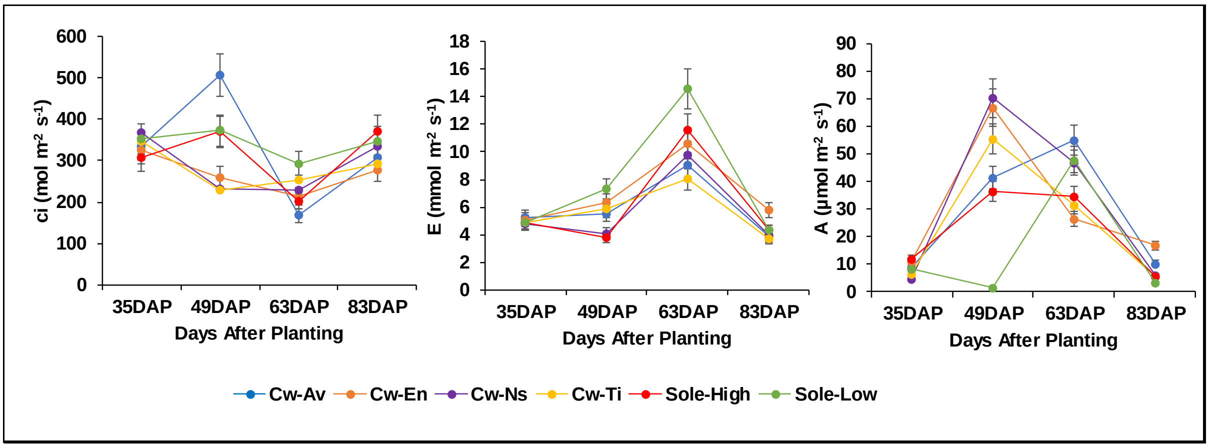

Figure 3.30 Sub-stomatal CO_2 concentration (ci), transpiration rate (E) and photosynthetic rate (A) of cowpea treatments in sole and binary cultures at Syferkuil during 2018/19 cropping season.

The results revealed significant variation in terms of gs of cowpea for interaction between density and sampling day (D x DAP) at Syferkuil during 2018/19 cropping season. Cowpea gs started at high rate at 35DAP with cowpea being superior in high density compared to low density (Figure 3.31). At 49DAP gs dropped in both densities however, higher gs was observed when cowpea was grown under low density compared to high density. high density cowpea had high gs at 83DAP compared to low density regardless of being low at 49DAP and 83DAP.

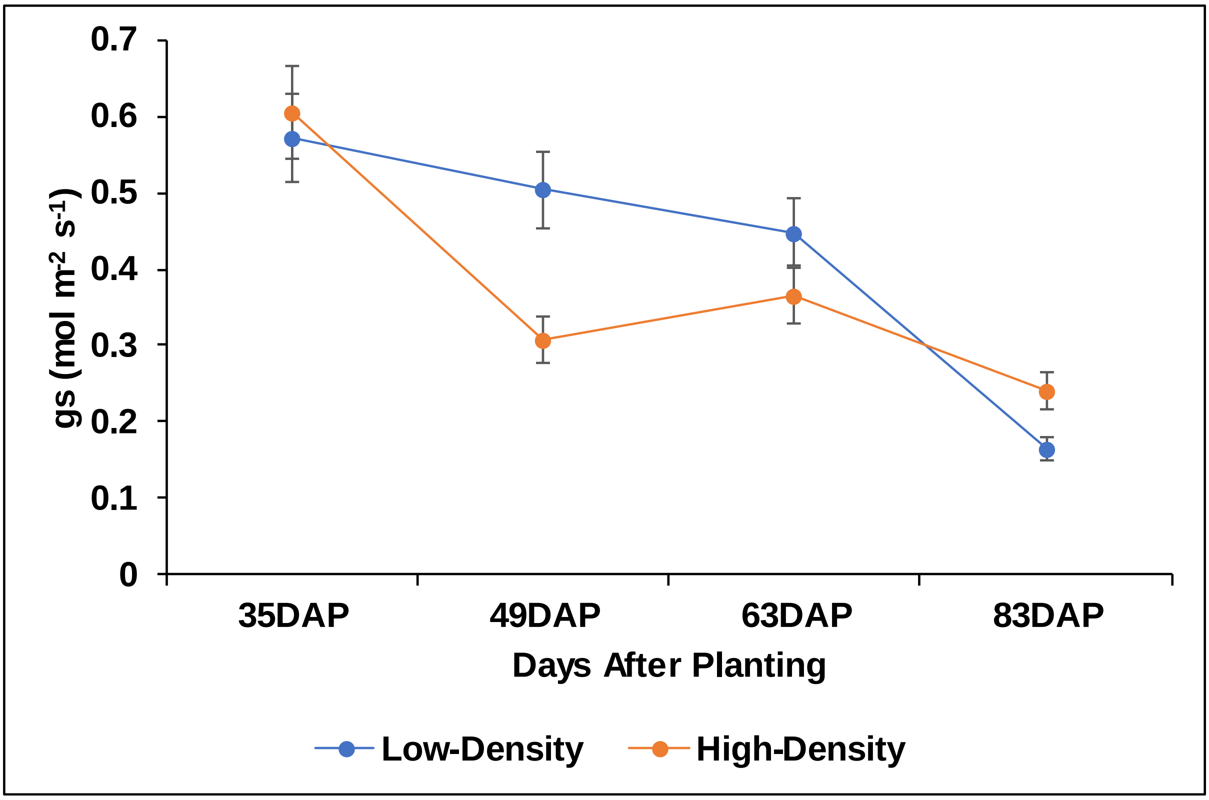

Figure 3.31 Stomatal conductance (gs) of cowpea in low and high density at Syferkuil during 2018/19 growing period.

During 2020/21 cropping season, only ci was significantly affected by the S x D x DAP at Syferkuil. Under low density, treatments had similar ci at 39DAP (Figure 3.32). All treatments excluding intercrop with NS5511 increased at 57DAP and dropped at 67DAP. The treatments reached highest peak at 91DAP with cowpea intercrop with avenger being the highest compared to all other treatments. In contrast, under high density cowpea treatments showed variation at 39DAP with intercrop with avenger having the highest ci whereas intercrop with titan had the lowest ci compared to all treatments (Figure 3.32). However, at 57DAP cowpea intercrop with titan was highest in terms of ci compared to all treatments followed by intercrop with avenger. At 67DAP ci dropped for all treatments and reached highest peak at 91DAP.

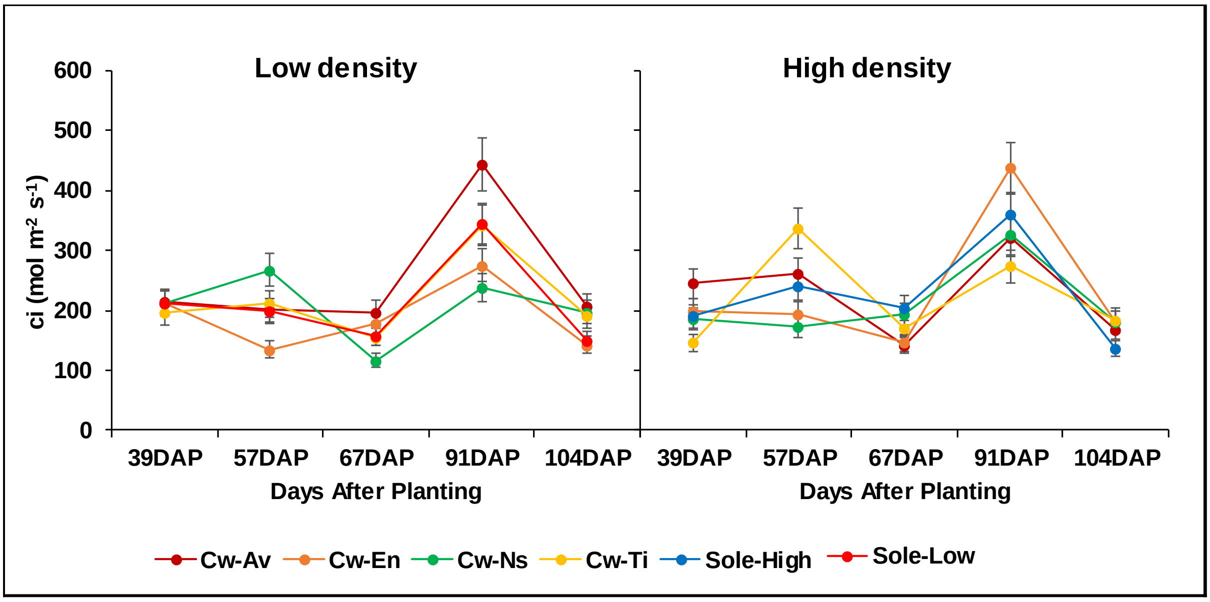

Figure 3.32 Sub-stomatal CO_2 concentration of cowpea sole and binary cultures under low and high density at Syferkuil during 2020/21 cropping season.

The significant variation in terms of S x DAP for E, gs as well as A at Syferkuil during 2020/21 cropping season is represented by Figure 3.33. All variables (E, gs and A) started at higher rate and decreased until 67DAP. At 91DAP all treatments were increasing ion terms of E excluding cowpea sole under low density and intercrop with avenger.in terms of A cowpea sole under high density was higher at 91DAP compared to all cowpea treatments in sole and binary cultures followed by cowpea sole under low density.

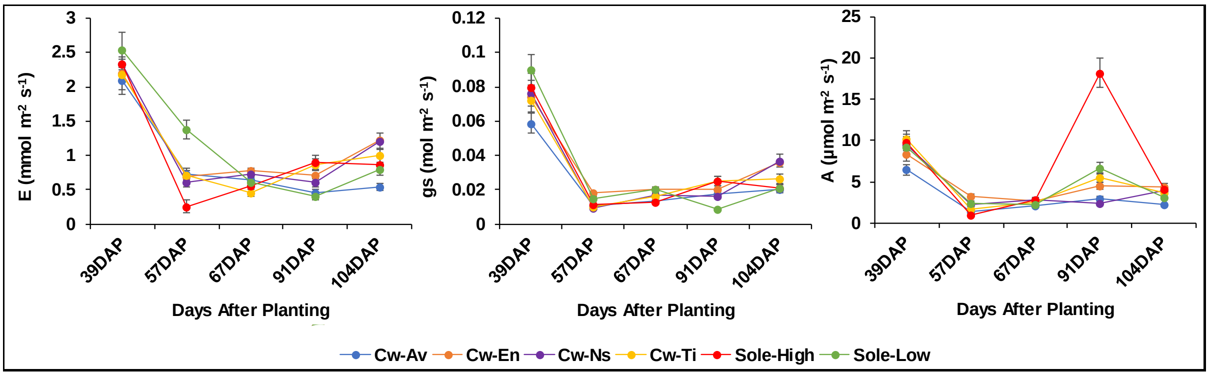

Figure 3.33 Transpiration rate (E), stomatal conductance (gs) and photosynthetic rate (A) of cowpea treatments in sole and binary cultures at Syferkuil during 2020/21 cropping season.

The density of cowpea and sampling day (S x DAP) interaction showed a significant difference among for E and A at syferuil during the second planting season. both high and low density started at higher rate for E and A at 39DAP and continue to decrease until 57DAP. High density cowpea started to increase from 67DAP until 104DAP for E whereas low density decreased and start to increase at 104DAP. The rate of photosynthesis (A) increased for high density from 67DAP and reached highest peak at 91DAP then drop at 104DAP. Under low density A was was similar between 57DAP and 67DAP and the increase at 91DAP and drop at 104DAP (Figure 3.34).

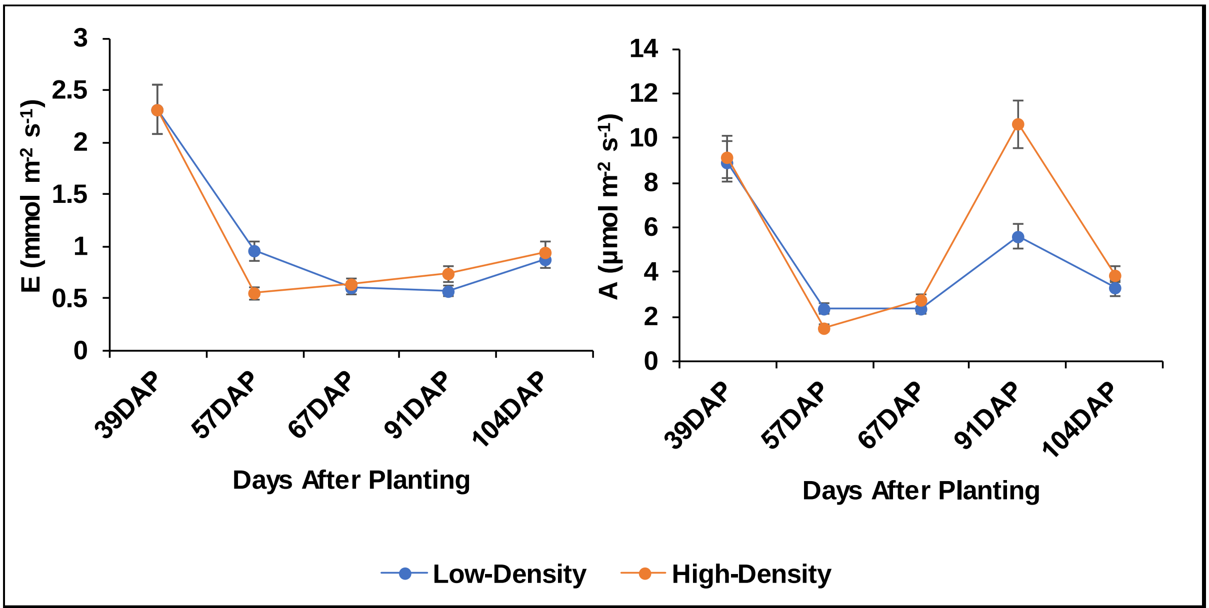

Figure 3.34 Transpiration rate (E) and photosynthetic rate (A) of cowpea in low and high density at Syferkuil during 2020/21 growing period.

During 2018/19 cropping season at Ofcolaco, cropping system and plant density did not show significant variation among cowpea treatments for E, gs and A. However, cropping system had significant effect on ci of cowpea treatments during the same cropping season. There was a highly significant variation among cowpea treatments for ci, E, gs, A. combined analysis conducted for these variables indicated that cropping system x density interaction had significant effect on gs only (Table 3.9). However, cropping system x sampling day interaction showed a significant variation among cowpea treatments for ci, gs and A. In the cases of density x sampling day there was significant difference among cowpea treatments for A. the results further revealed no significant variation of cowpea treatments for all leaf gaseous variables in combined analysis of cropping system x density x sampling day.

In 2020/21 cropping season, the results from Ofcolaco revealed that cropping system did not have significant variation among cowpea treatments for all leaf gaseous variables excluding A. In addition to cropping system, density did not show significant differences for ci, E, gs, A. However, there was a highly significant difference among all cowpea treatments for ci, E, gs and A during the growing period in the 2020/21 cropping season. Cropping system x density had a significant variation among cowpea treatments for all leaf gaseous variables. However, cropping system x sampling day interaction showed significant variation for ci and A only. Density x sampling day interaction had a significant effect on ci and gs and not E and A. in the case of cropping system x density x sampling day interaction only ci and A were significantly different (Table 3.9).

Table 3.9 Means square for leaf gaseous exchange of cowpea treatments in sole and binary cultures from Ofcolaco during the 2018/19 and 2020/21 cropping seasons.

Source	2018/19				
	DF	ci (mol m^{-2} s^{-1})	E (mmolm^{-2} s^{-1})	gs (molm^{-2} s^{-1})	A (µmolm^{-2} s^{-1})
System (S)	5	55912.7*	10.2	0.095	1836.04
Density (D)	1	61417.06	10.1	0.027	368.35
Sampling Day (DAP)	4	74998.0**	1481.3***	4.24***	29913.70***
System*Density	3	6226.2	13.5	0.184*	1511.42
System*DAP	20	84237.02***	14.7	0.101*	3996.30***
Density*DAP	4	184273.258	17.7	0.123	2438.53*
System*Density*DAP	12	0.000005	10.9	0.031	554.4423
	2020/21				
System (S)	5	2469.1	0.4	0.0004	15.239***
Density (D)	1	277.7	0.7	0.0008	0.035
Sampling Day (DAP)	4	25696.0***	9.1***	0.0039***	30.659***
System*Density	3	20839.5**	2.0**	0.0023**	34.846***
System*DAP	20	13860.5***	0.6	0.0007	32.572***
Density*DAP	4	38256.6***	1.2	0.0016*	3.134
System*Density*DAP	12	0.000002	0.1	0.0001	10.418***

Means squares with * = significant different at 5%, * = significantly different at 1%. ci = sub-stomatal CO_2 concentration, E = transpiration rate, gs = stomatal conductance, A = photosynthetic rate.**

The interaction of cropping system and density (S x D) revealed no significant variation for ci, E and A however significant difference among cowpea treatments for gs at Ofcolaco during 2020/21 cropping season. According to the results, the highest gs was observed when cowpea was intercropped with avenger under low density followed by intercrop with cowpea intercrop with NS5511 under high density. The lowest gs was obtained by cowpea intercrop with titan under high and low density (Figure 3.35).

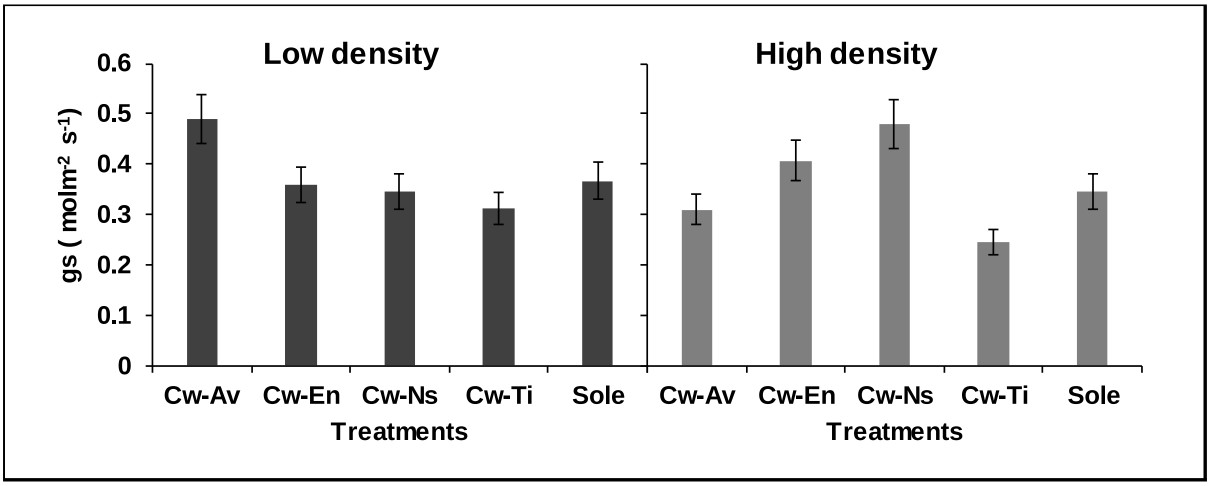

Figure 3.35 Stomatal conductance of cowpea treatments in binary and sole cultures of high and low density at Ofcolaco during 2018/19 cropping season.Cw-Av = cowpea intercrop with Avenger, Cw-En = cowpea intercrop with Enforcer, Cw-Ns = cowpea intercrop with NS5511, Cw-Ti = cowpea intercrop with Titan,Sole = cowpea sole.

There were significant interaction between cropping system and sampling day among cowpea treatments for ci, gs as well as A at Ofcolaco during 2018/19 cropping season. Cowpea treatments had fluctuating results of ci during the growing period with each treatment reaching peak at different sampling date (Figure 3.36). Cowpea intercrop with titan started at higher rate and dropped at 49DAP and reached highest peak at 83DAP. Sole cowpea with low density started at low rate and increased at 49DAP and 83DAP. However, sole high density started at low rate and reached peak at 64DAP and continue at constant rate until 91DAP. All cowpea treatment had high gs at 35DAP, decreased until 63DAP and continued to increase at 83DAP until 91DAP (Figure 4.36). In terms of A all treatments started at higher rate excluding cowpea sole low density and continued to decrease until 63DAP. At 83DAP all treatments excluding cowpea sole low density and intercrop with enforcer increased and dropped again at 91DAP (Figure 3.36).

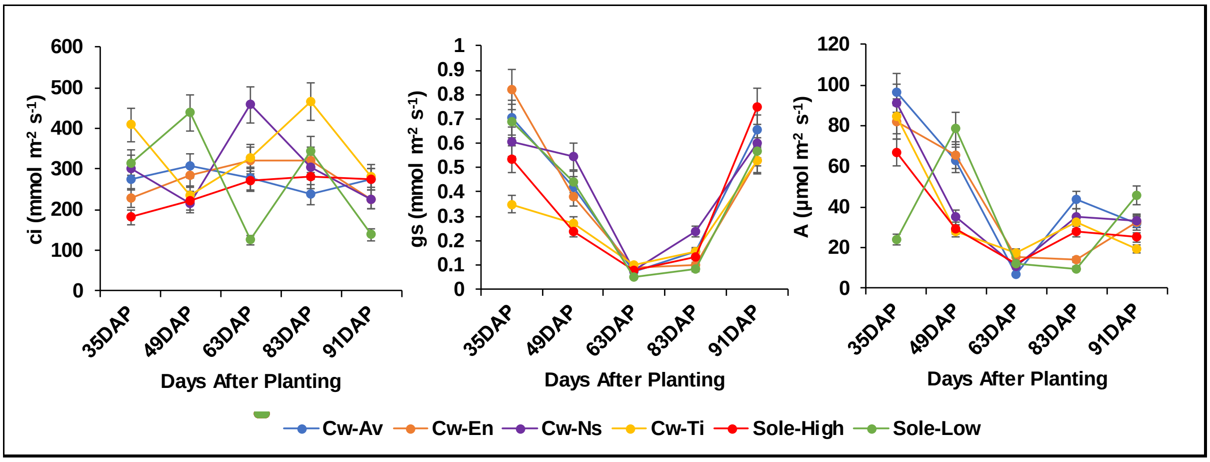

Figure 3.36 Sub-stomatal CO_2 concentration (ci), stomatal conductance (gs) and photosynthetic rate (A) of sole and binary treatments of cowpea at Ofcolaco during 2018/19 cropping season. Cw-Av = cowpea intercrop with Avenger, Cw-En = cowpea intercrop with Enforcer, Cw-Ns = cowpea intercrop with NS5511, Cw-Ti = cowpea intercrop with Titan,Sole = cowpea sole.

The results indicated that there was a significant interaction between density and days after plating for A and ci at Ofcolaco in 2018/19 cropping season. Low density cowpea had higher A at 49DAP and 91DAP whereas high density cowpea had high A at 35DAP, and 83DAP (Figure 3.37). The two cowpea densities accumulated equal A at 63DAP. The results further revealed that cowpea low density had high ci between 35DAP and 49DAP while under high density cowpea had high ci between 63DAP and 91DAP.

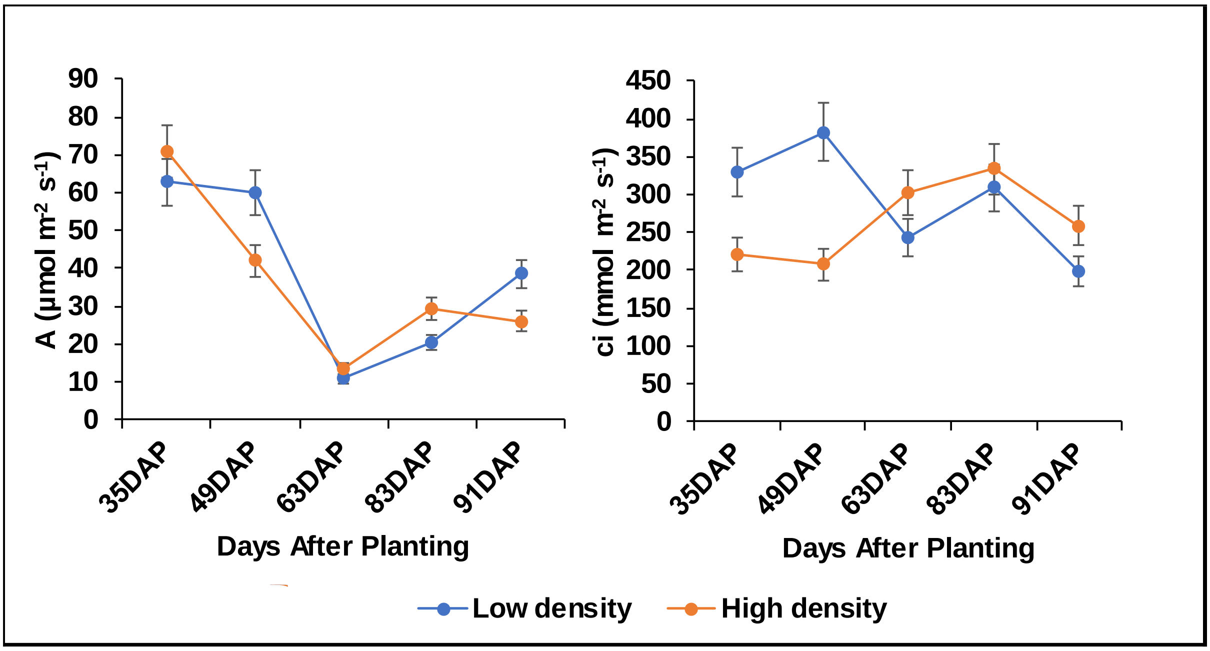

Figure 3.37 Photosynthetic rate (A) and sub-stomatal CO_2 concentration (ci) of cowpea in high and low densities at Ofcolaco during the 2018/19 cropping season.

The cropping system, density and sampling day had high significant interaction for A of cowpea during 2020/21 cropping season at Ofcolaco. Cowpea treatments varied in terms of A in low and high density during the growing period (Figure 3.38). For instance, under low density all treatments in binary cultures started at high rate and decreased until 63DAP and increased again at 83DAP. However, cowpea low density sole culture started at low rate and increased until 63DAP, then dropped at 83DAP and increase again at 91DAP. Under high density, all treatments in binary and sole cultures started at high rate and decreased until 63DAP. ALL binary cultures treatments started to increase at 63DAP whereas sole culture continued to decrease until 83DAP (Figure 3.38).

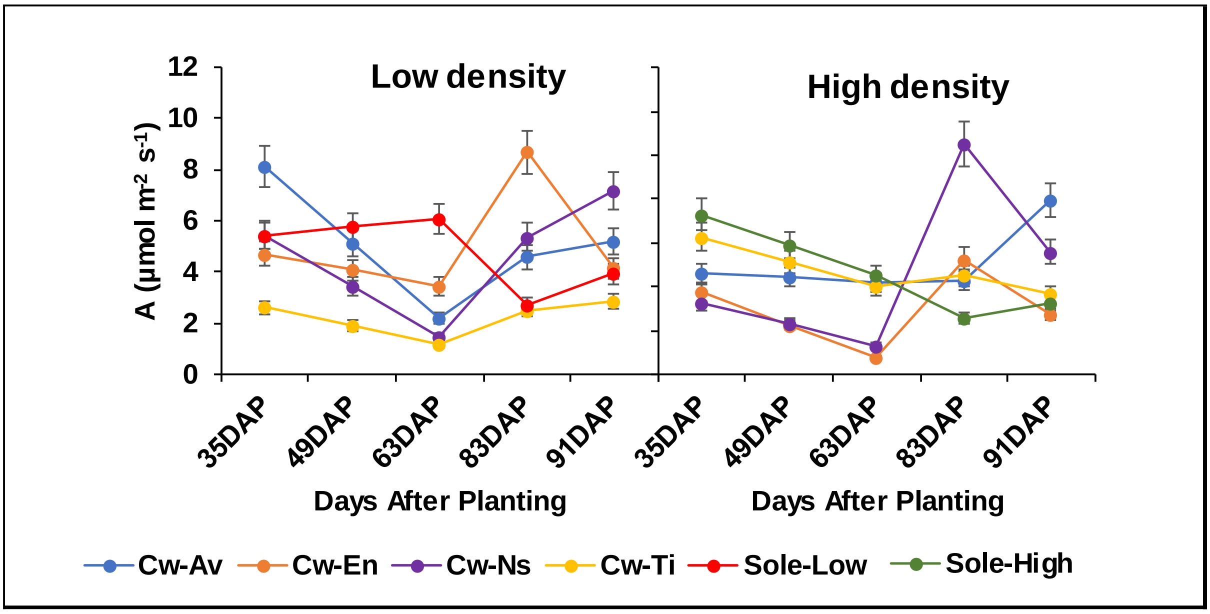

Figure 3.38 Photosynthetic rate (A) of cowpea treatments in sole and binary cultures under high and low density at Ofcolaco during 2020/21 cropping season. Cw-Av = cowpea intercrop with Avenger, Cw-En = cowpea intercrop with Enforcer, Cw-Ns = cowpea intercrop with NS5511, Cw-Ti = cowpea intercrop with Titan,Sole = cowpea sole.

There was a significant interaction of density and sampling day for ci and gs at Ofcolaco during 2020/21 cropping season. The results in figure 10 indicate that under high density cowpea had high ci and gs between 49DAP and 63DAP whereas high density had high ci and gs between 83DAP and 91DAP. The results further revealed that increase in ci resulted in decreased gs of cowpea in low and high density (Figure 3.39).

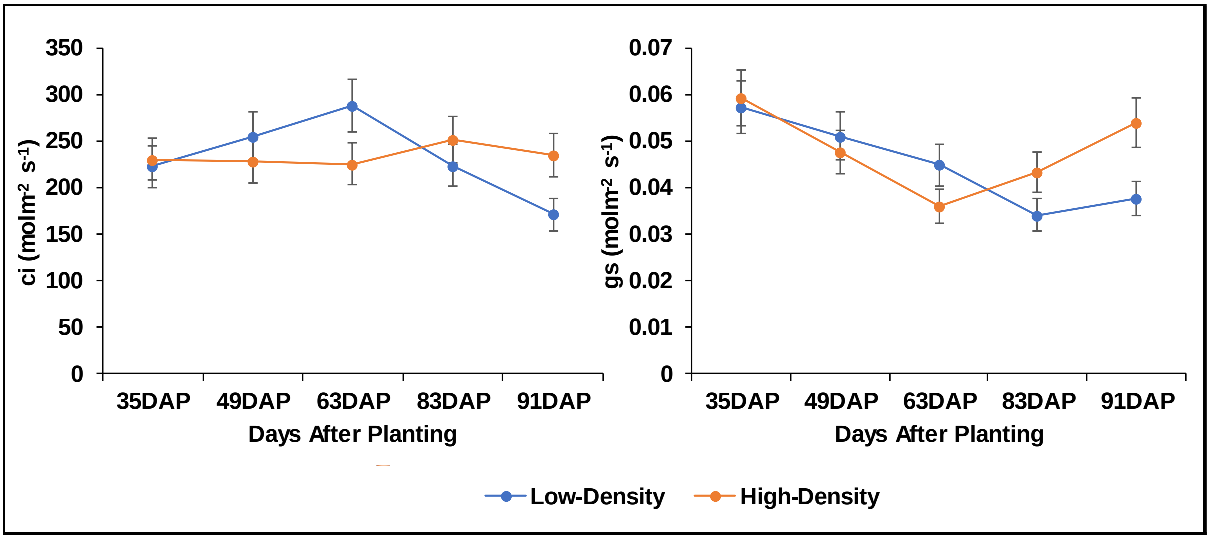

Figure 3.39 Sub-stomatal CO_2 concentration (ci) and stomatal conductance (gs) of cowpea in high and low density at Ofcolaco during 2020/21 cropping season.

The was a significant interaction between cropping system and sampling day for ci of cowpea treatments at Ofcolaco during 2020/21 cropping season. All treatments increased from 35DAP to 63DAP excluding cowpea sole under high density (Figure 3.40). Cowpea sole under high density started at decreasing rate until 63DAP and increased at 83DAP.

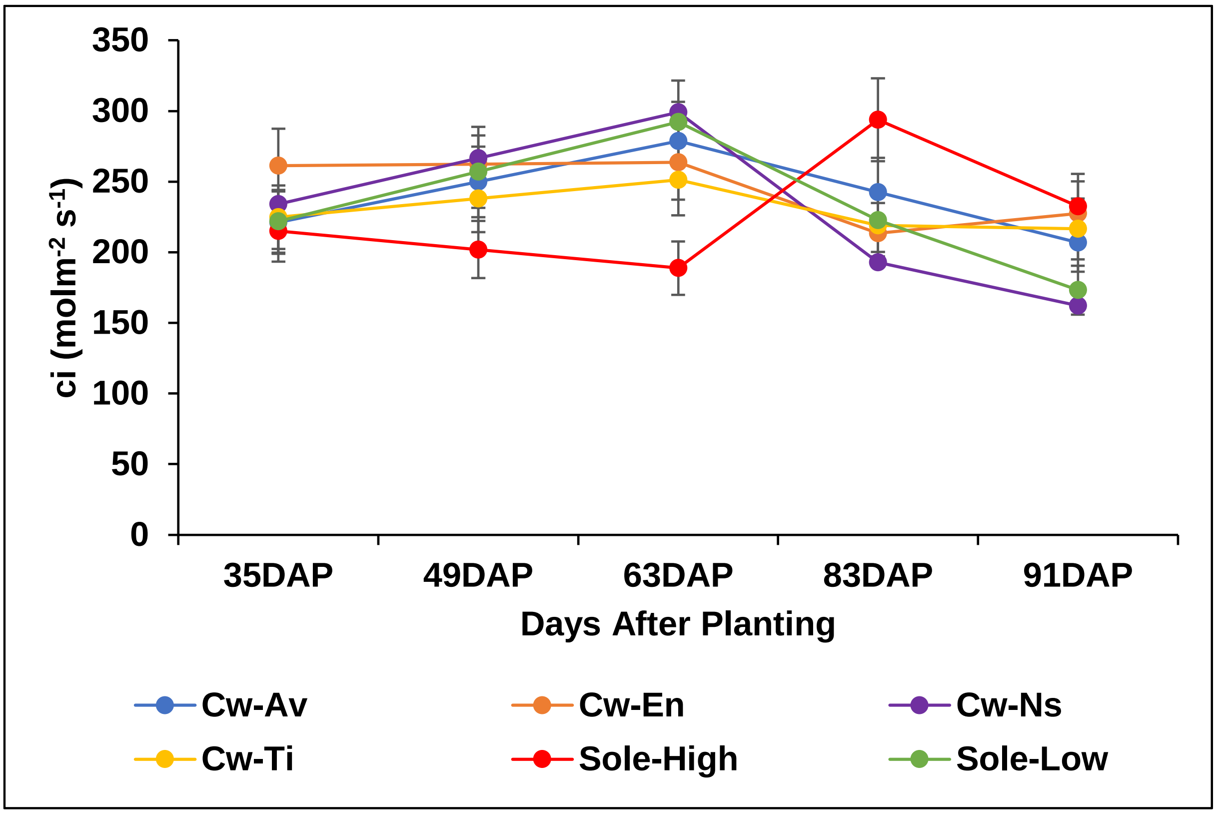

Figure 3.40 Sub-stomatal CO_2 concentration (ci) of cowpea treatments in sole and binary cultures at Ofcolaco during the 2020/21 cropping season. Cw-Av = cowpea intercrop with Avenger, Cw-En = cowpea intercrop with Enforcer, Cw-Ns = cowpea intercrop with NS5511, Cw-Ti = cowpea intercrop with Titan,Sole = cowpea sole.

3.3.3.2 Biomass accumulation of cowpea

There was a highly significant variation ($p < 0.0001$) between cowpea treatments in binary and sole cultures at Syferkuil during the 2018/19 cropping season at different crop stages. The regression line (Figure 3.41) revealed that over 90% ($R^2 > 0.9$) values fit the model for all the cowpea treatments in binary and sole cultures. At flowering and physiological maturity cowpea intercrop with NS5511 accumulated higher biomass compared to other treatments excluding sole cowpea at high density. However, at harvesting cowpea accumulated higher biomass in sole compared to binary cultures.

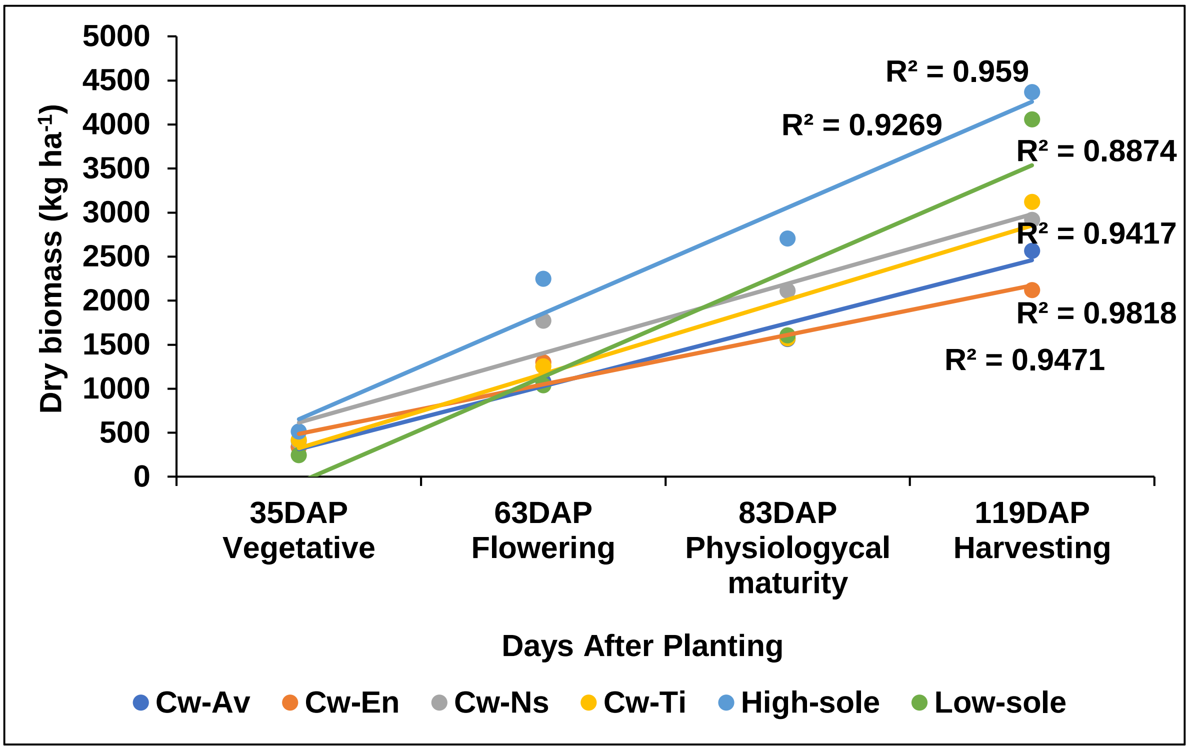

Figure 3.41 Dry biomass accumulation of cowpea in binary and sole cultures at Syferkuil during 2018/19 cropping season. Cw-Av = cowpea intercrop with Avenger, Cw-En = cowpea intercrop with Enforcer, Cw-Ns = cowpea intercrop with NS5511, Cw-Ti = cowpea intercrop with Titan,Sole = cowpea sole.

The density showed a highly significant effect ($p \leq 0.0001$) on the biomass accumulation of cowpea at four different crop stages at Syferkuil during 2018/19 cropping season (Figure 3.42). The results indicated that at each crop stage cowpea accumulated at biomass under high density compared to low density.

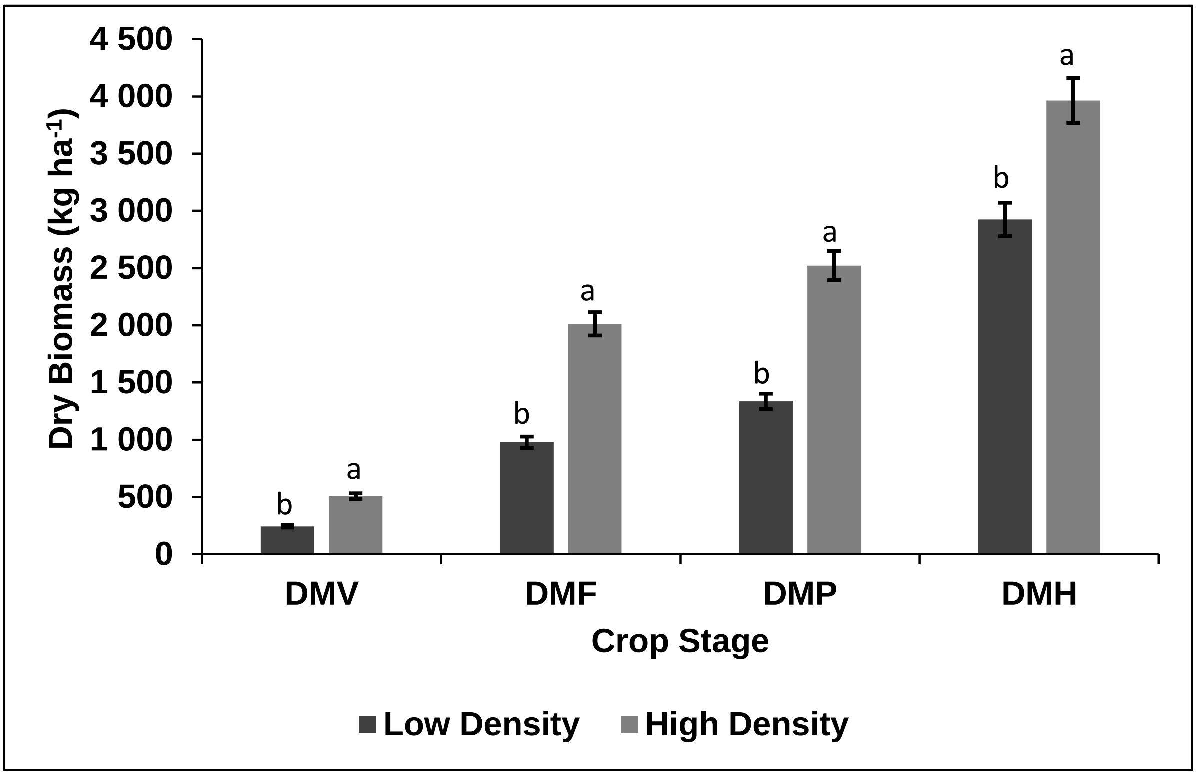

Figure 3.42 Dry biomass accumulation of high and low cowpea density at Syferkuil during the 2018/19 cropping season. DMV = dry matter at vegetative, DMF = dry matter at flowering, DMP = dry matter at physiological maturity, DMH = dry matter at harvesting.

There was no significant effect of cropping system on the cowpea treatments at vegetative stage in binary and sole cultures during 2020/21 cropping season. Furthermore, the density did not show a significant difference among cowpea treatments at all crop stages. At Flowering, physiological maturity and harvesting there was a highly significant variation in biomass accumulation of cowpea treatments in binary and sole cultures. all treatments had R^2 of 0.9 (Figure 3.43). Similar to 2018/19 cropping season, the results revealed that sole treatments accumulated higher biomass compared to binary treatments.

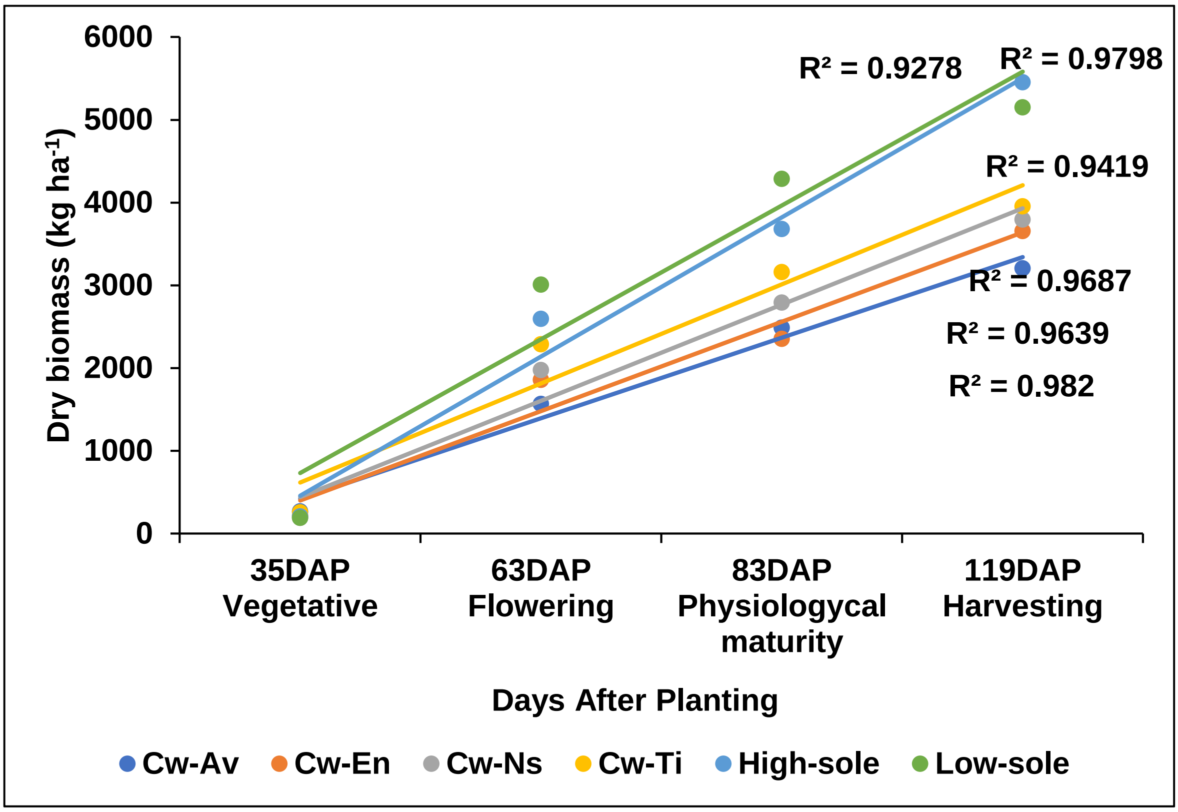

Figure 3.43 Dry biomass accumulation of cowpea in binary and sole cultures at Syferkuil during the 2020/21 cropping season. Cw-Av = cowpea intercrop with Avenger, Cw-En = cowpea intercrop with Enforcer, Cw-Ns = cowpea intercrop with NS5511, Cw-Ti = cowpea intercrop with Titan,Sole = cowpea sole.

There was a significant interaction between the cropping system and the density of cowpea for biomass at Syferkuil during the 2020/21 cropping season (Table 3.10).

Table 3.10 Interaction between cropping system and density of cowpea biomass at Syferkuil during 2020/21 cropping season.

Treatment	Low Density	High Density
Cw-Av	230.56	302.78
Cw-En	137.04	300.46
Cw-Ns	187.04	190.28
Cw-Ti	346.3	160.65
Sole-Low	188.43	-
Sole-High	-	205.09
Grand Mean	217.87	231.85
LSD (0.05)	0.0001	

Cw-Av = cowpea intercrop with Avenger, Cw-En = cowpea intercrop with Enforcer, Cw-Ns = cowpea intercrop with NS5511, Cw-Ti = cowpea intercrop with Titan,Sole = cowpea sole.

In the 2028/19 cropping season at Ofcolaco, biomass accumulation of cowpea was significantly affected by the cropping system for all the treatments. However, there was no significant interaction between the system and the density of cowpea. the regression lines in figure…indicates that all treatments in binary and sole cultures had r^2 of more than 0.9 (Figure 3.44). Sole cowpea under high density accumulated more dry biomass compared to all other treatments in binary culture as well as sole low density. Cowpea sole under low density and cowpea intercrop with Titan obtained the lowest dry biomass compared to all other treatments in binary and sole cultures.

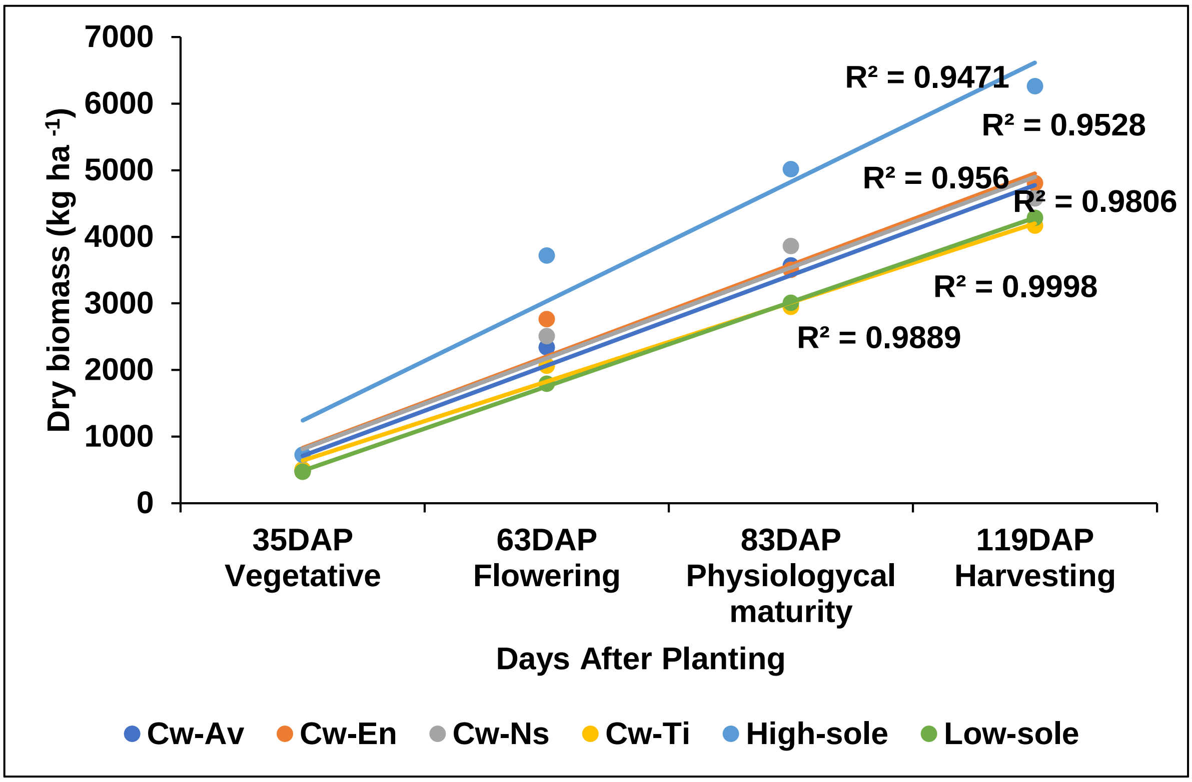

Figure 3.44 Dry biomass accumulation of cowpea in binary and sole cultures at Ofcolaco during 2018/19 cropping season. Cw-Av = cowpea intercrop with Avenger, Cw-En = cowpea intercrop with Enforcer, Cw-Ns = cowpea intercrop with NS5511, Cw-Ti = cowpea intercrop with Titan,Sole = cowpea sole.

The density of cowpea significantly affected biomass accumulation for all crop stages at Syferkuil during 2018/19 cropping season. Cowpea accumulated higher biomass when planted under high density during all crop stages compared to low density (Figure 3.45).

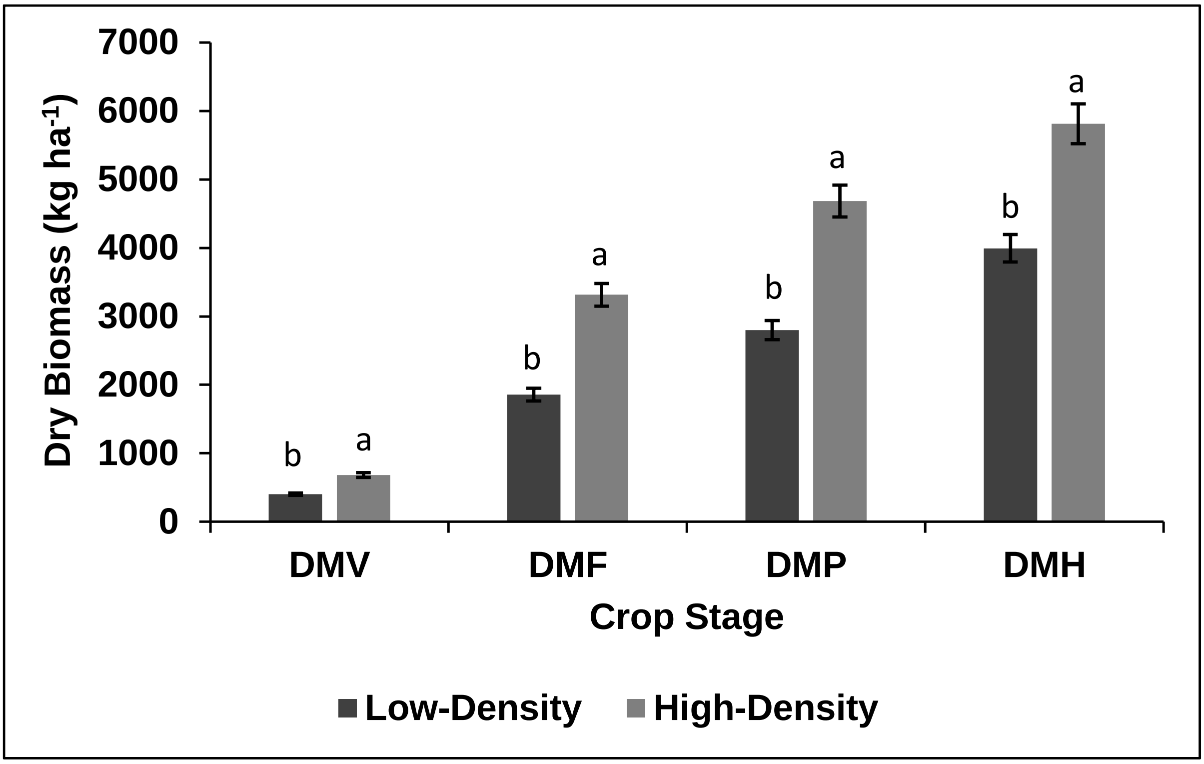

Figure 3.45 Dry biomass accumulation of high and low cowpea density at Ofcolaco during 2018/19 cropping season. DMV = dry matter at vegetative, DMF = dry matter at flowering, DMP = dry matter at physiological maturity, DMH = dry matter at harvesting.

The results from 2020/21 cropping season revealed that at Ofcolaco cowpea treatments in binary and sole cultures showed a significant variation for dry biomass at all crop stages excluding physiological maturity. All treatments had r^2 of 90% (Figure 3.46).

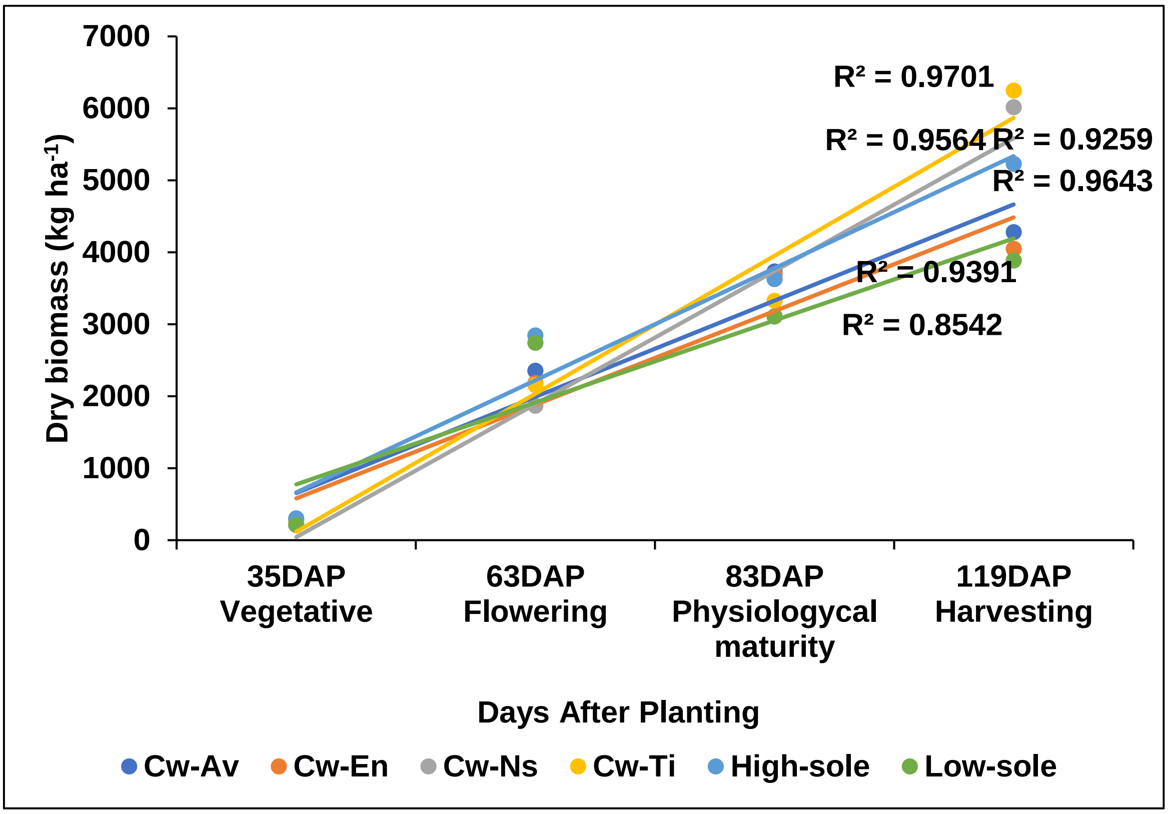

Figure 3.46 Dry biomass accumulation of cowpea in binary and sole cultures at Ofcolaco during 2020/21 cropping season. Cw-Av = cowpea intercrop with Avenger, Cw-En = cowpea intercrop with Enforcer, Cw-Ns = cowpea intercrop with NS5511, Cw-Ti = cowpea intercrop with Titan,Sole = cowpea sole.

For density of cowpea, there was no significant variation among the treatment at vegetative and physiological maturity. However, significant differences were observed among the cultivars form flowering and final harvesting (Figure 3.47).

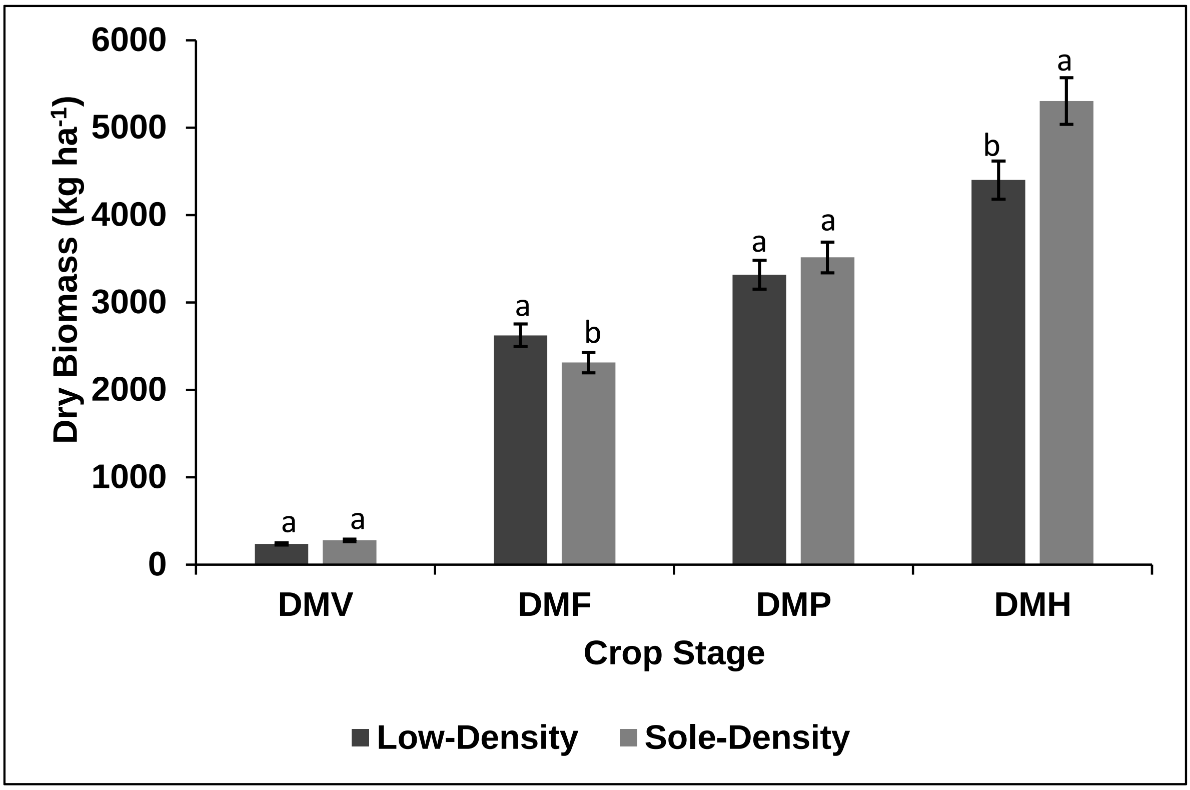

Figure 3.47 Dry biomass accumulation of high and low cowpea density at Ofcolaco during 2020/21 cropping season. DMV = dry matter at vegetative, DMF = dry matter at flowering, DMP = dry matter at physiological maturity, DMH = dry matter at harvesting.

3.3.4 Discussion

The primary advantage of intercropping system is the ability to sustainably change microclimate environment of crops in binary cultures (Guo *et al*., 2017). In this present study the leaf gaseous response of cowpea in sole and binary cultures depended highly on agro-ecological conditions which were different across the test locations and cropping seasons. Ofcolaco experienced higher temperatures compared to Syferkuil and that may have resulted in improved photosynthetic activities of cowpea and high translation of photo assimilates into dry matter accumulation (Gaju *et al*., 2016). The variation in precipitations also had an impact on A, gs, E as well ci of cowpea treatments in binary and sole cultures. Shafiq *et al*. (2020) and Du *et al*. (2020) reported that lower precipitations during growing period reduced leaf gaseous exchange which ultimately affected biomass accumulation.

The interaction between cropping system (S) x density (D) did not have significant effect on all leaf gaseous parameter at Syferkuil during the two cropping seasons excluding E in 2020/21 cropping season. In contrast, the results from Ofcolaco revealed that S x D showed significant difference for gs during 2018/19 and for ci, E, gs as well as A during 2020/21 cropping season. Cropping system (S) x sampling day (DAP) were significantly different for ci, E ad A at syferkuil during 2018/19 cropping season. However, in 2020/21 cropping season S x DAP had a significant effect on E, gs as well as A of cowpea treatments in sole and binary cultures. The interaction between cropping system, density and sampling day was due to variation in morphological response of cowpea when intercropped with varying cultivars of companion crop during the growing period. The difference in the leaf gaseous exchange was reported elsewhere (Su *et al.*, 2014).

The results revealed that intercropping cowpea at different densities influenced leaf gaseous response of cowpea depending on the treatment. For instance, E and gs were higher under low density sole treatments between 35DAP and 63DAP after which high density sole accumulated higher E and gs. Higher gs and E in low density compared to high density was also reported elsewhere (Makoi *et al*., 2010). The author further reported high A, E and gs in sole compared to binary cultures. However, in this study A, E and gs were different with each treatment as well as the sampling time. Moreira *et al*. (2015) reported low stomatal conductance and photosynthetic rate under low plant density of soybean. However, Mwamlima *et al*. (2020) reported that high density enhanced A, gs and ci compared to low density.

The results from 2018/19 cropping season revealed that at 63DAP (reproductive stage) all cowpea treatments had lower ci and higher E and A compared to other sampling days. Cowpea intercrop with Avenger (Cw-Av) had higher ci at 49DAP (vegetative stage) with lower E and A at the same sampling date. Yang and Chai, (2016), reported higher ci and A at reproductive stage. However, in this study ci was higher at vegetative stage whereas E and A we higher at reproductive stage (flowering). Cowpea sole low density (Sole-low) had higher E at 49DAP with the lowest A compared to other treatments in sole and binary cultures at Syferkuil during 2018/19 cropping season. However, during 2020/21 cropping season E, gs and A had similar trend during crop growth. Wu *et al*. (2018) reported that A, gs, and E had similar trends which were opposite to the trend of ci. In this study, the results indicated that increase in ci resulted in decreased A, E and gs depending on agro-ecological conditions of a cropping season. Cowpea sole high density (Sole-high) had the highest A compared to all treatments at 91DAP. The results indicated that under high density cowpea was able to reduce the interspecific competition with the companion crop which enhances the photosynthetic activities (Neumann *et al*., 2009; Echarte *et al*., 2011; Deressegn and Telele, 2017). However, Li *et al*. 2018 reported contradictory results, in the finding author reported that high plant density reduced A, gs and E.

Wang *et al*. (2018) described dry matter accumulation as a basis for crop growth which ultimately relates to crop productivity. In the case of dry biomass accumulation there was no significant interaction between cropping system x density at the two test locations excluding syferkuil 2020/21 cropping season. The results disagreed with Sibhatu *et al*. (2015) and Omae *et al*. (2014) who reported that interaction had significant effect on the dry biomass accumulation of cowpea. In this study, dry biomass accumulation of cowpea was significantly affected by the cropping system as well as the density of the crop. Similar results were reported by Antonietta (2014) and Getachew *et al*. (2013). Cowpea obtained higher biomass in sole compared to binary cultures due to less competition for growth resources such as light, water, nutrients in sole compared to binary cultures (Singh and Rana, 2006; Moriri *et al*., 2010; Lal *et al*., 2019). Furthermore, under high density cowpea was able to attain higher biomass compared to low density. Similar observations were reported elsewhere (Makoi *et al*., 2010). Furthermore, increased plant density enhanced A which led to higher grain yield and dry matter accumulation depending on environmental conditions (Fan *et al*., 2020).

3.3.5 Conclusion

Intercropping cowpea at high density enhances photosynthetic activities compared to low density which ultimately resulted in high biomass accumulation under high density. Multi-locational trails give clear understanding of the effect of environmental conditions on cowpea growth and leaf gaseous activities across different cropping seasons. Plant density can be used to as a catalyst to reduce competition for nutrients between cereal crops and cowpea in an intercropping system, it can also be used as a coping mechanism for cowpea to shade by companion crop. Hence, the study should be conducted under different cowpea densities to identify the correct density that will reduce interspecific competition and inter complement the companion crop for better growth and leaf gaseous response which will ultimately result in higher biomass accumulation.

CHAPTER 4: MEASURING THE IMPACT OF INTERCROPPING SYSTEM ON CO_2 EMISSION RATES AND SOIL CARBON STOCKS ACROSS DIFFERENT CLIMATIC AND SOIL ENVIRONMENTS OF LIMPOPO PROVINCE

Abstract

Understanding the carbon dioxide emission rates under different agricultural practices is a critical step in determining the role of agriculture in greenhouse gas emissions. One of the challenges in advocating for an intercropping system as a sustainable practice in the face of climate change is the lack of information on how much CO_2 is emitted by the system. A factorial randomized complete block design study was set up at two distinct agroecological locations (Syferkuil and Ofcolaco) in the Limpopo Province of South Africa to investigate carbon dynamics in sorghum-cowpea intercropping and sole cropping system over two seasons. The findings revealed that the cropping system and density of the companion crop had a significant impact on CO_2 emission rates at the test sites over two seasons. Intercropping system emitted less CO_2 compared to sole cropping system. In 2018/19 at Syferkuil and 2020/21 at Ofcolaco, intercropping systems emitted 11% and 19% less CO_2 respectively than sole cropping systems. In both agro-ecological regions, low cowpea density consistently resulted in higher CO_2 emissions than high density. According to the findings, cumulative CO_2 emissions differed by crop in sole cropping as well as crop combination. During the 2018/19 cropping season, sorghum emitted more CO_2 of 5.87 t ha^{-1} than cowpea with 5.14 t ha^{-1} in a sole cropping system at Syferkuil. Cowpea, on the other hand, emitted more CO_2 of 6.5 t ha^{-1} and 10.18 t ha^{-1} than sorghum during the 2020/21 cropping season at Syferkuil and Ofcolaco respectively. Furthermore, intercropping improved the carbon emission efficiency (CEE) of the individual crops in the system. The treatments used in the intercropping and sole cropping systems had a significant impact on the strength of the relationship between carbon stocks and CEE. Our results revealed that sorghum-cowpea intercropping system at a relatively higher cowpea density in a no-till system reduces the amount of CO_2 lost to the atmosphere. The system can thus, be promoted as one of the sustainable farming practices to reduce emissions and improve carbon storage in the soil.

Keywords: Carbon emission efficiency, intercropping system, plant density, soil organic carbon.

4.1 INTRODUCTION

Agricultural activities, such as crop production, are major contributors to global CO_2 emissions. Agriculture accounts for more than 21% of global greenhouse gas emissions (FAO, 2016). CO_2 emissions increased by 13% in the agricultural sector between 2007 and 2016 (IPCC, 2020). These emissions are a result of the need to increase food production to feed the world's growing population. Sustainable crop intensification is the key to producing food on less land while protecting the natural ecosystem (Ausubel *et al*., 2013). Preferred crop production practices such as sole cropping system coupled with conventional tillage do not enhance the retention of organic matter (Ruis *et al*., 2022). According to Paustian *et al*. (1997), crop production practices emit more greenhouse gases that contribute to climate change from planting to harvesting compared to other agricultural practices. Climate plays an important role in determining the potential of agricultural activities such as crop production in South Africa, with a particular emphasis on smallholder farmers (Laidler *et al*., 2007). As a result, climate change variability has a significant impact on smallholder farmers, particularly in Limpopo Province's semi-arid regions, where most farmers produce under rainfed conditions. As a climate-smart practice, intercropping has the potential to increase crop production while lowering greenhouse gas emissions and increasing resilience to climate change (FAO, 2016).

Sustainable crop production practices such as minimum tillage and intercropping systems are required for farmers to continue producing in a way that is environmentally friendly. Adoption of these practices necessitates a thorough understanding of the effects of farming practices on the soil and the environment (Tilman *et al*., 2011). Most of the research on intercropping systems in Limpopo Province has focused on productivity as well as nitrogen dynamics in the soil (Moriri *et al*., 2010, Rapholo *et al*., 2019). However, there is little to no information available on the system's impact on carbon dynamics in the soil, with a focus on CO_2 emissions in intercropping. Such information is critical in understanding the role of conservation practices in reducing greenhouse gases such as CO_2.

The study conducted in China revealed that when combined with other sustainable crop production practices such as mulching and conservation tillage, intercropping could reduce CO_2 emissions by more than 15% (Wang *et al*., 2020). According to research, intercropping systems combined with conservation tillage can help reduce CO_2 emissions while increasing soil organic carbon (Hu *et al*., 2017). However, carbon emissions are highly influenced by the growing conditions such as temperature, soil moisture, precipitation etc. Hence, the specific cropping system, as well as the agro-ecological condition, must be studied to determine the extent to which an intercropping system reduces CO_2 emissions. The study aimed at investigating soil carbon emissions and carbon stocks in intercropping versus sole cropping systems under distinct environmental conditions in Limpopo province.

4.2 MATERIALS AND METHODS

The study sites, experimental set-up and management, are the same as described in section 3.1.2. in chapter 3.

4.2.1 Installation of collars and Measurement of soil CO_2

For this research, CO_2 emission measurements were taken between 09h00 and 15h00 throughout the run of the experiment from each gas chamber. The CO_2 measurements were taken using the GMP343 CO_2 probe along with the MI70 data logger. The gas chambers were installed at each experimental unit from the onset of the experiment during the 2018/19 and 2020/21 cropping seasons. The chambers were installed in the middle rows of each plot and between sorghum and cowpea in intercropping (Figure 4.1). The gas chambers consisted of two separate PVC collars. One PVC ring (0.20 m diameter and 0.15 in height) was inserted into the ground using a hammer to about 0.05 m in. The other PVC collar (0.20 m diameter and 0.10 m height) was used as a lid, fitted CO_2 probe on it, had a small gas valve on it to discourage pressure build-up in the chambers during measurements. Modification of chambers, the size of PVC ring/collar, the information on the chamber lid, measurements and calculations of CO_2 were done following the procedure described by Munjonji *et al*. (2020).

Figure 4.1 (a) Installed PVC chamber/collar and (b) Soil CO_2 chamber to measure CO_2 emission rates.

CO_2 Flux calculations

The CO_2 collected from the field was in part per million, therefore was converted to mg m^{-3} using the following equation:

$$PV = nRT$$

Where P is the pressure, V the volume, n is the moles of gas, R is the constant value of gas law and T is the temperature.

The molar volume was calculated at different pressures using the following formular:

$$Molar\ Volume = \frac{RT}{P}$$

The CO_2 in mg m^{-3} was calculated at different temperatures and pressure as follows:

$$CO2\ (mgm/3) = \left(\frac{CO2ppmxMolarweight(CO2)}{22.4Lmol}\right) x \left(\frac{273.15K}{T(K)}\right) x \left(\frac{P(kPa)}{101kPa}\right)$$

CO_2 in ppm is measured every 0.5 second for 5 minutes, T represents the temperature of the chamber and P is the ambient pressure.

The CO_2 in mgm^{-3} was plotted against time to get the slope in mgm^{-3}min-1. The CO_2 Flux was calculated using the following formula:

$$CO2\ Flux\ (mgM/2\ min/1) = \frac{Slope\ x\ voleme\ of\ the\ chamber}{area\ covered\ by\ the\ chamber}$$

The cumulative CO_2 emission was calculated by assuming the CO_2 emission rate was constant from one data point to another.

4.2.2 Determination of Carbon dioxide emission efficiency (CEE)

Dry biomass was collected at harvest maturity of sorghum and cowpea at an area of 2.7 m^2 for each crop. At each harvesting area, a total of 10 plants were sampled. The samples were dried in the laboratory in an oven at 65 ^oC to a constant weight to determine biomass weight. The correlation between dry biomass (DB) and the rate of carbon dioxide emission (CO_2E) of each crop was measured using carbon dioxide emission efficiency (CEE) as described by Hu *et al*. (2015). The authors used the following formula to calculate carbon emission efficiency:

$$CEE = DB/CO2E$$

CEE is the carbon emission efficiency; DB is the weight of dry biomass (kg ha^{-1}) and CE (kg ha^{-1}) is the rate of CO_2 emission.

4.2.3 Determination of soil bulk density and soil carbon stocks

Bulk density was measured at two soil depths i.e. 0–10 cm and 10-20 cm, sampled four times per each level on plot using the core ring method. Cores with a diameter of 5 cm and a height of 5 cm were used. Sampled soils were then oven dried at a temperature of 105 ^oC for 24 hours. The bulk density was collected close to where the chambers for CO_2 emission rates were installed. Initial and final soil samples were collected per plot at two different depths i.e. 0-15 cm and 15-30 cm for two cropping seasons of 2018/19 and 2020/21. The drying of samples was done using the oven-dry method at a temperature of 105 ^oC for 24 hours before weighing them. The soil carbon stock was determined using soil organic carbon (SOC), bulk density (BD), and depth (D), from which soil samples were collected as described by Mbanjwa *et al*. (2022). The following formular was used:

$$CS = SOC\ x\ BD\ x\ D$$

CS is carbon stocks (kg m^{-2}), SOC is soil organic carbon (%), BD is soil bulk density (kg m^{-3}) and D is the soil depth (m).

4.2.4 Gravimetric water content and soil chemical analysis

Pre and post-planting soil samples were collected on each experimental unit at the depth of 0-30 cm using an auger at the two experimental sites. Each sample was stored in a zip bag and sealed after being collected to avoid moisture loss. The samples were taken to the laboratory where the fresh weight of each sample was determined using a weighing balance. The samples were air-dried for seven days in the laboratory and were weighed again to obtain dry weight. Gravimetric water content was calculated using the following formula:

$$GWC\ (\%) = \frac{Fresh\ wegiht - dry\ weight}{dry\ weight}\ x\ 100$$

The samples were sieved to pass through a 2 mm sieve and analysed for chemical properties. Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), manganese (Mn) and copper (Cu) were analysed following the procedure of Mehlich-III multi-nutrient extraction method. Soil organic carbon was determined using Walkley and Black method.

4.2.5 Statistical analysis

The relevant model assumptions, including normality, independence, and constant variance, were checked before data analysis. The Statistical Analysis System (SAS) version 9.4 was used to fit CO_2 emission and other soil data collected using a multivariate multi-factor analysis of variance (ANOVA) model. Mean separation was done where the means were different, using the least significant difference (LSD) at probability levels of $p \leq 0.05$. A regression analysis was done to test the relationship between the CO_2 emission rate and carbon stocks.

4.3 RESULTS

4.3.1 Weather conditions during growing seasons

The weather conditions during the growing seasons are outlined in chapter 3 section 3.1.

4.3.2 The effect of cropping system on soil physical and chemical properties

Bulk density (BD) was higher in sole compared to the binary culture at Syferkuil during the 2018/19 cropping season, with a mean of 1270.01 kg m^{-3} and 1260.41 kg m^{-3}, respectively (Table 4.1). The results indicated that binary cultures had more gravimetric water content (GWC) of 11% compared to sole cultures, which had 10%. Phosphorus (P), potassium (K), calcium (Ca) and zinc (Zn) concentrations were higher in the sole compared to the binary cultures, with means of 28.49 mg kg^{-1}, 301.84 mg kg^{-1}, 1061.30 mg kg^{-1} and 3.05 mg kg^{-1}, respectively. The results revealed that organic carbon, the C:N ratio, and carbon stocks were higher in binary compared to sole cultures. Phosphorus was higher, with a mean of 45.2 mg kg^{-1} in binary compared to sole culture, which had 29.21 mg kg^{-1} P. The soil had higher K and Mg in the sole compared to binary cultures. Organic carbon and carbon stocks were higher in sole compared to binary cultures during the 2020/21 cropping season.

Table 4.1 Soil chemical properties from Syferkuil collected at the end of 2018/19 and 2020/21 cropping seasons.

Chemical properties	2018/19		2020/21	
	Binary	sole	Binary	Sole
BD(kg m^{-3})	1260.41±192.30	1270.01±210.62	1463.10±412.10	1448.70±335.41
GWC(%)	11.08±5.99	9.61±4.46	10.74±2.06	10.80±2.49
P(mg kg^{-1})	25.29±14.19	28.49±20.71	45.20±18.65	29.21±11.74
K(mg kg^{-1})	250.87±81.60	301.84±82.55	255.60±56.18	325.09±53.90
Ca(mg kg^{-1})	1057.92±93.26	1061.30±88.68	992.79±72.97	1001.84±57.71
Mg(mg kg^{-1})	595.90±98.18	589.01±83.06	658.39±95.30	712.20±109.24
Zn(mg kg^{-1})	2.48±1.69	3.05±2.49	6.25±3.65	2.92±1.45
Mn(mg kg^{-1})	13.43±3.86	13.85±2.20	15.58±2.13	15.08±2.87
Cu(mg kg^{-1})	2.83±0.45	2.94±0.33	3.19±0.40	3.27±0.35
Org.C(%)	0.65±0.22	0.60±0.23	0.75±0.18	0.84±0.14
C:N ratio	13.93±8.10	11.83±7.97	12.68±2.87	12.68±3.60
CS(kg m^{-2})	1.46±0.60	1.40±0.63	2.88±0.87	3.19±0.66

BD = bulk density, GWC = gravimetric water content, P = phosphorus, K = potassium, Ca = calcium, Mg = magnesium, Zn = zinc, Mn = manganese, Cu = copper, Org.C = organic carbon, C:N ratio = carbon nitrogen ratio, CS = carbon stocks.

The results from Ofcolaco revealed that BD was higher in binary compared to sole cultures during the 2018/19 cropping season (Table 4.2). Sole cropping had a higher GWC of 26% compared to binary culture, which had 21%. The soil had higher P, Zn, and Mn in binary culture compared to sole culture. The results further revealed that soil under a sole cropping system had higher K and Ca compared to the soil under binary culture. The CN ratio was higher in binary cultures compared to sole cultures. The soil from Ofcolaco had a BD of 1277.48 kg m^{-3} compared to binary culture (Table 4.2) during the 2020/21 cropping season. P, Zn, and Mn were higher, whereas K was lower in binary compared to sole cultures. The soil had a higher CN ratio in the sole compared to binary culture.

Table 4.2 Soil chemical properties from Ofcolaco collected at the end of 2018/19 and 2020/21 cropping seasons.

Chemical properties	2018/19		2020/21	
	Binary	sole	Binary	Sole
BD(kg m^{-3})	1555.25±404.03	1440.97±269.56	1201.91±289.70	1277.48±368.98
GWC(%)	21.27±5.97	25.58±7.86	15.71±4.10	15.10±4.85
P(mg kg^{-1})	71.73±35.66	53.43±21.09	50.66±26.89	43.63±19.44
K(mg kg^{-1})	151.50±37.40	166.47±43.74	116.78±44.30	141.95±46.80
Ca(mg kg^{-1})	748.18±98.77	756.69±94.54	744.38±98.69	741.08±76.38
Mg(mg kg^{-1})	141.87±18.44	163.41±24.79	149.84±19.04	163.24±21.37
Zn(mg kg^{-1})	8.29±3.21	7.21±2.73	9.00±4.79	5.75±1.96
Mn(mg kg^{-1})	39.75±12.44	36.21±11.98	30.91±5.04	28.57±4.21
Cu(mg kg^{-1})	4.64±0.39	4.51±0.35	4.37±0.61	4.45±0.53
Org.C(%)	1.51±0.14	1.58±0.13	1.38±0.13	1.41±0.14
C:N ratio	70.50±30.05	50.96±26.67	69.68±57.48	71.88±36.03
CS(kg m^{-2})	6.99±1.82	6.84±1.49	2.49±0.56	2.67±0.84

BD = bulk density, GWC = gravimetric water content, P = phosphorus, K = potassium, Ca = calcium, Mg = magnesium, Zn = zinc, Mn = manganese, Cu = copper, Org.C = organic carbon, C:N ratio = carbon nitrogen ratio, CS = carbon stocks.

4.3.3 The effect of cropping system and temperature on CO_2 emission rate

During the 2018/19 growing season, the grain sorghum-cowpea intercropping system significantly ($p \leq 0.01$) influenced CO_2 emissions at 42, 28 and 56 sampling days at Syferkuil (Figure 4.2). The cropping system did not affect CO_2 emissions at 11, 78, 88, 98, and 112 sampling days. Sole CO_2 emissions were higher in sole cultures, ranging from 0.05 t ha^{-1} day^{-1} to 0.09 t ha^{-1} day^{-1}, compared to binary cultures, which were between 0.04 t ha^{-1} day^{-1} and 0.06 t ha^{-1} day^{-1} from 11 to 56 sampling day (Figure 4.2).

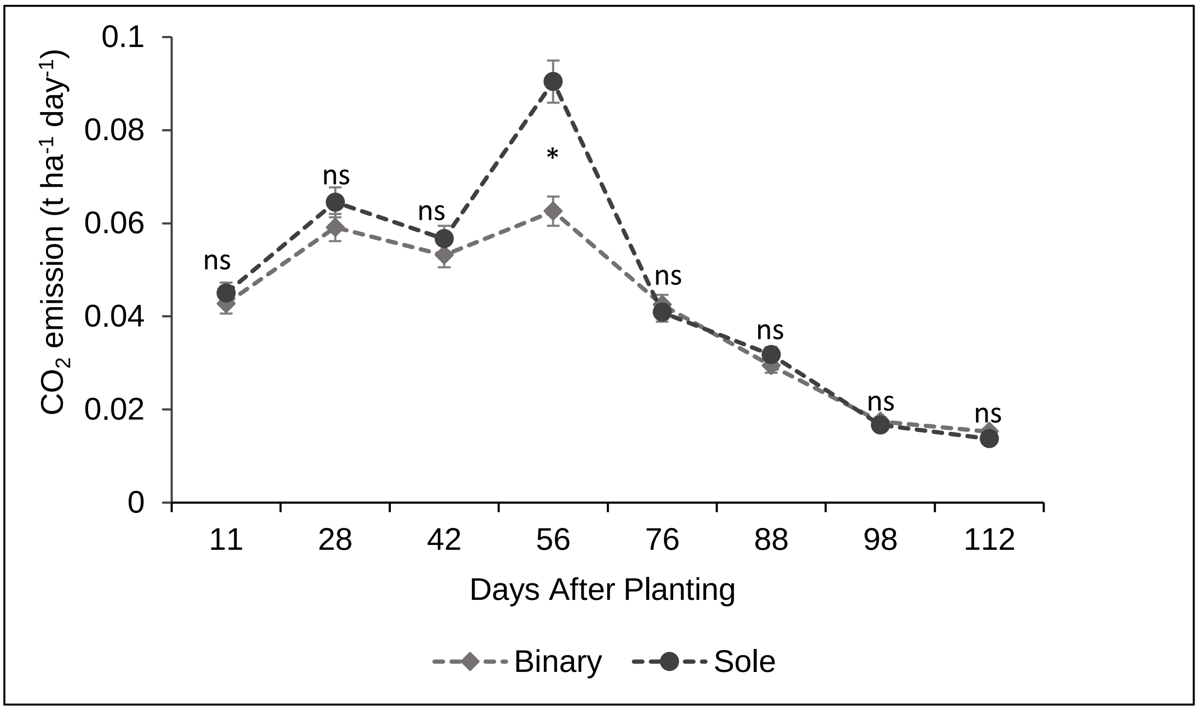

Figure 4.2 CO_2 emission rates in intercropping (Binary) and sole cropping system (sole) during the 2018/19 cropping season at Syferkuil. ns = not significant, * = significant at $p \leq 0.05$.

In the 2020/21 cropping season, the CO_2 emission rate was higher at Syferkuil in binary cultures compared to sole cultures between 39 and 67 sampling days, which ranged from 0.1 t ha^{-1} day^{-1} to 0.07 t ha^{-1} day^{-1} and 0.09 t ha^{-1} day^{-1} to 0.04 t ha^{-1} day-1, respectively. From 91 to 117 sampling day, the CO_2 flux dropped in binary and increased in sole cultures (Figure 4.3).

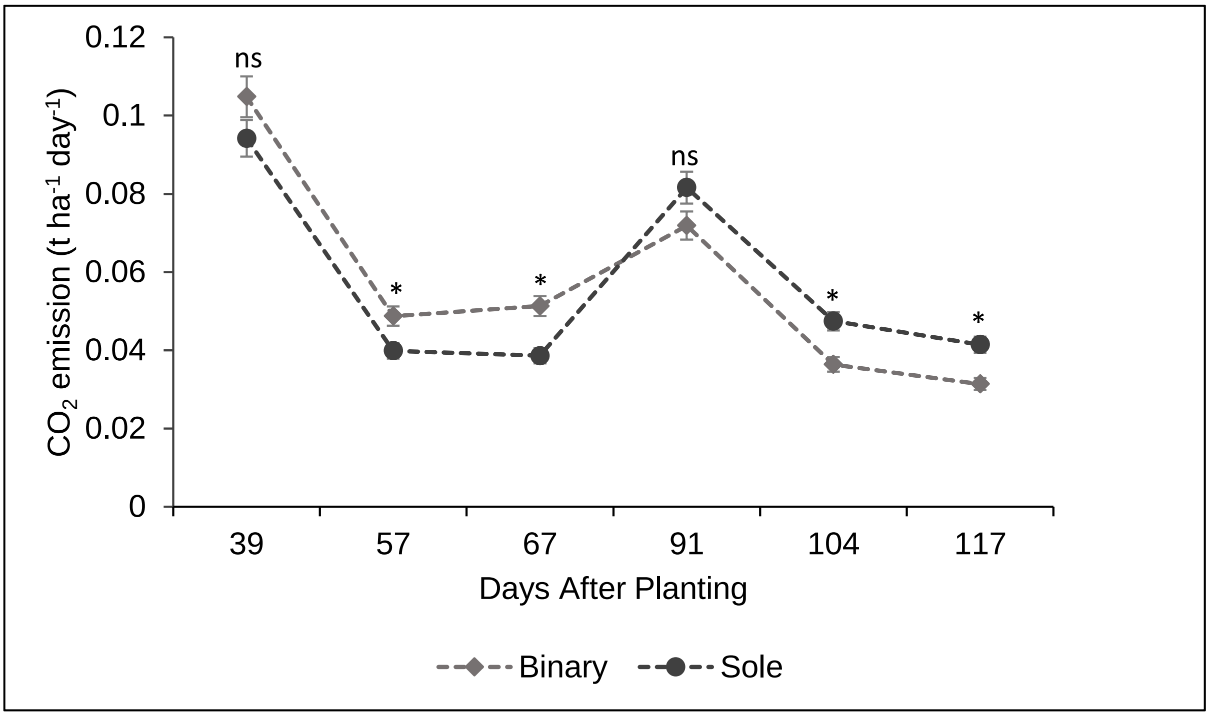

Figure 4.3 CO_2 emission rates in intercropping (Binary) and sole cropping system (sole) during the 2020/21 cropping season at Syferkuil. ns = not significant, * = significant at $p \leq 0.05$.

At Ofcolaco, the CO_2 emission rate was higher in sole compared to the binary culture at 39 sampling day, as shown in Figure 4.4 with the means of 0.1 t ha^{-1} day^{-1} and 0.07 t ha^{-1} day-1, respectively. However, at 49 and 63 sampling days, the CO_2 emission rate was similar in sole and binary cultures. The CO_2 emission rate continued to increase in sole culture from 83 to 101 sampling day (Figure 4.4).

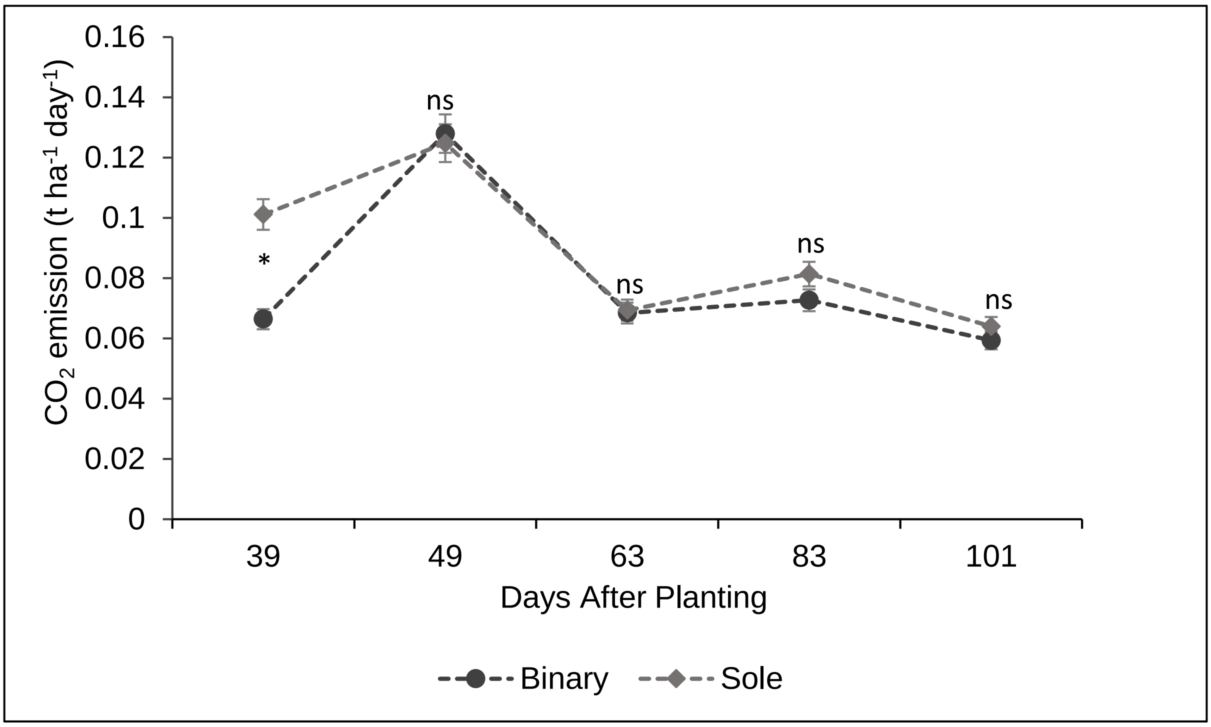

Figure 4.4 CO_2 emission rates in intercropping (Binary) and sole cropping system (sole) during the 2020/21 cropping season at Ofcolaco. ns = not significant, * = significant at $p \leq 0.05$.

Plant density had significant effect on CO_2 emission at Syferkuil from 28 to 56 sampling day during the 2018/19 cropping season. In the 2020/21 cropping season, CO_2 emission was significantly different between low and high density between 104 and 117 sampling day. During the 2018/19 cropping season, low density cowpeas emitted more CO_2 between 11 and 56 sampling day (DAP) than high density cowpeas (Figure 4.5a). CO_2 emissions ranged between 0.05 t ha^{-1} day^{-1} and 0.87 t ha^{-1} day^{-1} at low density, and between 0.05 t ha^{-1} day^{-1} and 0.058 t ha^{-1} day^{-1} at a high density from 11DAP to 56DAP. CO_2 emissions did not differ between binary and sole cultures, as well as low and high cowpea density, between 76 and 112 sampling day, according to the findings. CO_2 emissions rates in low and high density were comparable from 39 to 91 sampling day in the 2020/21 cropping season. Low density, on the other hand, emitted more CO_2 than high density from 104 to 117 sampling day (Figure 4.5b).

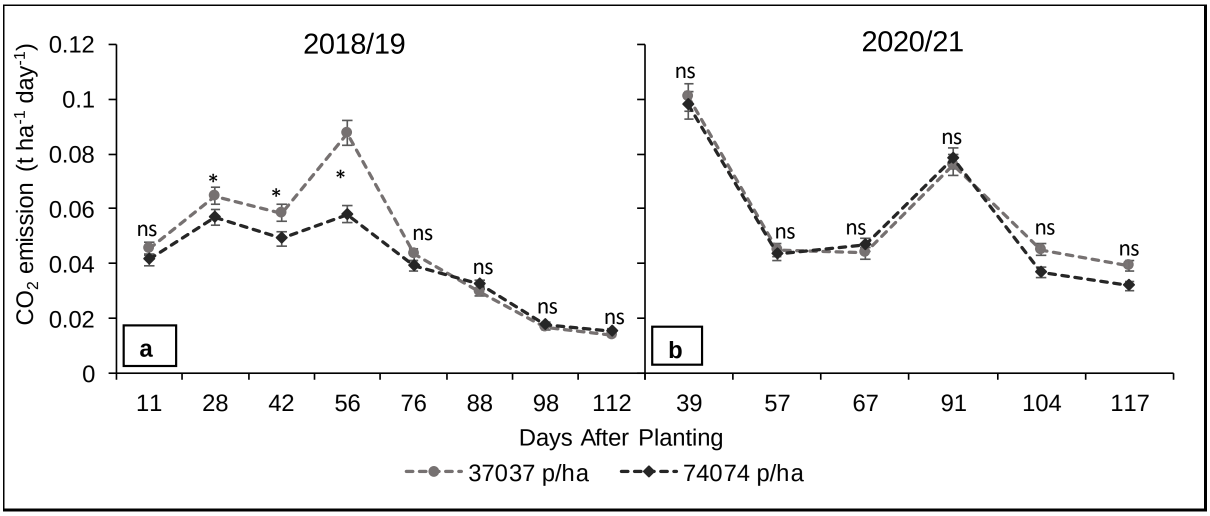

Figure 4.5 CO_2 emission rate in low and high density of cowpea at Syferkuil during the 2018/19 and2020/21 cropping seasons. ns = not significant, * = significant at $p \leq 0.05$.

The results further revealed that the low density of the companion crop emitted more CO_2 compared to the high density from 39 to 63 sampling day. However, between 83 and 101 sampling day, CO_2 emission rates were similar in low and high density (Figure 4.6). On average, low density emitted about 0.098 t ha^{-1} day^{-1} from 39DAP to 63DAP, while under high density, 0.086 t ha^{-1} day^{-1} was emitted between the same sampling day.

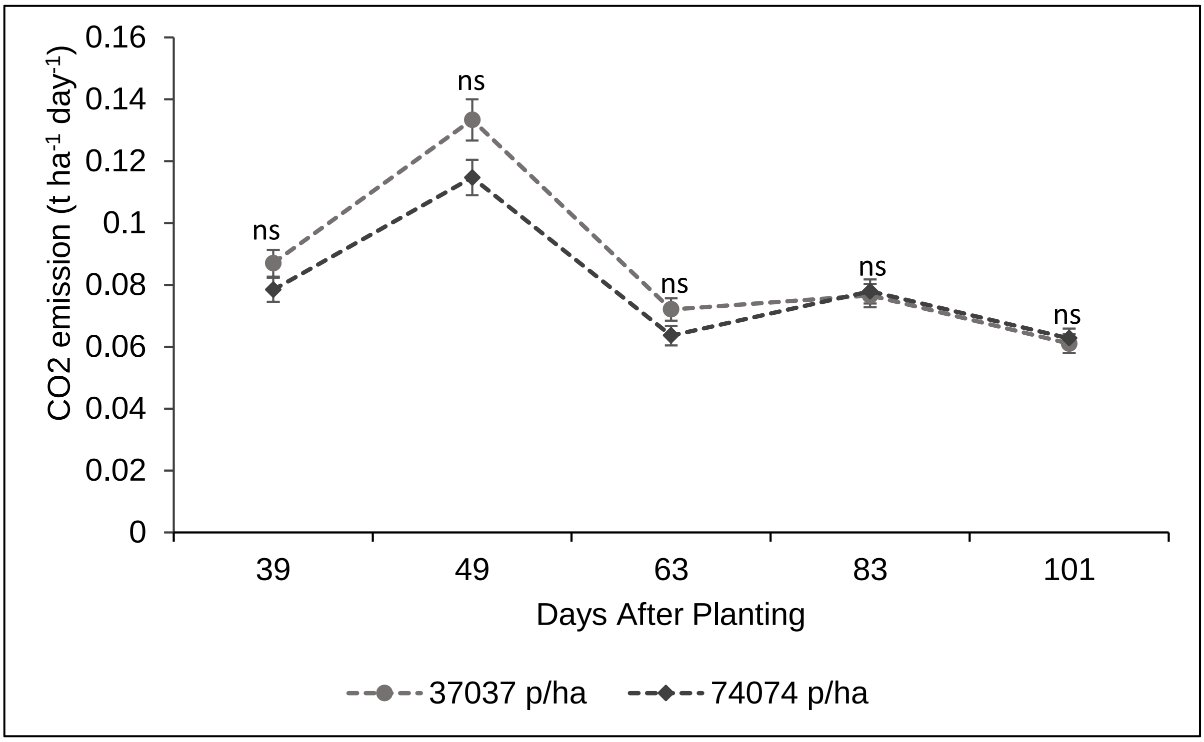

Figure 4.6 CO_2 emission rate in low and high density of cowpea at Ofcolaco during the 2020/21 cropping season. ns = not significant, * = significant at $p \leq 0.05$.

4.3.4 The CO_2 emission rate for each crop and the combination of the two crops

Sorghum had higher emissions of CO_2 in mono-cropping between 28 and 76 sampling day compared to cowpea in mono-cropping and the combination of sorghum and cowpea during the 2018/19 cropping season at Syferkuil (Figure 4.7a). The sorghum-cowpea combination emitted less CO_2 compared to when the two crops are planted in sole cultures between 28 and 76 sampling day. CO_2 emissions were similar in binary and sole cropping between 88 and 112 sampling day. When compared to other sampling dates during the 2020/21 cropping season, sorghum-cowpea combination and cowpea had high CO_2emissions 39 sampling day. Sorghum emitted less CO_2 in the sole at 39 sampling day. At 91 to 117 sampling day, CO_2 emissions were higher in cowpea soles compared to sorghum soles and the combination of sorghum and cowpea (Figure 4.7b). On average, cowpea sole emitted 0.060 t ha^{-1} day^{-1} of CO_2, while a combination of sorghum and cowpea and sorghum sole emitted 0.057 and 0.054 t ha^{-1} day^{-1}, respectively.

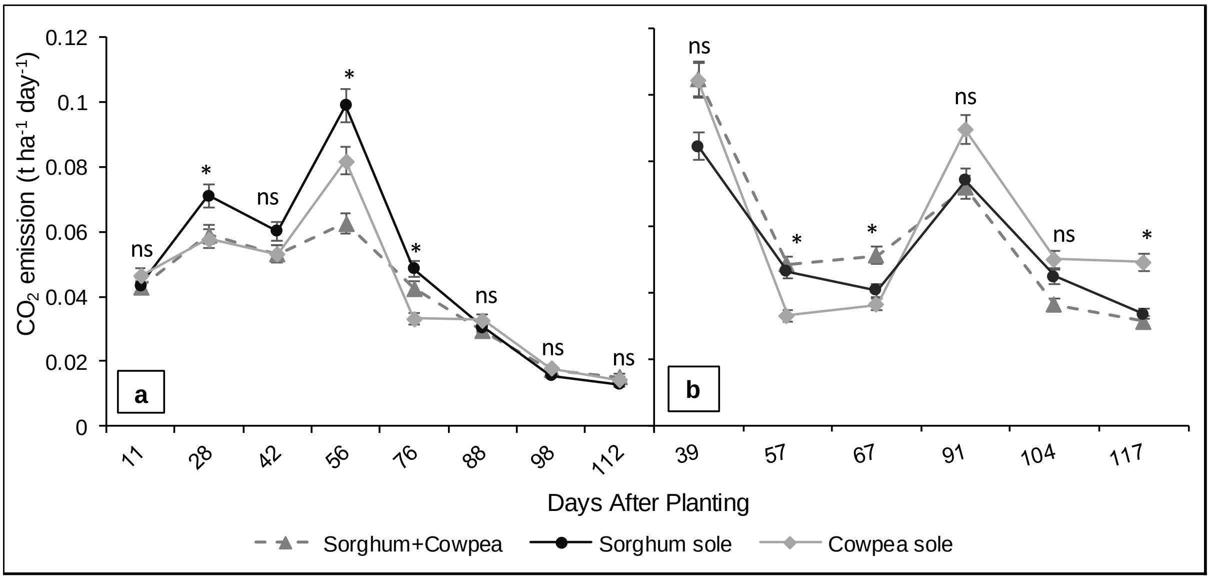

Figure 4.7 CO_2 emission rates of sorghum intercropped with cowpea, sorghum in sole and cowpea in sole cultures collected at Syferkuil during the 2018/19 (a) and 2020/21 (b) cropping seasons. ns = not significant, * = significant at p ≤ 0.05.

Cowpea sole had a higher CO_2 emission of 0.11 t ha^{-1} day^{-1} at 39 sampling day compared to sorghum sole (0.09 t ha^{-1} day^{-1}) and the combination of sorghum and cowpea (0.07 t ha^{-1} day^{-1}) at Ofcolaco (Figure 4.8). However, CO_2 emissions were similar for cowpea and sorghum in sole and binary at 49 sampling day. From 63 to 101 sampling day, cowpea sole had a higher emission of CO_2 compared to sorghum sole as well as the combination of the two crops.

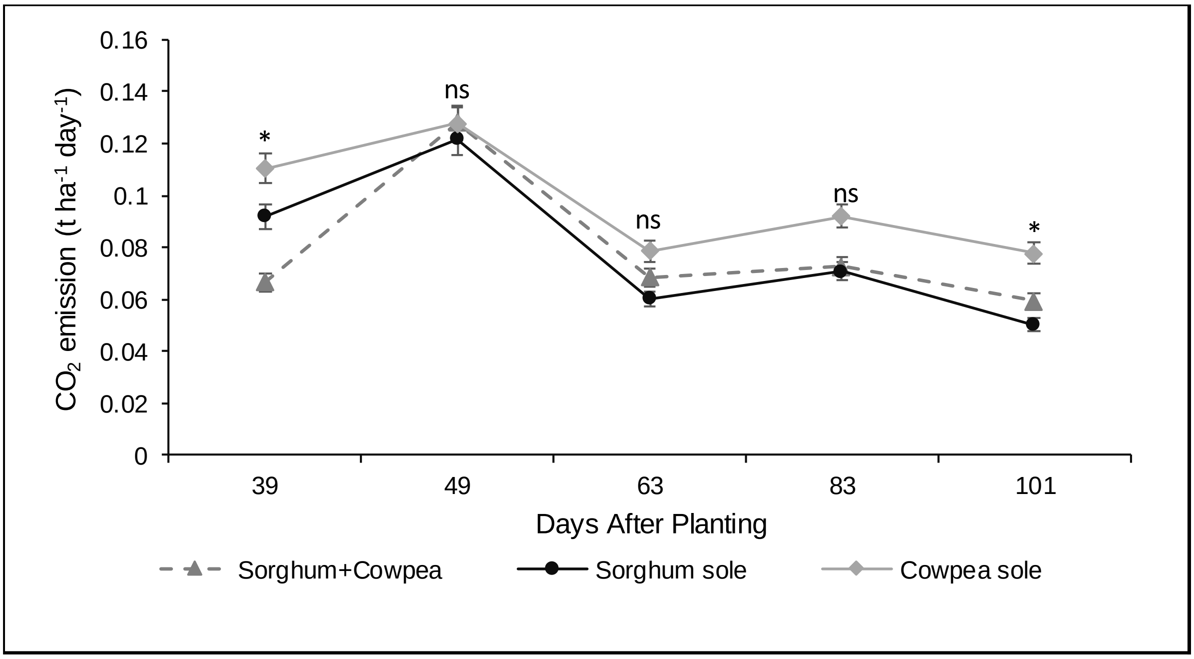

Figure 4.8 CO_2 emission rates of sorghum intercropped with cowpea, sorghum in sole and cowpea in sole cultures collected at Ofcolaco during the 2020/21 cropping season. ns = not significant, * = significant at $p \leq 0.05$.

4.3.5 The cumulative CO_2 emission during the growing seasons

The cumulative CO_2 emissions emitted during the 2018/19 cropping season were significantly different in binary and sole cultures (Figure 4.9a). In the 2020/21 cropping season, there was no variation in the cumulative CO_2 emitted in binary and sole cultures at Syferkuil. Ofcolaco showed a significant variation in cumulative CO_2 flux in sole and binary cultures during the 2020–21 cropping season. The cumulative CO_2 emissions were 13% and 26% more in sole compared to binary cultures at Syferkuil and Ofcolaco during the 2018/19 and 2020/21 cropping seasons, respectively (Figure 4.9a). The density of companion crops showed a significant variation in CO_2 emissions rates at Syferkuil during the 2018/19 cropping season. During the 2018/19 cropping season, there was a high emission of cumulative CO_2 at low density compared to high density. However, there was no significant difference in cumulative CO_2 flux at Syferkuil and Ofcolaco during the 2020/21 cropping season (Figure 4.9b). Although there was no statistical difference between low and high density during the 2020/21 cropping season at Syferkuil and Ofcolaco, more CO_2 was emitted under low density compared to high density (Figure 4.9b).

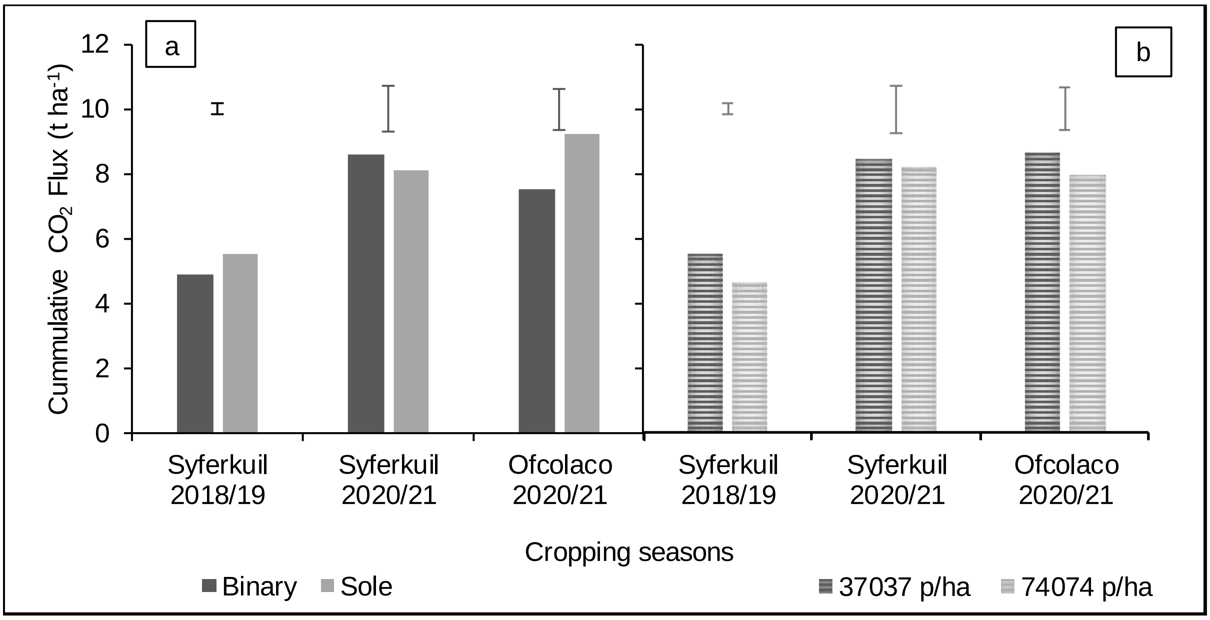

Figure 4.9 Cumulative CO_2 emission rates in binary and sole cultures (a) as well as low (37037 p/ha) and high (74074 p/ha) population density (b) at Syferkuil and Ofcolaco during the 2018/19 and 2020/21 cropping seasons.

Sorghum sole cumulatively emitted higher CO_2 in 2018/19 compared to cowpea sole and the intercrop of the two crops. However, in the 2020/21 cropping season, sorghum sole had the lowest cumulative CO_2 compared to cowpea when the two crops were intercropped together. At Ofcolaco cowpea sole had the highest cumulative CO_2 emitted followed by sorghum sole while the two crops emitted less when grown in intercropping system (Figure 4.10).

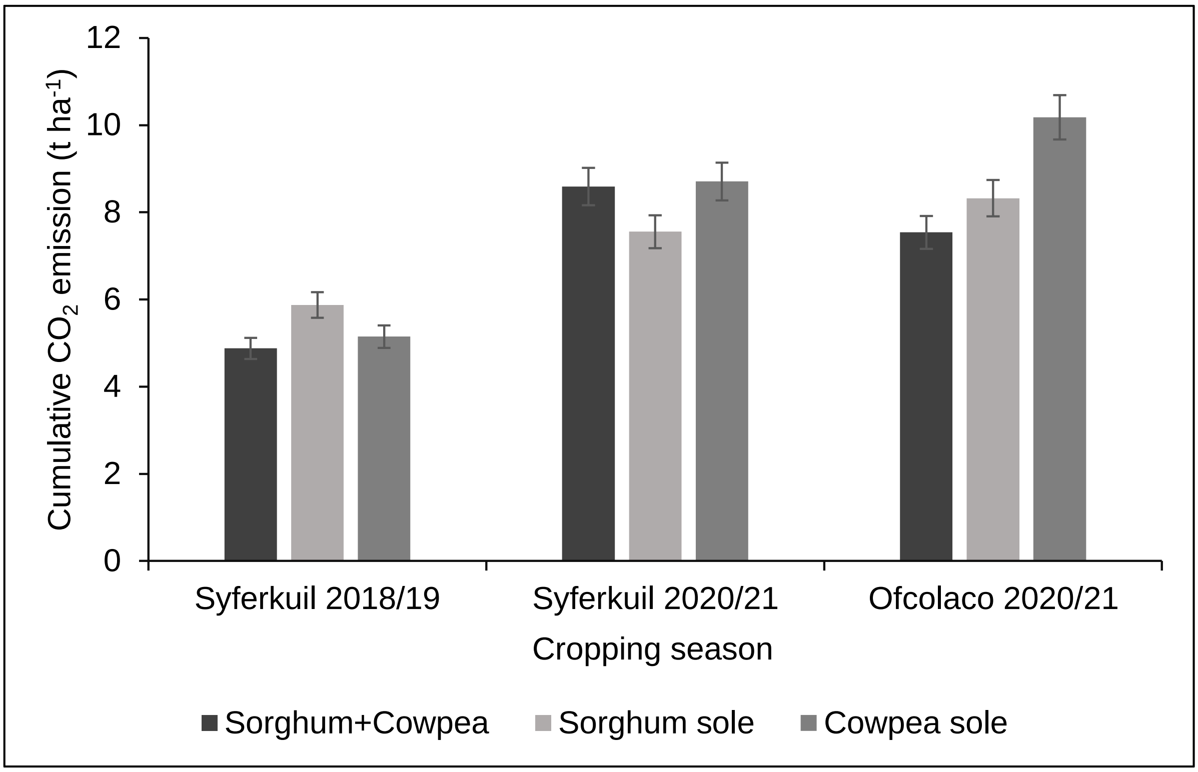

Figure 4.10 Cumulative CO_2 emission rates of sorghum and cowpea in binary and sole cultures at Syferkuil and Ofcolaco during the 2018/19 and 2020/21 cropping seasons.

The linear regressions of cumulative CO_2 at Syferkuil and Ofcolaco during the two cropping seasons are represented in Figure 4.11. The coefficient of determination (R^2) for all treatments in the sole cropping and intercropping systems was more than 0.9445 during the 2018/19 and 2020/21 cropping seasons. Sorghum intercropped with cowpea, sorghum and cowpea in sole cropping showed a strong linear relationship at the two locations. From 42DAP to 112DAP, a day increase resulted in cumulative CO_2 of sorghum sole increasing by 0.83 t ha^{-1} followed by cowpea sole with 0.70 ta ha^{-1}. Sorghum and cowpea intercrop emitted 0.66 t ha^{-1} CO_2 for an everyday increase during the 2018/19 cropping season (Figure 4.11a). At Syferkuil, the cumulative CO_2 was similar in sorghum sole cropping, cowpea sole, and a combination of sorghum and cowpea between 11DAP and 28DAP in the 2018/19 cropping season. In the 2020/21 cropping season, sorghum sole had 0.87 increase in CO_2 for every increase in days which was the lowest compared to cowpea sole and sorghum+cowpea at Syferkuil which had 0.92 and 0.94. The results from Ofcolaco indicated that cowpea sole had the highest cumulative CO_2 followed by sorghum sole during the 2020–21 cropping season (Figure 4.11b). At Ofcolaco, sorghum+cowpea had the lowest cumulative CO_2 flux compared to sole cultures. Cowpea sole had 1.5 t ha^{-1} followed by sorghum sole with 1.3 t ha^{-1} of CO_2 emitted with increase with each day whereas intercrop of the two crops had 1.2 t ha^{-1} of cumulative CO_2 emission (Figure 4.11c).

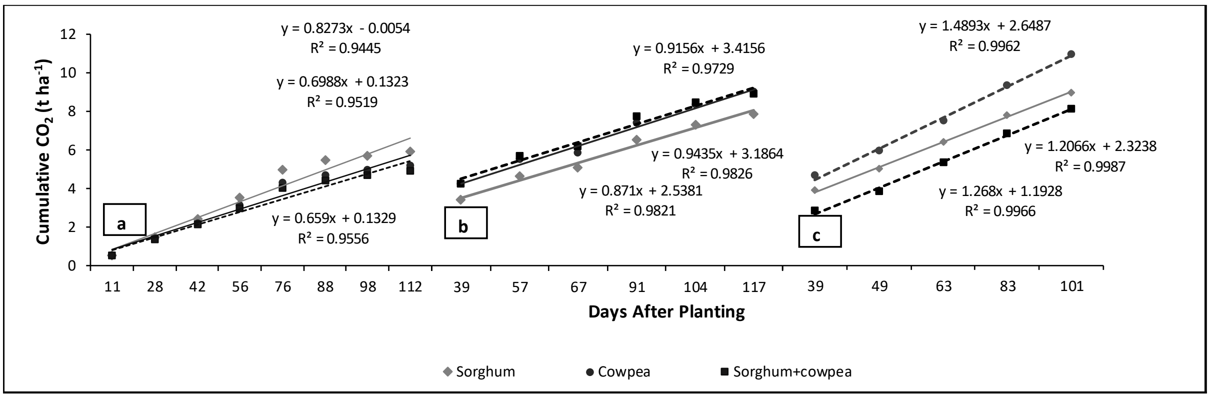

Figure 4.11 Cumulative CO_2 emissions during the growing seasons at Syferkuil during the 2018/19 (a) and 2020/21 (b) Ofcolaco in 2020/21 (c).

4.3.6 Carbon dioxide (CO_2) emission efficiency of sorghum and cowpea in sole cropping and intercropping system

The cropping system had a significant effect on the CO_2 emission efficiency (CEE) of sorghum and cowpea at Syferkuil in the 2018/19 cropping season. Cultivar NS5511 had a higher CEE when intercropped with cowpea, followed by cultivars Enforcer intercropped with cowpea and Enforcer sole, with means of 1.15, 1.10, and 1.00, respectively (Table 4.3). The treatments Avenger+Cowpea, Titan sole, and Avenger sole had lower CEE of 0.84, 0.82, and 0.74 compared to all other treatments. At Ofcolaco, the CEE of sorghum and cowpea was significantly affected by the cropping system in the 2020/21 cropping season. The treatment Avenger+Cowpea had a higher CEE of 0.75 compared to all other treatments in intercrop and sole systems (Table 4.3). The cultivar Enforcer utilized CO_2 emitted less efficiently compared to all other treatments.

Table 4.3 Carbon dioxide emission efficiency (CEE) of sorghum and cowpea in intercrop and sole systems at Syferkuil and Ofcolaco during the 2018/19 and 2020/21 cropping seasons.

Treatments	Syferkuil 2018/19	Syferkuil 2020/21	Ofcolaco 2020/21
NSS551-intercrop	1.15[a]	0.44	0.51[b]
Enforcer-intercrop	1.10[ab]	0.40	0.47[b]
Enforcer sole	1.00[abc]	0.41	0.27[c]
NSS5511 sole	0.97[abc]	0.51	0.45[b]
Titan-intercrop	0.90[bcd]	0.45	0.52[b]
Avenger-intercrop	0.84[cd]	0.44	0.75[a]
Titan sole	0.82[cd]	0.57	0.55[b]
Avenger sole	0.74[d]	0.49	0.58[b]
Grand mean	0.94	0.46	0.51

Means followed by the same letter were significantly different at $p \leq 0.05$

Cowpea sole had the highest CEE of 0.83 compared to all other cowpea treatments in the intercropping system. In the 2020/21 cropping season, the cropping system did not affect sorghum; only cowpea showed significant variation in terms of CEE (Table 4.4). In terms of cowpea, all cowpea treatments in the intercropping system utilized CO_2 emitted more efficiently at Ofcolaco compared to the sole system as shown in Table 5.4.

Table 4.4 Carbon dioxide emission efficiency (CEE) of sorghum and cowpea in intercrop and sole systems at Syferkuil and Ofcolaco during the 2018/19 and 2020/21 cropping seasons.

Treatments	Syferkuil 2018/19	Syferkuil 2020/21	Ofcolaco 2020/21
Cowpea sole	0.83[a]	0.65[a]	0.49[b]
Cowpea-intercrop with Titan	0.69[ab]	0.53[ab]	0.84[a]
Cowpea-intercrop with NS551	0.61[b]	0.51[b]	0.74[a]
Cowpea-intercrop with Avenger	0.50[b]	0.41[b]	0.66[ab]
Cowpea-intercrop with Enforcer	0.50[b]	0.41[b]	0.63[ab]
Grand mean	0.63	0.50	0.67

Means followed by the same letter were significantly different at $p \leq 0.05$

4.3.7 The relationship between carbon stocks and CO_2 emission rate of intercropped and sole treatments

Carbon stocks and CO_2 flux were regressed for each treatment in binary and sole cultures for the two cropping seasons at the test locations (Figure 4.12, 4.13 & 4.14). The results presented are of the treatments that showed either a strong negative or strong positive relationship between carbon stock and CO_2 flux. At Syferkuil, Avenger+cowpea, Enforcer+cowpea, and cowpea sole showed negative regression, whereas Titan+cowpea had a strong positive linear regression between carbon stocks and CO_2 flux during the 2018/19 cropping season (Figure 4.12).

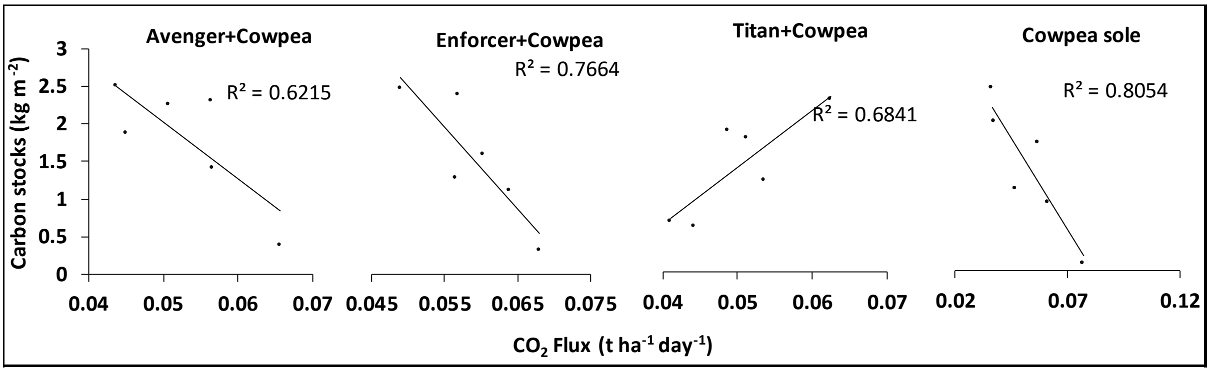

Figure 4.12 Carbon stocks (y-axis) versus CO_2 emission rate (x-axis) of sorghum and cowpea in binary and sole cultures at Syferkuil during the 2018/19 cropping season.

During the 2020/21 season, the intercropping systems, Avenger+cowpea, Titan+cowpea, and NS5511+cowpea resulted in a negative linear relationship between carbon stocks and CO_2 flow at Syferkuil (Figure 4.13). Cowpea sole showed a positive relationship between carbon stock and CO_2 flux.

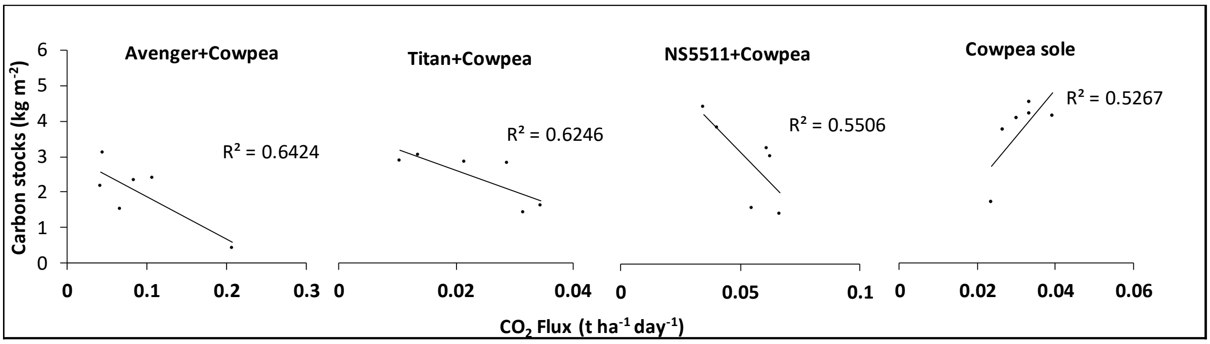

Figure 4.13 Carbon stocks (y-axis) versus CO_2 emission rates (x-axis) of sorghum and cowpea in binary and sole cultures at Syferkuil during the 2020/21 cropping season.

The results from Ofcolaco revealed that the relationship between carbon stock and CO_2 flux in Avenger+cowpea intercrop was best described using a polynomial (Figure 4.14). The treatments Enforcer+cowpea and cowpea sole indicated a strong negative linear regression between carbon stocks and CO_2 flux at Ofcolaco during the 2020/21 cropping season. Of all the treatments, NS5511+cowpea was the only treatment to show a strong linear regression between carbon stocks and CO_2 flux at Ofcolaco in the 2020/21 cropping season.

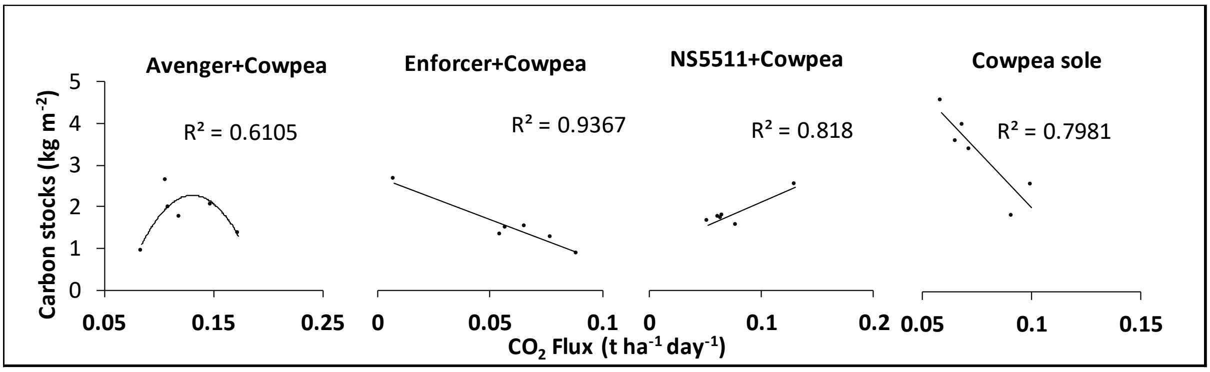

Figure 4.14 Carbon stocks (y-axis) versus CO_2 emission rates (x-axis) of sorghum and cowpea in binary and sole cultures at Ofcolaco during the 2020/21 cropping season.

4.4 DISCUSSION

4.4.1 Weather conditions during the growing seasons and the effect on carbon emissions

The amount of carbon stored in the soil is calculated by balancing the carbon inputs from crop residues with the carbon loss from emissions into the atmosphere (Hu *et al*., 2015). These carbon dynamics in crop production are influenced by cropping systems, management practices, soil conditions such as soil moisture and bulk density as well as climatic variability. The amount of CO_2 emitted in this study was influenced by the cropping system, the number of plants per unit area (plant density), and the environmental conditions such as temperatures and precipitation of each growing season. Weather variables such as temperature and precipitation were found to play a significant role in the variation in CO_2 emissions from one cropping season to the next in this study. The rainfall and temperature in this study were different from one season to another and across locations. High rainfall in 2020/21 and the minimum temperature of more than 10 ^{o}C resulted in higher CO_2 emission rates. Warmer summer temperatures, according to Munjonji *et al*. (2021), are the driving factors in the soil releasing more cumulatively CO_2.These findings suggest that seasonal environmental conditions especially temperature and precipitations had an impact on CO_2 emissions. The fluctuations and seasonal variations were also reported by other authors (Munjonji *et al*., 2021, Gou *et al*., 2021).

4.4.2 CO_2 emission under monocrop and intercrop systems

During the 2018/19 season at Syferkuil and 2020/21 seasons at Ofcolaco, intercropping systems emitted 11% and 19% less CO_2 respectively compared to sole cropping systems. Other authors have also reported relatively low CO_2 emissions in intercropping systems (Chai *et al*., 2014, Gou *et al*., 2021, Pereira *et al*., 2021). Therefore, planting two crop species on the same plot of land reduces CO_2 emissions compared to planting only one species as a result of the interaction between intercropping populations (Małecka *et al*., 2015). Furthermore, Hauggaard-Nielsen *et al*. (2016) reported that the lower CO_2 emissions in cereal-legume intercropping compared to sole cropping are due to the use of fewer amounts of nitrogen fertilizers. Synthetic fertilizers are the primary source of greenhouse gas emissions in cropping systems and thus, planting in a sole cropping system would require more fertilizers to improve productivity. However, in an intercropping system, cereal plants could benefit from the legume thereby reducing the cost of fertilizer. Cereal-legume intercrop may be an appropriate production practice for mitigating high CO_2 emissions as shown by the findings of this study (Tongwane *et al*., 2016).

Our findings also revealed that sorghum sole cropping produced more CO_2 than cowpea sole cropping or the intercrops. Many studies have found that cereal crops emit significantly more CO_2 than legumes or cereal-legume intercrops (Makumba *et al*., 2007, Yin *et al*., 2017, Yang *et al*., 2021). According to Shao *et al*. (2018), as a coping mechanism for high competition in an intercropping system, cereal crops inhibit growth by reducing their root node. As a result, more CO_2 may be emitted by crops rather than utilized for photosynthetic activities. In this study, sorghum in intercropping system emitted more CO_2 during the growing period and began to decrease when cowpea was harvested 76 sampling day. The author also stated that the CO_2 peak occurred at the same time in intercrop and sole cropping and decreased significantly as crops matured and harvested. A similar pattern was observed in this study. CO_2 emission rate decreased after crops have reached flowering and milking stages and were moving towards maturity.

4.4.3 Different cowpea densities and CO_2 emissions

Plant density is frequently used to gain yield advantage per unit area. The density of the companion crop cowpea had a significant effect on CO_2 emissions in this study where a relatively higher emission of CO_2 was recorded at low density than at high density. The findings contradicted what Yang *et al*. (2021) discovered, as the author reported that high maize density increased CO_2 emissions compared to low density. High density increases plant community components such as dry biomass as a result of efficient utilization of carbon in the soil (Wang *et al*., 2018).

4.4.4 Carbon dioxide emission efficiency of intercropping and sole cropping sorghum and cowpea

CO_2 emission efficiency is used to calculate how much dry biomass or grain yield is accumulated per unit of carbon emitted under various crop production practices (Hu *et al*., 2015). The study's findings revealed that cropping system had a significant effect on the CEE of sorghum and cowpea across various agro-ecological conditions. Intercropping has a higher CEE than sole cropping, according to Yin *et al*. (2017). The higher CEE for cultivars NS5511 and Enforcer reported in this study indicates that the cultivars were able to accumulate more biomass per unit of carbon emitted from the soil. CEE by sorghum cultivars, on the other hand, was influenced by cropping season and agro-ecological regions. When compared to Syferkuil, Avenger was able to use carbon more efficiently in intercrop and monocrop at Ofcolaco. The results also revealed that cowpea sole cropping had higher CEE than intercropping at Syferkuil due to less competition and an improved root system (Chen *et al*., 2013). Cowpea intercropping had a higher carbon use efficiency than sole cropping at Ofcolaco. According to Mathew *et al*. (2020), carbon allocation is affected by crop species and growing environment temperature.

4.4.5 Physical and chemical properties of the soil

Regression analysis can be used to determine the relationship between carbon stocks and CO_2 emission rates. Intercropping and sole cropping treatments were used in this study to regress CS and CE. The findings revealed that the strength of the relationship between the two variables varied according to the treatment, which differed from one agro-ecological region to the next. At Syferkuil, soil carbon stocks increased with an increase in gravimetric water content which also resulted in high organic carbon. Although the cropping system had no significant effect on the physical and chemical properties of the soil, visualization revealed variation from one location to another and across seasons. For example, BD, org.C, and CS were higher in 2020/21 at Syferkuil compared to the 2018/19 cropping season. However, at Ofcolaco, BD, org.C, and CS were higher during the 2018/19 cropping season than during the 2020/21 cropping season. The results were in contrary with what Abbady *et al*. (2016) reported. The author indicated that soil properties such as BD and moisture content were significantly affected by the cropping system. Furthermore, the seasonal variability and treatment effect showed differences in soil properties in intercropping and sole cropping systems. The seasonal variability effect on soil physical and chemical properties was also observed in this study. Across all cropping seasons of test locations, cropping system did not affect P, K, Ca, Mg, Zn, Mn, and Cu. Munjonji *et al*. (2020) reported no significant difference for P, K, Ca, Mg, Zn, Mn and Cu under drought conditions.

4.5 CONCLUSION

Findings from the study revealed that cowpea-sorghum intercrop released less soil CO_2 compared to the monocrops of the two crops and hence, could be a more sustainable crop production practice. This assists with provision of data on intercropping system as a sustainable crop production practice with protection to cultivated land. Furthermore, growing crops in intercrops improved the crop's carbon emission efficiency. More dry matter (biomass) is accumulated with the reduction in CO_2 emission. When the two crops were planted as monocultures, sorghum was found to emit more CO_2 than cowpea. Cowpea density also significantly impacted CO_2 emission rates, with high density (74074 plants per hectare) emitting less soil CO_2. Furthermore, the study found that agro-ecological conditions that differ from season to season play an important role in carbon dynamics in the soil. This implies that the long-term seasonal CO_2 emissions in intercropping system is required to understand the patterns of flux over a magnitude of growing period. The findings from this study may be useful in understanding the importance of intercropping systems on carbon storage and loss. However, more research is needed to fully understand how intercropping systems and conservation practices such as no-till systems affect CO_2 emissions. Furthermore, root activities should be investigated to observe the carbon dynamics between plants and soil.

CHAPTER 5: THE EFFECT OF GRAIN SORGHUM-COWPEA INTERCROPPING ON BIOLOGICAL NITROGEN FIXATION (BNF) OF COWPEA IN CONTRASTING ENVIRONMENTS OF LIMPOPO PROVINCE.

Abstract

Nitrogen recycling under sustainable agricultural practices such as intercropping system has not been investigated in diverse low soil fertility agro-ecological regions. A randomized complete block design in a factorial arrangement was conducted to determine the biological nitrogen fixation (BNF) of cowpea when intercropped with different cultivars of grain sorghum at the two test locations of Limpopo province. The nitrogen (N) from the isotopes ($\delta\ ^{15}N$‰) ranged from 0.2 ‰ to 4‰ at Ofcolaco whereas at Syferkuil, the range was from 2 ‰ to 7 ‰. The N derived from the air (Ndf) was from 35% to 92% at Ofcoalco and from 4% to 70% at Syferkuil during the two cropping seasons. During the cropping seasons, cowpea had more N derived from the atmosphere at Ofcolaco than at Syferkuil. However, the ^{15}N at Ofcolaco was lower than at Syferkuil. This was a result of low soil N at Ofcolaco compared to at Syferkuil. A significant variation in N-fixed by cowpea in intercropping system was observed during the 2020/21 cropping season at Ofcolaco, but not at Syferkuil. The amount of N_2 fixed across locations and seasons ranged from 1 kg ha^{-1} to 70 kg ha^{-1}. Cowpea fixed and accumulated approximately 42 % more N in sole cultures in 2020/21 than binary cultures. Cowpea in sole accumulated approximately 50% more N than binary cultures at Syferkuil. Cowpea fixed more N under high density compared to low density. According to the findings of this study, an intercropping system can improve the biological nitrogen fixation of cowpea at high than low density in an intercropping system. Furthermore, the companion crop sorghum cultivar should be considered because it influenced N_2 fixation and uptake by cowpea in the system.

Key words: ^{15}N natural abundance, Nitrogen accumulation, plant density, intercropping system

5.1 INTRODUCTION

Food insecurity in Sub-Saharan Africa has become one of the topics that researchers pay attention to in recent years. Some of the major staple crops including grain sorghum and cowpea have declined in terms of production due to extreme weather events such as drought and heat waves. Modern agricultural production practices such as conventional tillage and excessive application of fertilizers have resulted in environmental problems such as pollution and ultimately crop productivity(Sánchez, 2010; van Ittersum, 2016). Nitrogen (N) is one of the essential yet liming nutrients that is required by plants in large quantities for increased growth and productivity (Salgado *et al*., 2021). Plants access N through soil, biological nitrogen fixation and application of chemical and organic fertilizers, with the application of chemical N fertilizers being the common practice in Africa (de Freistas *et al*., 2012). The practice has proved to be ineffective due to fertilizer costs which weaken the revenues of smallholder farmers (Bado *et al*., 2018). Deployment of sustainable agricultural practices is required to improve soil fertility while increasing the N cycle and availability in the soil.

Intercropping system which is the planting of two crops simultaneously on the same piece of land has been widely adopted as sustainable practice in Africa. The practice is known for its ability to utilize nutrients in the soil efficiently while enhancing land productivity (Khashi u Rahman *et al*., 2021). Recycling of N through BNF in the intercropping system is important in areas with poor soil fertility to enhance crop production. Cowpea is one of the legume crops grown for its grain and livestock feed in many rural areas of South Africa, particularly Limpopo Province. The crop like other legumes such as soybean, groundnut etc is grown on soil with poor soil fertility due to its ability to fix atmospheric nitrogen (N_2) (Keston *et al*., 2017). Bado *et al*., 2006 explained that legumes such as groundnut and cowpea increase N by up to 52% in the soil as a result of efficient use of N which may be beneficial to cereal crops in intercrop or rotation systems. Hence, biological nitrogen fixation (BNF) plays a key role in the provision of N to legumes as well as its component crop in the intercropping system (de Freitas *et al*., 2012). BNF by legumes in an intercropping system increases the availability of N which is beneficial in areas with poor soil fertility (Nezomba *et al*., 2015).

Most cropping systems' studies in the Limpopo Province of South Africa have focused on BNF in sole cropping or maize-legume intercrop and little on grain sorghum intercrops. Furthermore, not much has been done on how N_2 fixation by cowpea is influenced by different cultivars of cereal crops in intercropping system. There is also limited information on the influence of different populations of cowpea on BNF under different climatic conditions in Limpopo Province. Hence, this paper aimed at (i) comparing biological nitrogen fixation of cowpea in binary and sole cultures grown under no-tillage, (ii) documenting the effect of different densities of cowpea on N_2 fixation, and (iii) determining the quantity of biological N_2 fixed by cowpea when intercropped with different cultivars of sorghum under contrasting agroecological conditions.

5.2 MATERIALS AND METHODS

The study sites, soil sampling, experimental set-up and managemnet, are the same as described in section 3.1.2. in chapter 3.

5.2.1 Sampling details

Cowpea and sorghum aboveground biomass was collected 63 and 83 sampling days respectively in intercropping and sole cropping systems at an area of 2.7 m^2 during the two cropping seasons at Syferkuil and Ofcolaco. Collected samples were oven-dried at the temperature of 65 ^oC until they reached constant mass. The samples were ground using a Wiley mill and taken to the laboratory for analysis.

5.2.2 $\delta\,^{15}N$ Natural Abundance ($\delta^{15}N‰$)

The total nitrogen (%) and natural abundance of ^{15}N ($\delta\,^{15}N‰$) were analyzed in the laboratory using an isotope ratio mass spectrometer with an N analyzer (IRMS)-N 20-20 ANCA GSL. The following standard formula was used to determine the natural abundance of ^{15}N as described by (Salgado *et al*., 2021):

$$\delta\,^{15}N‰ = [(R_{sample} / R_{standard})-1] \times 1000$$

where:

$\delta^{15}N_{sample} = [(R_{sample}/R_{standard}) -1] \times 1000$ where; $\delta^{15}N_{sample}$ is the value of the $\delta^{15}N$ of the N_2 fixing plant (cowpea), R_{sample} is the sample isotope ratio ($^{15}N/^{14}N$), $R_{standard}$ is $^{15}N/^{14}N$ for atmospheric N_2 (0.0036765)

5.2.3 Biological Nitrogen Fixation (BNF)

Biological Nitrogen Fixation was determined using N derived from the atmosphere (%Ndfix) using ^{15}N natural abundance method as shown in the formula below:

$$\%NDFA = (\delta^{15}N_{referenceplant} - \delta^{15}N_{legume})/(\delta^{15}N_{referenceplant} - \beta)$$

where: $\delta^{15}N_{referenceplant}$ is the value of the $\delta^{15}N$ of the N taken up from the soil, obtained in leaves of the spontaneous plants used as the non-fixing reference (sorghum), $\delta^{15}N_{legume}$ is the value of the $\delta^{15}N$ of the N_2 fixing plant (cowpea), β is the ^{15}N value of cowpea.

NDFA is nitrogen derived from the air.

5.2.4 Nitrogen fixed and accumulated

Nitrogen accumulated and fixed were determined using the following formular:

$$N\ accumulated = \%N\ x\ Biomass$$

$$N\ fixed = (Ndfa\ x\ N\ accumulated)/100$$

5.3 RESULTS

5.3.1 Post-harvest soil analysis

Cropping system did not have significant effect on residual soil N and organic carbon at the end of each experimental period during the two cropping seasons (Table 5.1). However, the organic carbon at Ofcolaco was higher throughout the two seasons compared to Syferkuil. The soil carbon stocks as well as CN ratio were also generally higher at Ofcolaco compared to Syferkuil but the %residual N was higher at Syferkuil compared to Ofcolaco.

Table 5.1 Soil Nitrogen and carbon data collected at Ofcolaco and Syferkuil at the end of 2018/19 and 2020/21 cropping seasons.

Soil properties	Ofcolaco 2018/19		Ofcolaco 2020/21		Syferkuil 2018/19		Syferkuil 2020/21	
	Sole	Binary	Sole	Binary	Sole	Binary	Sole	Binary
Org.C (%)	0.02±0.03	0.02±0.04	0.01±0.04	0.01±0.03	0.30±0.03	0.30±0.03	0.79±0.40	0.77±0.30
N(%)	0.03±0.04	0.03±0.03	0.02±0.03	0.03±0.03	0.05±0.04	0.05±0.05	0.07±0.40	0.06±0.40
C:Nratio	65.20±8.00	56.50±6.70	93.00a±10.60	58.30±8.3	13.00±1.8	13.60±1.1	12.20±0.75	13.00±0.6
CS(kg m^{-2})	6.20±0.5	7.50±0.42	2.30±0.13	2.70±0.10	1.20±0.12	1.30±0.09	3.00±0.19	3.00±0.15

Org.C = organic carbon, N = nitrogen, C:N ratio = carbon nitrogen ratio, CS = carbon stocks.

5.3.2 The effect of cropping system on δ15N‰, Ndfa%, N-fixed and N accumulated by Cowpea

The cropping system did not affect N isotopic composition ($\delta^{15}N$‰) and nitrogen accumulated from biological nitrogen fixation (Ndfa%) at Ofcolaco and Syferkuil during the two cropping seasons of 2018/19 and 2020/21. There was also no effect of cropping system on the amount of nitrogen fixed and accumulated by cowpea at Ofcolaco in 2018/19 or Syferkuil in 2018/19 or 2020/21. However, in 2020/21, cowpea fixed approximately 42 % more N in sole compared to binary at Ofcolaco. Only N-accumulated differed between sole and binary cultures at Syferkuil. Cowpea accumulated approximately 55% more N in sole compared to binary culture in the 2020/21 cropping season at Syferkuil (Figure 5.1).

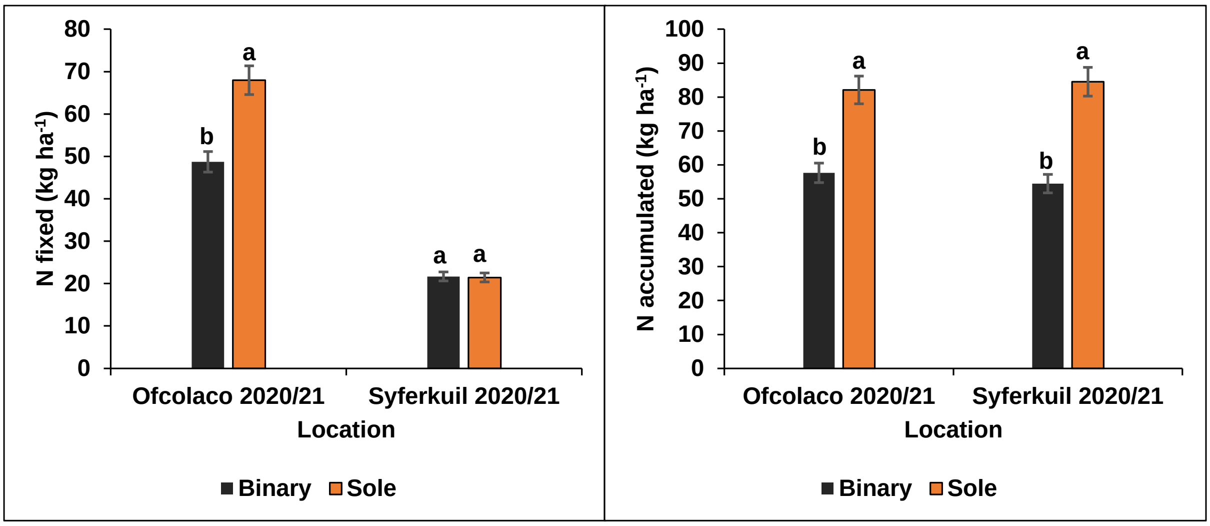

Figure 5.1 Nitrogen fixation and accumulation in cowpea sole and binary cultures at Ofcolaco and Syferkuil during 2020/21 cropping season.

5.3.3 The effect of plant density on δ15N‰, Ndfa%, N-fixed and N accumulated by Cowpea

During the two cropping seasons, cowpea density had no effect on ^{15}N and Ndfa at Ofcolaco and Syferkuil. In 2020/21 cropping season, N_2 fixed and accumulated were not significantly different at Ofcolaco under high and low density.However, in the 2018/19 cropping season, the N_2 fixed and N accumulated significantly varied ($p \leq 0.05$) between cowpea densities at the two test locations. Cowpea fixed and accumulated more N when planted at a density of 74074 plants ha^{-1} relative to 37037 plants ha^{-1}. The amount fixed and accumulated was more than half in high density compared to low density at Ofcolaco and Syferkuil (Figure 5.2).

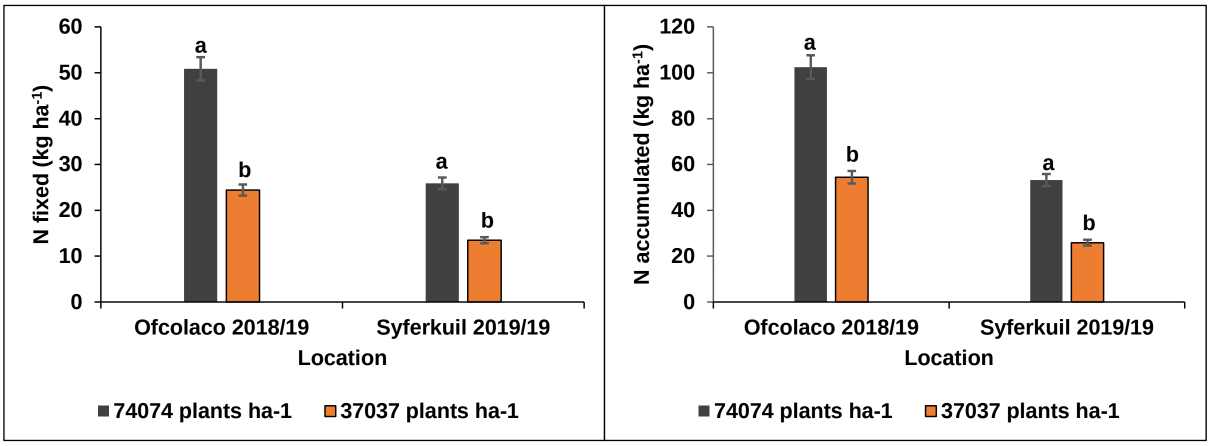

Figure 5.2 Nitrogen fixation and accumulation in different cowpea densities at Ofcolaco and Syferkuil during the 2018/19 cropping season.

5.3.4 The response of cowpea treatments in binary and sole culture

The cowpea treatments showed no significant variation in terms of ^{15}N and Ndfa in sole and binary cultures at Ofcolaco during the 2018/19 and 2020/21 cropping season. At Syferkuil ^{15}N and Ndfa were not significantly different in 2018/19 but in 2020/21, the treatments in sole and binary cultures were different at $p \leq 0.05$ (Table 5.2). Although the results revealed that statistically, cowpea in binary and sole culture was not different, high cowpea density in an intercropping system with NS5511 had the highest ^{15}N of 4.2‰ followed by low-density cowpea with Titan and low-density cowpea with NS5511 treatments. The results from Syferkuil indicated that ^{15}N and Ndfa were not different in the 2018/19 season but differences were observed among cowpea treatments in the 2020/21 cropping season. Cowpea low-Avenger, cowpea low-sole, cowpea high-Avenger and cowpea high NS5511 had higher ^{15}N compared to all other cowpea treatments with the means of 5.78‰, 4.85‰, 4.30‰ and 4.24‰ respectively at Syferkuil in 2020/21 season. Cowpea had the lowest ^{15}N when intercropped with Enforcer under low density. However, the same treatments (cowpea low-Enforcer) had the highest Ndfa of 56% compared to all the treatments in sole and binary cultures (Table 5.2).

Table 5.2 δ15N natural abundance (15N‰) and nitrogen accumulated from biological nitrogen fixation (Ndfa%) of cowpea in sole and binary cultures at Ofcolaco and Syferkuil during the two cropping seasons.

	Ofcolaco				**Syferkuil**			
	2018/19		**2020/21**		**2018/19**		**2020/21**	
Treatments	**δ15N**	**Ndf**	**δ15N**	**Ndf**	**δ15N**	**Ndf**	**δ15N**	**Ndf**
Cowpea low-Avenger	2.99^{abc}	54.57^{abc}	0.38	88.68	4.19^{ab}	65.69^{ab}	5.78^{a}	4.61^{c}
Cowpea low-sole	3.22^{abc}	51.01^{abc}	0.45	86.20	6.61^{ab}	45.71^{ab}	4.85^{ab}	20.10^{bc}
Cowpea high-avenger	3.84^{abc}	41.39^{abc}	0.38	84.35	4.28^{ab}	64.95^{ab}	4.29^{abc}	29.41^{abc}
Cowpea high-sole	3.94^{abc}	39.86^{abc}	0.63	80.09	6.27^{ab}	48.55^{ab}	3.72^{bc}	38.88^{bc}
Cowpea low-Enforcer	2.30^{c}	65.23^{a}	0.73	76.97	6.05^{ab}	50.34^{ab}	2.69^{c}	55.98^{a}
Cowpea low-NS5511	4.15^{ab}	36.75^{bc}	0.71	77.60	5.92^{ab}	51.38^{ab}	3.25^{bc}	46.75^{ab}
Cowpea high-Titan	3.28^{abc}	50.02^{abc}	0.67	77.74	6.74^{ab}	44.64^{ab}	3.04^{bc}	50.21^{ab}
Cowpea high-NS5511	4.22^{a}	35.59^{c}	0.25	92.96	7.10^{a}	41.68^{b}	4.24^{abc}	30.28^{abc}
Cowpea high-Enforcer	2.32^{bc}	64.84^{ab}	0.64	79.72	3.58^{b}	70.76^{a}	2.57^{c}	57.90^{a}
Cowpea low-Titan	4.19^{a}	36.14^{c}	0.29	91.70	4.65^{ab}	61.88^{ab}	3.60^{bc}	40.92^{ab}
Grand mean	3.45	47.54	0.53	83.7	5.54	54.56	3.80	37.50

Means with the same letters were not different at $p \leq 0.05$. Ndf = nitrogen derived from the air, 15N = the value of N_2 fixed by cowpea.

The amount of N_2 fixed, accumulated in the tissue and aboveground dry matter produced were significantly different among cowpea treatments in sole and binary cultures at Ofcolaco during the two cropping seasons (Table 5.3). The cowpea intercrop with Enforcer at high density fixed more N of about 60 kg ha^{-1} compared to other treatments in sole and binary cultures in the 2018/19 season. Cowpea sole high density also fixed more N compared to other treatments with the mean of 59.7 kg ha^{-1} at Ofcolaco during 2018/19 season. Sole cowpea under high density accumulated 117.04 kg ha^{-1} of N whereas the aboveground biomass produced was 3701.2 kg ha^{-1}. The results also revealed that sole cowpea, as well as cowpea intercropped with Titan, and Avenger under low density fixed the lowest N_2 and also accumulated the lowest tissue nitrogen compared to all the treatments in the 2018/19 cropping season. In terms of aboveground dry matter production, low-density cowpea intercropped with Avenger and Titan were reduced compared to all other treatments, with means of 1378.7 kg ha^{-1} and 1459.3 kg ha^{-1} respectively. During the 2020/21 cropping season, cowpea sole under low density fixed and accumulated more N of 96 kg ha^{-1} and 82 kg ha^{-1} respectively than any other treatment in sole and binary cultures (Table 5.3). Cowpea intercrop with NS5511 under high density accumulated the lowest N of 43 kg ha^{-1} with lower aboveground dry matter of 1314 kg ha^{-1} compared to all other treatments in sole and binary cultures.

Table 5.3 N fixation, accumulation and aboveground dry matter of cowpea in sole and binary cultures at Ofcolaco during the two cropping seasons.

	Ofcolaco					
	2018/19			**2020/21**		
	kg ha^{-1}					
Treatments	**N_2 fixed**	**N accumulated**	**Dry matter**	**N_2 fixed**	**N accumulated**	**Dry matter**
Cowpea low-Avenger	25.148^{cd}	$48.41d^{e}$	1387.7^{e}	66.03^{ab}	72.749^{abc}	2468.3^{abc}
Cowpea high-sole	59.697^{ab}	117.04^{a}	3701.2^{a}	64.98^{ab}	81.885^{a}	2850.6^{a}
Cowpea high-Avenger	37.592^{bc}	93.55^{ab}	3022.2^{abc}	49.17^{b}	57.764^{abcd}	1870.4^{bcd}
Cowpea low-sole	24.208^{cd}	59.18^{bcde}	1974.1^{cde}	70.93^{a}	82.292^{a}	2496.3^{ab}
Cowpea low-Enforcer	39.507^{abc}	57.89^{cde}	2004.9^{cde}	36.19^{b}	46.816^{cd}	1582.1^{cd}
Cowpea low-NS5511	20.468^{cd}	55.26^{cde}	1932.9^{de}	40.75^{ab}	49.917^{bcd}	1584^{cd}
Cowpea high-Titan	36.140^{cd}	75.14^{bcd}	2621.4^{bcd}	59.50^{ab}	76.913^{ab}	2464.2^{abc}
Cowpea high-NS5511	32.296^{cd}	89.84^{abc}	3145.7^{ab}	39.55^{b}	42.612^{d}	1314.2^{d}
Cowpea high-Enforcer	62.048^{a}	92.98^{ab}	3392.6^{ab}	54.19^{b}	66.334^{abcd}	2050.0^{abcd}
Cowpea low-Titan	13.475^{cd}	36.89^{e}	1459.3^{e}	44.44^{b}	48.128^{bcd}	1714.8^{bcd}
Grand mean	35.060	72.62	2464.2	52.57	62.540	2039.5

Means with the same letters were not different at $p \leq 0.05$. N_2 fixed = the amount of nitrogen fixed by cowpea, N accumulated = the amount of nitrogen accumulated by cowpea.

The results from Syferkuil indicated that N_2 fixed and accumulated as well as the aboveground dry matter production were significantly different among cowpea treatments in binary and sole cultures during the two growing seasons. In 2018/19, cowpea fixed more N when intercropped with Enforcer under high density followed by intercrop with NS5511 high density with the means of 30.23 kg ha^{-1} and 27.34 kg ha^{-1}. Cowpea also fixed higher N of 25 kg ha^{-1} when grown in sole under high density and intercrop with Avenger at high density compared to other treatments. The N accumulated in 2018/19 ranged from 17.20 kg ha^{-1} and 66 kg ha^{-1} at Syferkuil with cowpea intercrop with NS5511 under high density accumulating more N compared to all other treatments. The results further revealed that the treatments which accumulated higher N also obtained the highest aboveground biomass. For instance, cowpea intercropped with NS5511 in high density produced higher aboveground biomass compared to all other treatments followed by sole cowpea under high density with the means of 2217.3 kg ha^{-1} and 1924.7 kg ha^{-1} respectively. Cowpea low density intercropped with Avenger accumulated the lowest N hence low aboveground dry matter compared to all other treatments (Table 5.4). Cowpea fixed more N of between 20 to 38 kg ha^{-1} when intercropped with Enforcer and Titan under low and high density as well as in sole during the 2020/21 cropping season. However, the crop fixed the lowest N of 1.844 kg ha^{-1} when intercropped with Avenger in low density compared to all other treatments. Cowpea sole high density accumulated more N and aboveground dry matter compared to all other treatments with the means of 112.83 kg ha^{-1} and 3566 kg ha^{-1}. Cowpea low density intercrop treatments that fixed the lowest N, also accumulated lower N and aboveground biomass of 30.27 kg ha^{-1} and 1166.7 kg ha^{-1} respectively compared to the other treatments.

Table 5.4 N fixation, accumulation and aboveground dry matter of cowpea in sole and binary cultures at Syferkuil during the two cropping seasons.

	Syferkuil					
	2018/19			2020/21		
	kg ha^{-1}					
Treatments	**N_2 fixed**	**N accumulated**	**Dry matter**	**N_2 fixed**	**N accumulated**	**Dry matter**
Cowpea low-Avenger	11.124^{d}	17.198^{e}	615.4^{e}	1.844^{d}	30.27^{d}	1166.7^{d}
Cowpea high-sole	25.982^{ab}	56.967^{ab}	1924.7^{ab}	22.675^{abc}	112.83^{a}	3566.0^{a}
Cowpea high-avenger	25.342^{ab}	42.135^{bcd}	1454.3^{bcd}	15.899^{bcd}	54.95^{bcd}	1867.3^{cd}
Cowpea low-sole	14.535^{cd}	29.339^{cde}	1006.8^{cde}	20.178^{abcd}	56.22^{bc}	2034.6^{bc}
Cowpea low-Enforcer	10.867^{d}	21.669^{e}	785.8^{e}	25.393^{abc}	47.74^{cd}	1597.7^{cd}
Cowpea low-NS5511	12.420^{cd}	25.028^{e}	888.9^{de}	18.528^{bcd}	42.92^{cd}	1503.7^{cd}
Cowpea high-Titan	20.240^{bc}	43.945^{bc}	1506.2^{bc}	34.975^{ab}	76.61^{b}	2877.8^{ab}
Cowpea high-NS5511	27.339^{ab}	65.977^{a}	2217.3^{a}	15.273^{cd}	60.45^{bc}	2166.0^{bc}
Cowpea high-Enforcer	30.230^{a}	45.522^{bc}	1516.0^{bc}	38.189^{a}	65.94^{bc}	2204.3^{bc}
Cowpea low-Titan	15.144^{cd}	25.662^{de}	$903.7d^{e}$	23.349^{abc}	56.86^{bc}	2042.6^{bc}
Grand mean	19.320	37.340	1281.9	21.630	60.48	2102.7

Means with the same letters were not different at $p \leq 0.05$. N_2 fixed = the amount of nitrogen fixed by cowpea, N accumulated = the amount of nitrogen accumulated by cowpea.

Cowpea showed a strong positive relationship between N and biomass accumulated at Ofcolaco and Syferkuil during the two cropping seasons. At the two experimental sites, the R^2 was more than 0.9. These reveal that increase in N accumulation resulted in cowpea attaining more biomass irrespective of the system or the density. According to the results, for every increase in the N accumulation cowpea obtained about 30 kg ha^{-1} of biomass at each location across all the seasons (Figure 5.3).

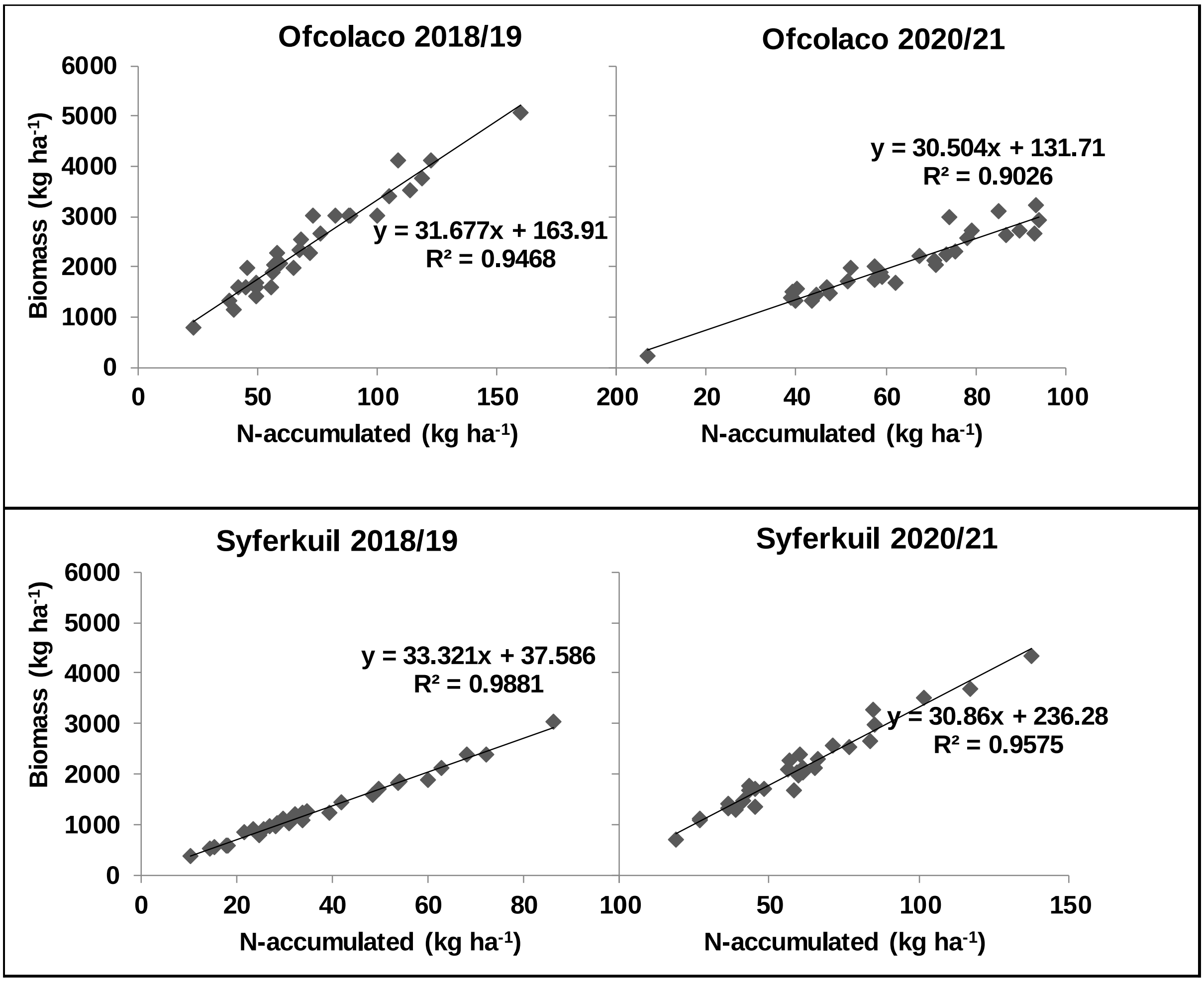

Figure 5.3 The relationship between aboveground biomass and N accumulation at Ofcolaco and Syferkuil during the 2018/19 and 2020/21 cropping seasons.

5.4 DISCUSSION

The amount of nitrogen fixed by cowpea varied depending on the experimental site and cropping season. Cowpea, for example, fixed low N in 2018/19 compared to the 2020/21 cropping season. However, the soil at Ofcolaco in 2018/19 had higher organic carbon, which is a driver of organic matter decomposition, resulting in high N accumulation by cowpea. Although cowpea fixed more N in the 2020/21 season at Ofcolaco, it was not accumulated in large quantities compared to the previous season due to low organic carbon and carbon stocks. During the two cropping seasons, seasonal variations were also observed at Syferkuil. Although cowpea fixed more N in the 2018/19 cropping season than in the 2020/21 cropping season, accumulation was lower, resulting in less cowpea biomass production. More than 30% of N at Ofcolaco was derived from air rather than soil, owing to low N in the soil, which forced cowpea to fix more N. However, at Syferkuil, the N derived from cowpea was between 4% and 71% during the two cropping seasons. According to Munjonji *et al*. (2018), cowpea had approximately 34% of its N derived from the air at Syferkuil, implying that the plant had to rely on N from the soil. Similar findings were made in this study, with more than 5% of N found in the soil during the two cropping seasons. Salgado *et al*. (2021) reported a decrease in N accumulation due to low N in the soil.

Cowpea fixed more N in sole cultures than in binary cultures, according to the findings. The higher N_2 fixed and accumulated in the soil was due to the low N available in the soil, which required the crop to exert more effort in increasing BNF than in intercropping with sorghum where inorganic N fertilizer was applied (Chu *et al*., 2004), (Fan *et al*., 2006). Cowpea fixed more N in the sole system when the density was 74074 plants ha^{-1} compared to 37037 plants ha^{-1}. Furthermore, treatments in a binary system with a high density fixed more N than treatments in a low density. Other authors have also reported variations in N accumulation in intercropping systems (Tang *et al*., 2018). Over two seasons, cowpea fixed and accumulated more than half of the N derived from the atmosphere high density compared to low density at the two locations. Cowpea biomass was increased due to high N accumulation. The strong positive relationship observed in this study between cowpea indicated that high N accumulation resulted in higher biomass obtained. N_2 fixation and accumulation were also affected by the companion crop sorghum cultivar. However, when compared to sole treatments, all cowpea binary treatments had higher BNF and accumulation. Zhang *et al*. (2017) reported that in intercropping, legumes fix nitrogen and release it into the soil, allowing the non-legume crop to use it. Cowpea fixed more N in high density intercropping in our study due to increased competition for N with sorghum. This could provide an alternative N source to inorganic fertilizer while also lowering grower costs (Ashworth *et al*., 2015).

The amount of N_2 fixed by cowpea in this study was influenced by cropping practices (system, density), as well as soil conditions, which ultimately influenced partition into biomass. The intercropping system reduced fixed N while improving N utilization and efficiency. Peoples *et al*. (2009) reported similar findings that intercropping legumes with cereals increased N mineralization, resulting in more N from the soil being used with less N_2 fixation. Cowpea fixed less N at Syferkuil and was dependent on the N available in the soil. However, because there was less N available in the soil (2%), the crop fixed more N at Ofcolaco. As a result, Ofcolaco accumulated more biomass than Syferkuil during the two cropping seasons.

5.5 CONCLUSION

Biological nitrogen fixation in an intercropping system is complicated, necessitating extensive research into nitrogen supply and uptake by the two crops. When researching BNF by cowpea, factors such as plant density and companion crop cultivar should be taken into account. In this study, high cowpea density consistently increased N_2 fixation and accumulation in sole and binary cultures relative to low density, resulting in high biomass accumulation. In general, Ofcolaco had high N_2 fixed compared to Syferkuil. Cowpea N_2 fixation was also influenced by available soil N. Cowpea intercropping with Enforcer at high density under these conditions can be considered a sustainable way to produce sorghum and cowpea simultaneously due to high N_2 fixation and accumulation. Intercropping with other cultivars, such as NS5511, can also be considered, as cowpea performed better in terms if N_2 fixation and accumulation when intercropped with the cultivar at high density than intercropping with Titan and Avenger. Finally, high cowpea density intercropping improves N in the soil, which increases cowpea production and, ultimately, sorghum production under a variety of agro-ecological conditions. The system can be implemented in Limpopo Province for the sustainable production of cereal and legume crops.

CHAPTER 6: THE PERFORMANCE OF APSIM IN VALIDATING BIOMASS AND GRAIN YIELD OF GRAIN SORGHUM AND COWPEA IN INTERCROPPING SYSTEM

Abstract

The information on grain sorghum and cowpea management practices in an intercropping system is critical for understanding the interaction with crop characteristics. However, there is a scarcity of model-based information on the interaction of crop traits and management practices in intercropping systems, particularly in Limpopo Province's dryland areas. The study used the Agricultural Production System sImulator (APSIM) crop model in Limpopo Province to generate data on grain sorghum-cowpea productivity in an intercropping system in response to different management practices. Growth (biomass) and yield (grain) data obtained from APSIM were compared with data collected from a two-year field experiment at Syferkuil. The field data collected from 2018/19 was used to calibrate the model whereas the second season data (2020/21) was used to run simulations. The model was able to capture the dynamics of biomass and grain yields in sole and intercropping systems under different densities of cowpea. Sorghum sole had R^2 value of 0.77, while in the intercropping system, the R^2 was 0.93 and 0.88 at low and high densities, respectively. Cowpea sole had R^2 of 0.77 low and 0.86 high densities and in intercropping the R^2 were 0.95 low and 0.91 high density, respectively. The model was accurate in terms of simulating sorghum and cowpea biomass yields in the intercropping system with RMSE of 341 for sorghum, RMSE of 316 for cowpea, NRMSE of 0.14 for sorghum and NRMSE of 0.12 for cowpea. However, under the increased cowpea density, the model was not satisfactory when simulating biomass yields with RMSE of 577 and 629 and its normalization of 0.18 and 0.15 for cowpea and sorghum respectively. The model over predicted grain yield of sorghum in sole culture (simulated = 4946 kg ha^{-1}, observed = 2116 kg ha^{-1}) and intercrop under low density with simulated mean and observed values of 1720 kg ha^{-1} and 1012 kg ha^{-1}. Under high density, the model under performed in simulating grain yield of sorghum with a simulated mean of 1095 kg ha^{-1} and an observed value of 1816 kg ha^{-1}. In the case of cowpea, the model under predicted the grain yield in both densities and cropping systems, meaning that all simulated values were lower than observed values. The model predicted that under these conditions, the sorghum cultivar (Enforcer) used

for this simulation will be sensitive to the density of the cowpea cultivar Betch Wich used. The adoption of an intercropping system should be based on low density for high yields of sorghum and adjusted to a high density of cowpea if the grower is interested in optimizing the yields of the two crops. The model still needs to be improved with the provision of more field data to improve its accuracy and robustness for both sorghum and cowpea.

Keywords: Crop modeling, cowpea, intercropping, sorghum

6.1 INTRODUCTION

Agricultural simulation models are used globally by various stakeholders to address the issue of climate change, which results in a decrease in food security (Holzworth *et al*., 2014). Crop-based models, also known as crop simulation models, are used to mathematically or statistically explain crop biological processes (Ahmed *et al*., 2016). Crop models are used to aid in crop management and cropping systems under a variety of agro-ecological conditions (Martín *et al*., 2014). Crop modeling aids in the reduction of yield gaps, cultivar selection, and the implementation of appropriate management practices such as planting time (Wallach *et al*., 2016). The Agricultural Production System sImulator (APSIM) is a crop model that is used around the world to facilitate different crop dynamics in response to agro-ecological conditions. APSIM is defined as a modular modeling framework developed to simulate biophysical processes in a farming system (Keating *et al*., 2003). Furthermore, the model evaluates the economic and ecological outcomes of a crop under various management practices under changing climate conditions.

APSIM has been used for different grain crops such as pearl millet (van Oosterom *et al*., 2001), maize (Chauhan *et al*., 2013), legumes crops (Chen *et al*., 2016), sorghum (Akinseye *et al*., 2017) and wheat (Brown *et al*., 2018) to run simple simulations for different purposes. However, APSIM has also been used to run complex simulations such as crop rotation (Mohanty *et al*., 2012;Wang *et al*., 2014) and intercropping systems. In intercropping system most studies focused on water use efficiency (Chimonyo *et al*., 2016a), fertiliser rates and different densities (Berghuijs *et al*., 2021), different row arrangements (Wu *et al*., 2021), drought mechanism (Nelson *et al*., 2021). Most studies have simulated growth, light, yield and water dynamics under intercropping system focusing on one area. The information provides crop dynamics under intercropping systems, which will aid in assessing the effectiveness of model prediction, particularly under changing climate conditions for sustainable crop production.

Sorghum and cowpea are two of the most widely grown crops in South Africa's Limpopo Province. The crops are grown for food and feed for livestock in sole cropping or mixed cropping systems. Simulating sorghum and cowpea intercropping using APSIM for growth and yield will help growers and policymakers make decisions for the two crops' long-term production. However, the effectiveness of APSIM in predicting cereal-legume intercrop under various management and agro-ecological conditions is poorly documented, particularly in South Africa. The majority of APSIM simulations were single crop simulations and were climate-specific. The differences in climatic regions in terms of weather variables make recommending crop production practices difficult. As a result, running complex APSIM simulations in different agro-ecological regions will aid in understanding the model's efficiency and making appropriate recommendations. The study was carried out to validate and simulate the growth and yield of sorghum and cowpea in an intercropping system under different growing seasons in Limpopo Province (Syferkuil). The study also aimed to simulate the effect of crop density on sorghum and cowpea in an intercropping system.

6.2 MATERIALS AND METHODS

6.2.1 Study site and conditions

The study was conducted at the University of Limpopo Experimental Farm Syferkuil during the 2018/19 and 2020/21 cropping seasons. Syferkuil is situated at 23°50'02.7"S; 29°41'25.5"E. The area receives an annual rainfall of about 350 to 500 mm with average maximum and minimum temperatures of 15 ^{o}C and 30 ^{o}C respectively. During the trial period, Syferkuil had daily average minimum and maximum temperatures of 12 ^{o}C and 27 ^{o}C respectively with a total rainfall of 719 mm from 2018/19 to 2020/21 growing period. Rains were received throughout the planting period at Syferkuil in both seasons. The area received a maximum rainfall of about 160 mm during the month of planting (Figure 6.1). In the 2020/21 cropping season, Syferkuil received rainfall throughout the trial period, with maximum rainfall of more than 100 mm occurring in January. The location also has a soil type of sandy clay.

6.2.2 APSIM description

In this study, the Agricultural Production System Simulator (APSIM) model version 7.10 was used to predict grain sorghum and cowpea growth and productivity under dryland conditions in Limpopo Province. In APSIM, the sorghum model follows continuous sorghum to simulate aboveground biomass (stems and leaves) and grain yield (Chimonyo *et al*., 2016a). To simulate development, growth, grain yield, and nitrogen accumulation, the APSIM cowpea model uses the generic APSIM plant description model (Nelson *et al*., 2021). For intercropping system, the APSIM Canopy module was used to simulate allocation (Keating *et al*., 2003) as well as the interspecific competition (Carberry *et al*., 1996) for resources such as light, water and nitrogen.

6.2.3 Field data

APSIM data was gathered from field trials conducted at Syferkuil during the 2018/19 and 2020/21 cropping seasons. The treatments tested were binary versus sole cultures, four grain sorghum cultivars, and two cowpea densities of 20 and 10 plants m^{-2} (reported as high and low densities). The sorghum cultivars used were Enforcer, NS5511, Avenger, and Titan, while the cowpea cultivar used was Betch, which was planted concurrently (Mogale *et al*., 2022). The experiment was designed in a factorial arrangement with a randomised complete block design (RCBD). By cutting sorghum and cowpea plants from above the soil surface, biomass was harvested at vegetative, flowering, physiological maturity, and maturity. The grain yield of each crop was done separately.

6.2.4 Model calibration

Met data

APSIM simulations require daily weather data, soil parameters, management practices, and cultivar information. Daily weather data from two automatic weather stations near or at the experimental sites were used to create the Met file. Maximum and minimum temperatures (^{o}C), solar radiation (Rad MJ m^{-2}) and rainfall were all included in the met file (mm) (Figure 6.1).

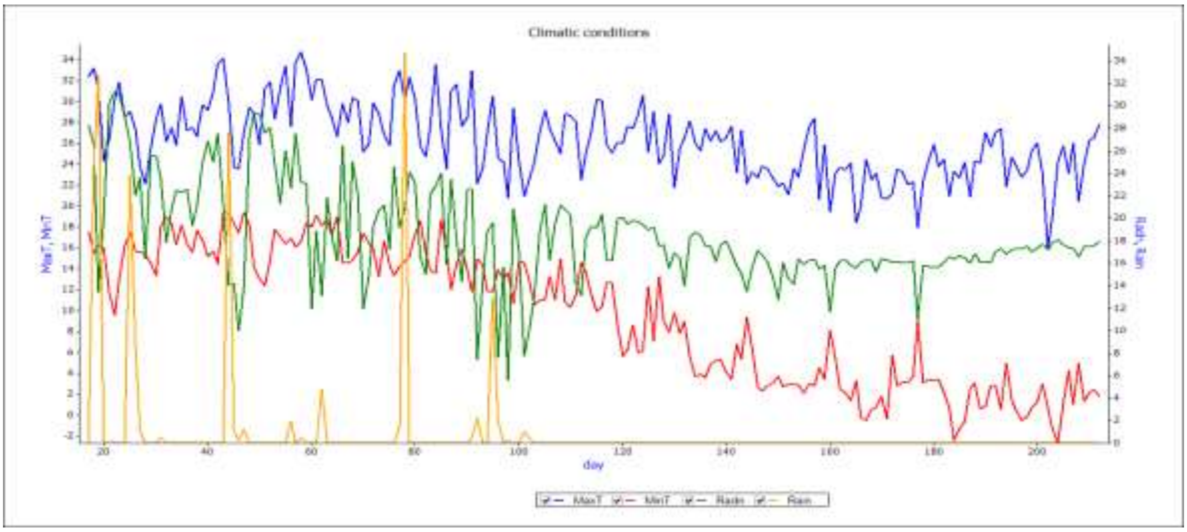

Figure 6.1 Maximum (maxT) and minimum (minT) temperatures, rainfall and radiation (Radn) from Syferkuil the during 2018/19 growing season.

Soil parameterization

The model was calibrated using soil and cultivar data from the 2018/19 cropping season at Syferkuil for sorghum and cowpea sole. In the absence of missing soil parameters such as total water extraction by crop (KL), crop lower limit (CLL), and drained upper limit (DUL), standard values from the literature were used for soil parameterization (DUL) (Table 6.1). Following the procedure described by (Dalgliesh *et al*., 2016), CLL and DUL were used to determine plant available water holding capacity for sorghum and cowpea. Prior to the study, soil bulk density was measured from 0 to 180 cm. During the experimental period, management practices such as planting time and method, fertilizer application, and irrigation were collected in the field.

Table 6.1 Soil physical properties for the estimated rooting depth, including bulk density (BD), lower limit of available soil water for each crop (LL), draining upper limit (DUL) and saturation (SAT).

	Soil				Sorghum			Cowpea		
Depth	BD	AirDry	DUL	SAT	LL	KL	XF	LL	KL	XF
cm	g/cc		mm/mm			/day	0-1		/day	0-1
0-15	1.45	0.11	0.15	0.40	0.11	0.06	1.00	0.06	0.16	1.00
15-30	1.45	0.11	0.16	0.40	0.11	0.12	1.00	0.07	0.16	1.00
30-60	1.45	0.11	0.16	0.40	0.11	0.08	1.00	0.11	0.16	1.00
60-90	1.45	0.11	0.16	0.40	0.11	0.06	1.00	0.11	0.16	1.00
90-120	1.45	0.11	0.16	0.40	0.11	0.04	0.00	0.11	0.15	1.00
120-150	1.45	0.11	0.16	0.40	0.11	0.02	0.00	0.11	0.15	1.00
150-180	1.45	0.11	0.16	0.40	0.11	0.01	0.00	0.11	0.15	1.00

Cultivar parameterization

Enforcer sorghum cultivar, which was added to APSIM, was used, and a spreading cowpea cultivar was used. The phenology and canopy development of field-collected cultivars were used to re-parameterize the cultivars in the APSIM model (Table 6.2).

Table 6.2 Default and adapted sorghum and cowpea cultivar parameters used for APSIM. tt represents the unit thermal time.

Sorghum	Default	Adapted sole	Adapted intercrop Low	Adapted intercrop High	Cowpea	Default	Adapted-sole Low	Adapted-intercrop Low	Adapted-sole High	Adapted-intercrop High
tt_emerg_to_endjuv	100.00	100.00	100.00	100.00	x_pp_hi_incr	1-24	1-24	1-24	1-24	1-24
photoperiod_crit1	12.30	12.30	12.30	12.30	y_hi_incr	0.01-0.01	0.01-0.01	0.016-0.016	0.019-0.019	0.014-0.014
photoperiod_crit2	14.60	14.60	14.60	14.60	x_hi_max_pot_stress	0.0-0.01	0.45-0.45	0.0-10	0.0-10	0.0-10
photoperiod_slope	25.00	35.00	18.00	21.00	y_hi_max_pot	0.2-0.2	0.18-0.18	0.18-0.27	0.45-0.45	0.18-0.26
tt_endjuv_to_init	115.00	100.00	100.00	100.00	cumvd_emergence	0-100	0-100	0-100	0-100	0-100
tt_flag_to_flower	100.00	129.00	80.00	80.00	tt_emergence	552.0-552.0	552.0-552.0	552.0-552.0	552.0-552.0	552.0-552.0
tt_flower_to_start_grain	30.00	85.00	30.00	30.00	est_days_emerg_to_init	20.00	20.00	20.00	20	20.00
tt_maturity_to_ripe	1.00	1.00	1.00	1.00	x_pp_end_of_juvenile	13.3-18.0	13.3-18.0	13.3-18.0	13.3-18.0	13.3-18.0
tt_flower_to_maturity	695.00	895.00	800.00	800.00	y_tt_end_of_juvenile	1-229	1-229	1-229	1-229	1-229
dm_per_seed	0.00083	0.0001	0.0008	0.0008	x_pp_floral_initiation	1-24	1-24	1-24	1-24	1-24
maxGFRate	0.09	0.04	0.15	0.15	y_tt_floral_initiation	20.0-20.0	20.0-20.0	20.0-20.0	20.0-20.0	20.0-20.0
x_stem_wt	0-80	0-80	0-80	0-80	x_pp_flowering	1-24	1-24	1-24	1-24	1-24
y_height	0-2000	0-2000	0-2000	0-2000	y_tt_flowering	100-100	100-100	145.0-145.0	100-100	145.0-145.0
dm_leaf_init	0.10	0.10	1.70	0.80	x_pp_start_grain_fill	1-24	1-24	1-20	1-24	1-20
dm_root_init	0.10	0.10	1.70	0.80	y_tt_start_grain_fill	361.7-361.7	361.7-361.7	361.7-361.7	361.7-361.7	361.7-361.7
dm_stem_init	0.10	0.10	1.70	0.80	tt_end_grain_fill	24.30	24.30	24.30	24.30	24.30
rue	1.25	0.75	0.85	0.85	tt_maturity	5.00	5.00	5.00	5.00	5.00
transp_eff_cf	0.009	0.005	0.90	0.90	x_stem_wt	0-25	0-25	0-25	0-25	0-25
svp_fract	0.75	0.25	0.15	0.15	y_height	0-250	0-250	0-250	0-250	0-250
frac_stem2flower	0.30	0.10	0.10	0.06	svp_fract	0.75	0.68	0.75	0.60	0.75

Calibration output for sole biomass

The biomass of sole cultivars simulated was virtually matched with that observed for sorghum and cowpea. The cultivar parameters were set within reasonable ranges guided by the literature (Brown *et al*., 2014; Nelson *et al*., 2021). The model was able to fit the observed mean of biomass sole collected at different stages (Figure 6.2).

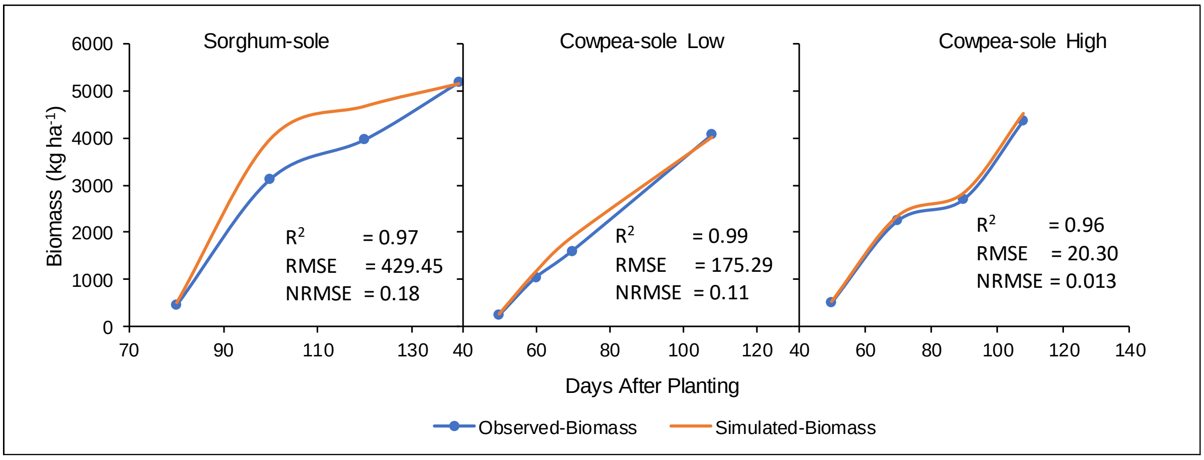

Figure 6.2 Calibration runs for modeled and observed of biomass in sole system during the growing season of 2018/19 at Syferkuil.

Calibration output for intercrop biomass

Calibration in the intercropping system was done by setting the parameters of the cultivars within the range. The biomass for each crop in the intercropping system is shown in figure 6.3.

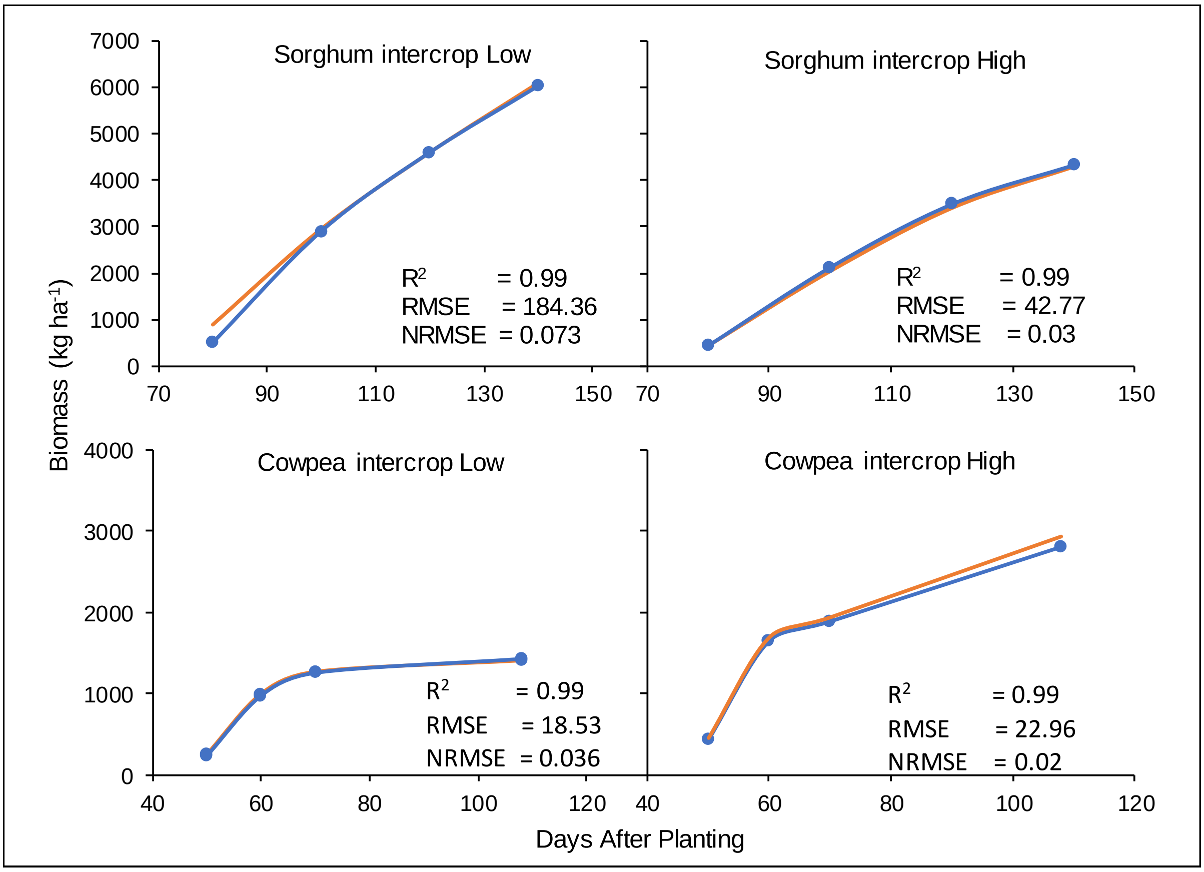

Figure 6.3 Calibration runs for modeled and observed of biomass in intercropping system during the growing season of 2018/19 at Syferkuil.

Calibration output for grain yield

The model was calibrated for grain yield by matching the final yield of the model with the observed yield as shown in Table 6.4.

Table 6.3 Calibration runs for modeled and observed of grain yield in sole and intercrop systems during the growing season of 2018/19 at Syferkuil.

Treatment	Units	N	Simulated	Observed	RMSE	NRMSE
Sorghum-sole	kg ha^{-1}	63	4598.70	4486.20	167.76	0.13
Cowpea-sole low density	kg ha^{-1}	33	712.60	690.71	41.65	0.17
Cowpea-sole high density	kg ha^{-1}	33	1897.70	1835.56	110.67	0.17
Sorghum intercrop low density	kg ha^{-1}	55	4630.40	4735.46	199.59	0.14
Sorghum intercrop high density	kg ha^{-1}	55	3652.40	3643.61	159.44	0.14
Cowpea intercrop low density	kg ha^{-1}	44	377.50	382.31	16.78	0.15
Cowpea intercrop high density	kg ha^{-1}	44	751.00	755.13	35.67	0.15

6.2.5 Model validation and simulation

The model was validated by comparing the model output to the field outputs; the parameters used were biomass, grain yield, and leaf area index (LAI). Each experimental site had a simulation experiment to determine biomass and grain yield accumulation of sorghum and cowpea in sole and binary cultures with different cowpea densities. The soil information was the same as that used for validation at each experimental site. The calibration treatments were not used for validation. The same parameterisation, however, was used to run simulations on the remaining treatments. From 2018 to 2021, the simulation experiments used weather data collected from stations installed at each experimental site to run for 2 years. At Syferkuil, the sowing date was the 17th of January. Because the experiments were conducted under rainfed conditions, irrigation water of 20 mm was only used at planting for seed establishment. Plant densities were set at 20 plants m^{-2} and 10 plants m^{-2}, with an intra-row spacing of 15 cm and 30 cm, respectively. The distance between rows for sole cultures was 90 cm and 45 cm for binary cultures. The initial soil water level was set to 50% from the top. For 2 years, two systems (sole and binary) and two plant densities (20 and 10 plants per m^{-2}) were simulated. The performance of APSIM was validated using the Root Mean Square Error (RMSE) and its normalisation (NRMSE) using the following formulars:

$$RMSE = \frac{1}{n}\sum_{i=1}^{n}(yi - \hat{y}i)^2$$

RMSE is the root mean square error, yi is the observed values, ŷ represents predicted values. N is the number of populations.

$$NRMSE = \frac{RMSE}{(Ymax - Ymin)}$$

NRMSE is the normalisation root mean square error, Ymax and Ymin represent maximum and minimum values of the observed values respectively.

6.3 RESULTS

6.3.1 Model validation

The accuracy of the APSIM model in predicting biomass and grain yield of sorghum and cowpea varied with each crop, the cropping system, as well as the density of cowpea. The NRMSE values of sorghum biomass were 0.25 in sole, 0.14 intercrop low density and 0.18 intercrop high density. This indicates that the model was able to predict the biomass of grain sorghum in sole and intercropping systems. The model was also able to predict cowpea biomass in the sole and intercrop with NRMSE values of 0.26 sole low, 0.19 sole high, 0.12 intercrop low and 0.15 intercrop high density. Therefore, the model was successful in predicting the biomass of grain sorghum and cowpea under different cropping systems and densities as the NRMSE was closer to zero. The results revealed that the model did not accurately predict the grain yield of sorghum and cowpea under different cropping systems and the density of the companion crop cowpea. The results indicated that the model over predicted the grain yield of sorghum in the sole and intercrop with low density, whereas in intercrop with high density, the model under performed. Hence, the model accuracy for predicting sorghum yield was not good enough with the NRMSE of 0.41 sole, 0.38 intercrop low density and 0.39 intercrop high density. Cowpea grain yield predictions were also not good in all cropping systems and under different densities with the NRMSE of 0.43, 0.45, 0.38 and 0.37 for sole in low and high density and intercrop in low and high density, respectively.

6.3.2 Simulation experiment

6.3.2.1 Sole biomass under different densities of cowpea

The simulation experiment determined the effect of different cowpea densities on sole and intercrop sorghum and cowpea biomass and grain yield. Under the sole cropping system, sorghum predicted biomass yield ranged from 71.7 kg ha^{-1} to 5810.2 kg ha^{-1}. Cowpea biomass yield was affected by the density, with high biomass accumulation under high density (from 29.8 kg ha^{-1} to 6039.6 kg ha^{-1}) as compared to low density (32.3 kg ha^{-1} to 5864.6 kg ha^{-1}) as shown in Figure 6.4. The results indicated that the model was able to predict cowpea final biomass under low and high density. However, in terms of sorghum, the model over predicted the final biomass yield.

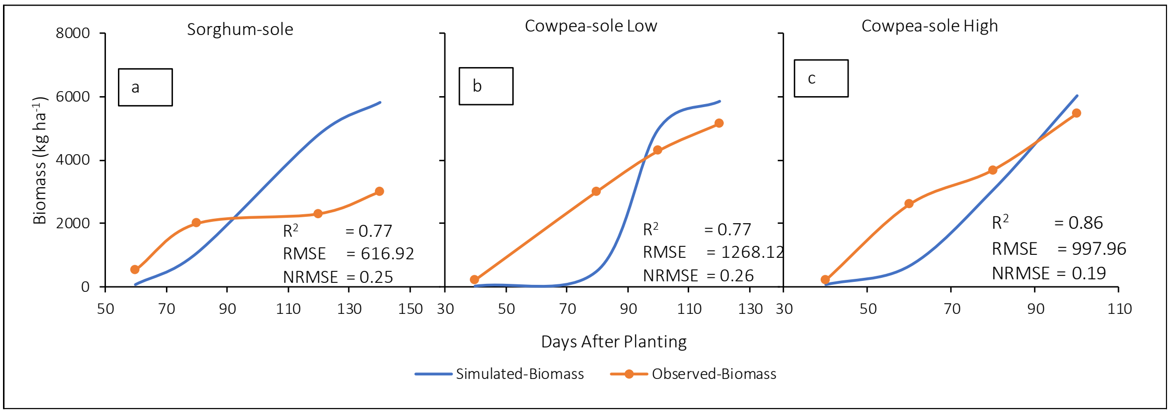

Figure 6.4 Simulated and observed lines of sole biomass under different densities of cowpea and uniform density of sorghum.

6.3.2.2 Intercrop biomass under different densities of cowpea

Different densities of cowpea also affected biomass yield of cowpea and sorghum in intercropping system. Cowpea intercrop under high density had higher biomass yield ranging from 739.3 kg ha^{-1} to 4541.60 kg ha^{-1} as compared to low density which ranged from 295.60 kg ha^{-1} to 3790.60 kg ha^{-1} (Figure 6.5). The sorghum biomass yield was higher when intercropped with cowpea low density (746.50 kg ha^{-1} to 1909.80 kg ha^{-1}) compared to intercrop under low density of cowpea (620.00 kg ha^{-1} to 1893.20 kg ha^{-1}) as shown in Figure 6.5.

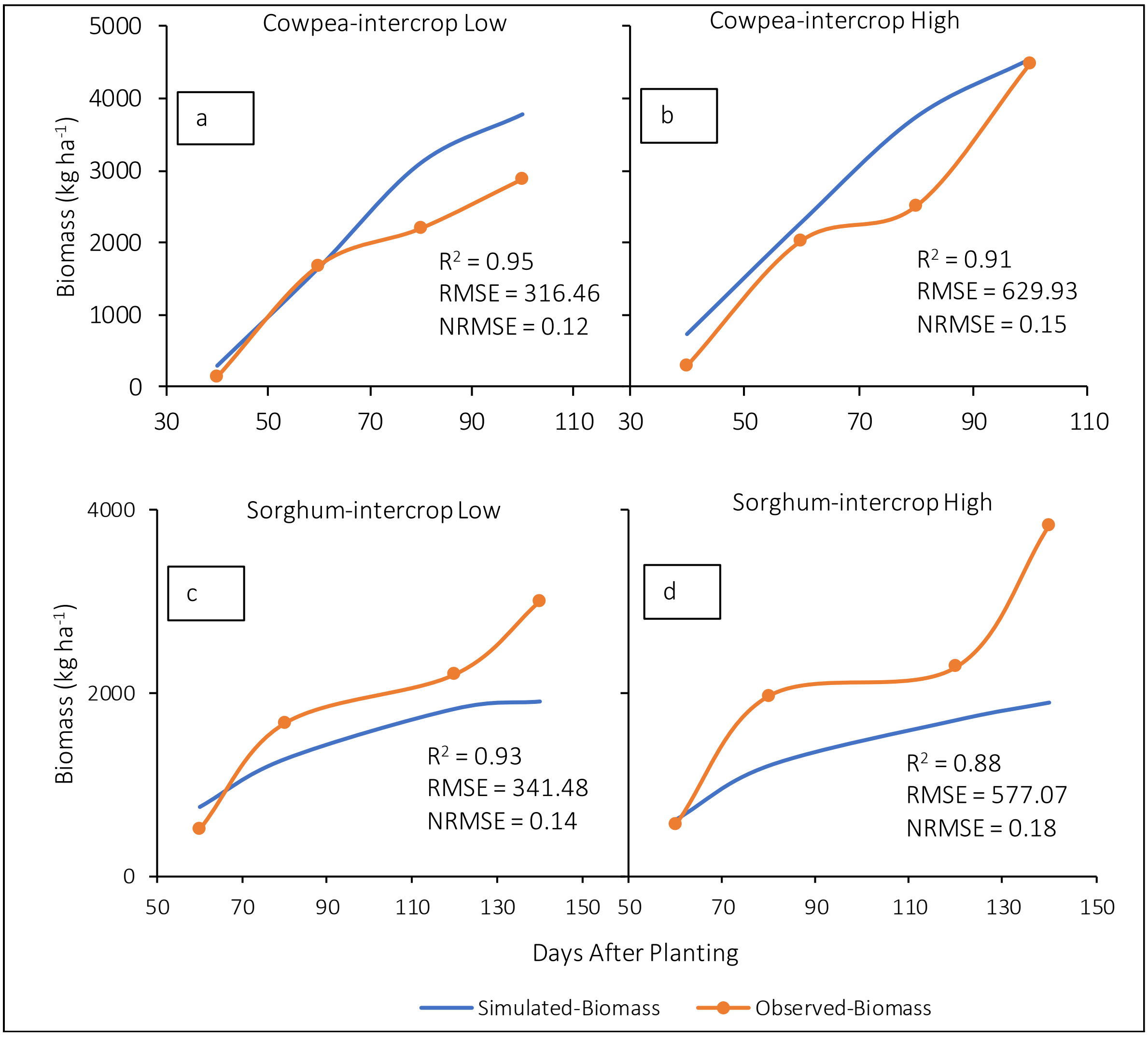

Figure 6.5 Simulated and observed lines of intercropped biomass under different densities of cowpea.

6.3.2.3 Grain yield of sorghum and cowpea under sole and intercrop with different densities

Simulation results indicated that grain yield will be affected by cropping system as well as the density of the companion cropw cowpea.. For instance, sorghum yield in the sole system was 4946.40 kg ha^{-1} whereas in the intercropping system it was 1720.28 kg ha^{-1} and 1094.70 kg ha^{-1} under low and high density respectively (Table 6.4). Cowpea grain yield was 1042.70 kg ha^{-1} and 2696.10 kg ha^{-1} in low and high density sole systems respectively. However, in intercropping system cowpea had a high grain yield of 1016.10 kg $^{ha-1}$ under low density as compared to high density which had 1002.50 kg ha^{-1}.

Table 6.4 Simulated runs for modeled and observed of grain yield in sole and intercrop system during the growing season of 2020/21 at Syferkuil.

Treatment	Units	N	Simulated	Observed	RMSE	NRMSE
Sorghum-sole	kg ha^{-1}	63	4946.40	2115.74	259.60	0.41
Cowpea-sole low density	kg ha^{-1}	33	1042.70	2773.61	657.44	0.43
Cowpea-sole high density	kg ha^{-1}	33	2696.10	3609.72	427.16	0.45
Sorghum intercrop low density	kg ha^{-1}	55	1720.28	1011.70	432.43	0.38
Sorghum intercrop high density	kg ha^{-1}	55	1094.70	1815.88	370.41	0.39
Cowpea intercrop low density	kg ha^{-1}	44	1016.10	1360.19	274.65	0.38
Cowpea intercrop high density	kg ha^{-1}	44	1002.50	2015.74	163.38	0.37

6.4 DISCUSSION

The finding of the study revealed that the APSIM model can reproduce crop dry matter accumulation based on the response to the soil, management as well as weather conditions. However, the accuracy of the model in predicting biomass and grain yield still needs improvement especially on the water uptake in the intercropping system to allow co-existence between the two crops. The adoption of a sorghum-cowpea intercropping system depends on the farmer's preference.

6.4.1 Model performance and improvement

This study indicated that the model was able to capture biomass and grain yield dynamics in an intercropping and sole cropping system. However, the biomass yield of cowpea was captured better in both cropping systems under different densities compared to sorghum. The results contradicted what Nelson *et al*. (2021) found. The author reported that pearl millet was well captured by APSIM compared to cowpea. The model was not able to capture biomass yield of cowpea, especially at the final stages of crop growth when APSIM over predicted sorghum biomass. However, the NRMSE of sorghum was within the accepted range 0.14 to 0.26 indicating that the model accurately captured the response to crop management (Gaydon *et al*., 2017). Chimonyo *et al*. (2016a) reported an accurate prediction of sorghum and cowpea biomass yield in intercropping system. The accuracy of APSIM in predicting yields of cereal-legume intercrop varies with agro-ecological conditions as well as the treatment investigated. In this study APSIM was poor in predicting the grain yield of sorghum and cowpea under dry conditions of Limpopo Province. Similar observations were reported elsewhere (Berghuijs *et al*., 2021). These findings indicate that APSIM improvement should be environment specific to be able to capture grain yield and biomass well. Rötter *et al*. (2018) reported that more data is required to evaluate the performance of models under extreme weather events. Furthermore, other model parameters such as soil water, inter and intra-specific competition which plays a role in yields accumulated should be well-calibrated. According to (Nelson *et al*., 2021), the intercropping simulation can be improved through well-calibrated soil water. Hence, model parameterizations such as soil and cultivar should be improved to enhance the performance of the APSIM. Gaydon *et al*. (2017) reported that APSIM performance should be improved to reduce input parameter challenges under different cropping systems of Asia.

6.4.2 Plant density effect on Intercropping vs sole cropping system of sorghum and cowpea biomass and grain yield

The model predicted that grain sorghum and cowpea would accumulate more biomass and grain yield when planted in a sole cropping system compared to intercropping system. Furthermore, cowpea density plays a key role in determining biomass and grain yield accumulation of the two crops. APSIM considered sorghum as the main crop in intercrop whereas cowpea as an additional crop. This explains why under uniform densities cowpea is outperformed by sorghum in both grain and biomass yields. However, the model is implying that under increased cowpea density sorghum will be outperformed by cowpea. The model outputs are not far from what was observed in the field in terms of density effect on the performance of sorghum and cowpea. From the field observations, cowpea accumulated more biomass and grain yield when the density was increased to 20 plants m^{-2} compared to 10 plants m^{-2}. However, intercropped field observations revealed that although increased density enhanced the productivity of cowpea, sorghum still accumulated more grain and biomass yield than cowpea. This may be due to the model not being well-calibrated in terms of the co-exiting of the two crops as well as the response to different management practices. Nonetheless, the APSIM model can be used to predict the productivity of sorghum-cowpea intercropping.

6.5 CONCLUSION

The APSIM model was able to successfully run a complex simulation of the sorghum-cowpea intercropping system under two varying seasons in Limpopo Province. The model further gave simulated output on the response of sorghum and cowpea when intercropped under different densities of cowpea. The model simulated sorghum grain and biomass yields which were dependent on the density of the companion crop cowpea. Furthermore, cowpea biomass and grain yield simulated were outperformed by sorghum under low density and improved when the cowpea density increased. The findings of the study revealed a few insights: firstly, the intercropping system can be adopted as a sustainable production practice under semi-arid conditions of Limpopo Province as it promotes efficient utilization of production land. Secondly, if the farmers are interested in high sorghum grain yield, intercropping under low cowpea density may be an appropriate system as it enhances the grain yield of cereal. However, for farmers who are interested in optimizing the yield of both crops, high density is appropriate as it increases the grain yield of each crop to more than 1 t ha^{-1}. According to the findings of the study, the productivity of intercropping system depends on the inter and intra-specific competition between crops. Hence, future field experiments and model improvement should focus on competition and interaction between the two crops in intercropping system. More longterm field data is required to improve the model performance.

CHAPTER 7: GENERAL CONCLUSIONS AND RECOMMENDATIONS

Objective 1: To assess growth, yield and physiological response of grain sorghum and cowpea under intercropping system across two agro-ecological locations over two seasons

Hypothesis: There was no significant difference in growth, yield and physiological responses of sorghum and cowpea intercrop grown in distinct environments in Limpopo Province

Conclusion: Grain sorghum yield and yield components was neither affected by cropping system or the density of the companion cowpea. There was a significant difference among the grain sorghum cultivars for yield and yield components. Enforcer and NS5511 produced higher grain yield at the two test locations compared to Avenger and Titan. The yield of cowpea was influenced by the cropping system as well as the crop density. Cowpea produced a higher grain yield in sole compared to the binary cultures. However, the yield of cowpea was improved in binary cultures when the density was 74074 plants ha^{-1}. The physiological responses and growth of grain sorghum cultivars and cowpea were significantly affected by the intercropping systems but that depended on the agro-ecological conditions and cropping season. Ofcolaco had higher photosynthetic activities compared to Syferkuil due to warmer temperatures. The hypothesis that stated that there is no significant difference in growth, physiology and yield is therefore rejected. Increased density of cowpea enhanced photosynthetic activities compared to low density resulting in high biomass accumulation under high density. Enforcer and NS5511 responded better in terms of biomass accumulation than Avenger and Titan to climate variability and cropping systems at Ofcolaco and Syferkuil during the 2018/19 and 2020/21 cropping seasons.

Recommendation: Based on the results of this study grain sorghum–cowpea intercrop can be adopted as a climate-smart practice to improve yield compared to sole cropping. However, the density of cowpea and grain sorghum cultivars should be taken into consideration as they affect the productivity of the two crops. Photosynthetic activities and the effects of biomass and grain yield accumulations should be investigated along with local landraces grown by local farmers of Limpopo Province. The study should be conducted under different cowpea densities to identify the correct density that will reduce competition and enhance complementarity for better growth and leaf gaseous response which will ultimately result in higher biomass accumulation. The data generated from this study could be useful in simulating the productivity of intercropping practice as a climate-smart method using crop modeling techniques. Intercropping has proved to improve yield, growth and physiology. Hence, the system could be adopted for sustainable production under changing climate in Limpopo Province provided cultivars and density are taken into consideration.

Objective 2: To measure the effect of intercropping system on CO_2 emission and soil carbon stocks across different climatic and soil environments of Limpopo Province

Hypothesis: Intercropping system has no effect on CO_2 emission rates and soil carbon stocks across different climatic and soil environments of Limpopo Province.

Conclusion: Cowpea-sorghum intercrop released less soil CO_2 compared to the monocrops of the two crops and hence, more dry matter (biomass) is accumulated with the reduction in CO_2 emission. The hypothesis that intercropping system will not affect CO_2 emission rates and carbon stocks is thus, rejected. When the two crops were planted as monocultures, sorghum was found to emit more CO_2 than cowpea. Cowpea density also significantly impacted CO_2 emission rates, with high planting density (74074 plants per hectare) emitting less soil CO_2. Furthermore, the study found that agro-ecological conditions that differ from season to season play an important role in carbon dynamics in the soil.

Recommendation: More research is needed to fully understand how intercropping systems and conservation practices such as no-till systems affect CO_2 emissions. Furthermore, plant root and soil microbial activities should be investigated to observe the carbon dynamics between plants and soil.

Objective 3: To determine the effect of grain sorghum-cowpea intercropping on biological nitrogen fixation (BNF) of cowpea in contrasting environments of Limpopo Province

Hypothesis: Grain sorghum/cowpea intercropping does not affect cowpea biological nitrogen fixation under varying test locations in Limpopo Province

Conclusion: Intercropping system had a significant effect on biological nitrogen fixation of cowpea under different densities in all agro-ecological regions over two seasons.

The hypothesis is rejected as the intercropping system significantly influenced BNF. In this study, high cowpea density consistently enhanced biological N_2 fixation and accumulation in sole and binary cultures, resulting in high biomass accumulation. Cowpea N_2 fixation was also influenced by available soil N.

Recommendation: The system can be implemented in Limpopo Province for the sustainable production of cereal and legume crops. Cowpea intercropping with Enforcer at high density under these conditions can be considered a sustainable way to produce sorghum and cowpea simultaneously due to high N_2 fixation and accumulation.

Objective 4: To assess the performance of APSIM in calibrating and validating biomass and grain yield of grain sorghum and cowpea in intercropping system.

Hypothesis: APSIM cannot simulate biomass and grain yield of sorghum/cowpea.

Conclusion: The APSIM model was able to successfully run a complex simulation of sorghum-cowpea intercropping system under two varying seasons of Limpopo Province. However, APSIM could not simulate the grain yield of sorghum and cowpea in intercropping and sole cropping systems. Therefore, the hypothesis of no challenges during validation is rejected. The model further gave simulated biomass and grain yield output on the response of sorghum and cowpea when intercropped under different densities of cowpea. The model simulated grain and biomass of yields of sorghum which were dependent on the density of the companion crop cowpea.

Recommendation: Future field experiments and model improvement should focus on competition and interaction between the two crops in intercropping system. More long-term field data is required to improve model performance.

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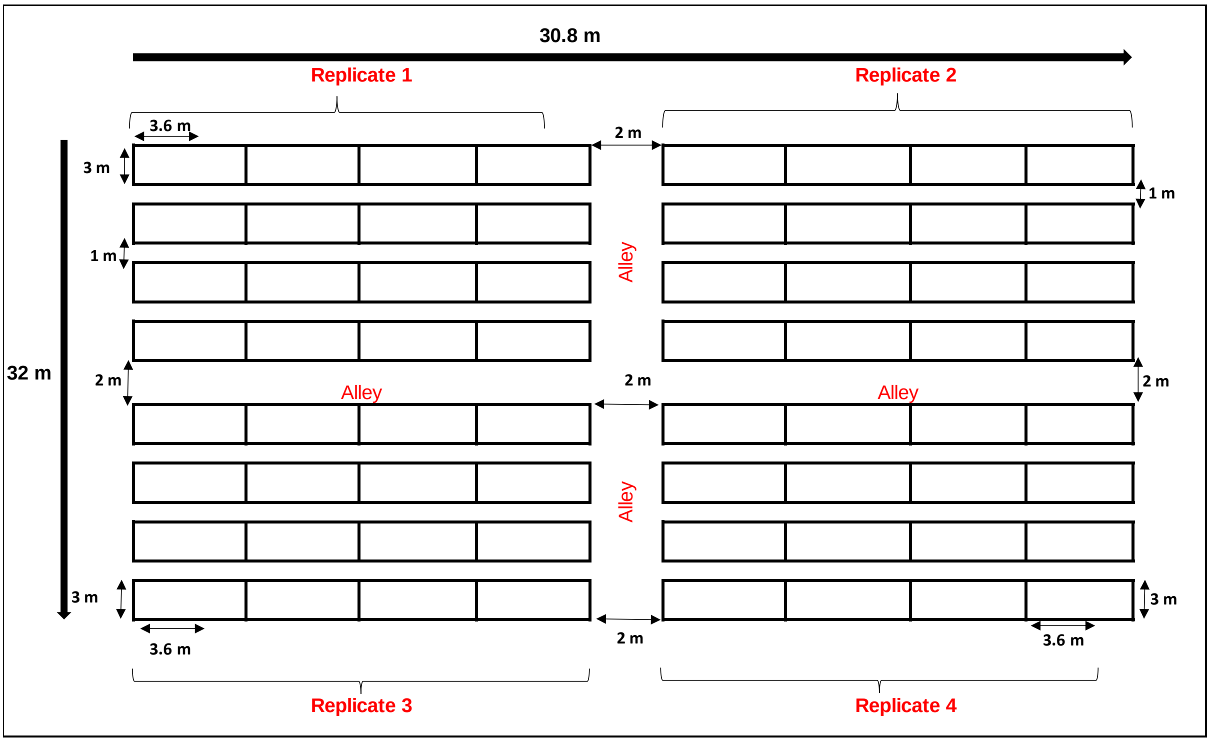
APPENDICES



Appendix 4.1 Field layout

Appendix 4.2 ANOVA of grain sorghum Head length (HL) at Syferkuil in 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	58.3350694	19.44502315	3.03	0.0366
System	1	54.390625	54.390625	8.49	0.0051
Cultivar*System	3	2.890625	0.96354167	0.15	0.9291

Appendix 4.3 ANOVA of grain sorghum head weight (HW) at Syferkuil in 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	185636.023	61878.6742	8.75	<.0001
System	1	16869.9208	16869.9208	2.38	0.1282
Cultivar*System	3	18259.711	6086.5703	0.86	0.4671

Appendix 4.4 ANOVA of grain sorghum shelled head weight (SHW) at Syferkuil in 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	12105.1478	4035.04928	1.85	0.1485
System	1	20303.318	20303.31801	9.31	0.0035
Cultivar*System	3	2240.45919	746.81973	0.34	0.7946

Appendix 4.5 ANOVA of grain sorghum 1000 seed weight (1000SW) at Syferkuil in 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	465.17125	155.0570833	33.99	<.0001
System	1	2.89	2.89	0.63	0.4295
Cultivar*System	3	49.70875	16.5695833	3.63	0.0182

Appendix 4.6 ANOVA of grain sorghum seed weight per head (SWH) at Syferkuil in 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	1621131.13	540377.042	11.1	<.0001
System	1	106697.668	106697.668	2.19	0.1444
Cultivar*System	3	280613.082	93537.694	1.92	0.1367

Appendix 4.7 ANOVA of grain sorghum yield (GY) at Syferkuil in 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	39392364.6	13130788.19	19.05	<.0001
System	1	137689.1	137689.1	0.2	0.6566
Cultivar*System	3	1858269.09	619423.03	0.9	0.4477

Appendix 4.8 ANOVA of grain sorghum harvest index (HI) at Syferkuil in 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	951.856255	317.2854183	12.83	<.0001
System	1	6.9945892	6.9945892	0.28	0.597
Cultivar*System	3	50.8419165	16.9473055	0.69	0.5648

Appendix 4.9 ANOVA of grain sorghum Head length (HL) at Syferkuil in 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	62.8896007	20.96320023	7.1	0.0004
System	1	0.75835069	0.75835069	0.26	0.6143
Cultivar*System	3	9.51890625	3.17296875	1.07	0.3673

Appendix 4.10 ANOVA of grain sorghum head weight (HW) at Syferkuil in 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	2289.97107	763.32369	2.85	0.0456
System	1	774.868413	774.868413	2.89	0.0946
Cultivar*System	3	324.253224	108.084408	0.4	0.7512

Appendix 4.11 ANOVA of grain sorghum shelled head weight (SHW) at Syferkuil in 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	159.809462	53.2698206	3.1	0.0337
System	1	51.062934	51.062934	2.97	0.0901
Cultivar*System	3	105.851129	35.2837095	2.06	0.1165

Appendix 4.12 ANOVA of grain sorghum 1000 seed weight (1000SW) at Syferkuil in 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	182.043125	60.6810417	0.74	0.5301
System	1	12.780625	12.780625	0.16	0.6936
Cultivar*System	3	362.158125	120.719375	1.48	0.2295

Appendix 4.13 ANOVA of grain sorghum seed weight per head (SWH) at Syferkuil in 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	38140.0555	12713.35184	3.53	0.0206
System	1	3470.62811	3470.62811	0.96	0.3308
Cultivar*System	3	4067.48179	1355.82726	0.38	0.7707

Appendix 4.14 ANOVA of grain sorghum yield (GY) at Syferkuil in 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	3205146.58	1068382.193	7.09	0.0004
System	1	9595.23	9595.23	0.06	0.8018
Cultivar*System	3	656409.879	218803.293	1.45	0.2377

Appendix 4.15 ANOVA of grain sorghum harvest index (HI) at Syferkuil in 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	796.320688	265.4402295	8.22	0.0001
System	1	8.2779928	8.2779928	0.26	0.6147
Cultivar*System	3	227.189208	75.7297359	2.34	0.0827

Appendix 4.16 ANOVA of grain sorghum Head length (HL) at Ofcolaco in 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	802.6702229	267.556741	3.98	0.0122
System	1	6.764334	6.764334	0.1	0.7523
Cultivar*System	3	518.7436729	172.9145576	2.57	0.0632

Appendix 4.17 ANOVA of grain sorghum head weight (HW) at Ofcolaco in 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	301175.1892	100391.7297	23.89	<.0001
System	1	7116.9707	7116.9707	1.69	0.1985
Cultivar*System	3	21752.5911	7250.8637	1.73	0.1722

Appendix 4.18 ANOVA of grain sorghum shelled head weight (SHW) at Ofcolaco in 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	5052.75763	1684.252543	11.42	<.0001
System	1	35.667438	35.667438	0.24	0.6248
Cultivar*System	3	128.896862	42.965621	0.29	0.8314

Appendix 4.19 ANOVA of grain sorghum 1000 seed weight (1000SW) at Ofcolaco in 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	934.50875	311.5029167	4.85	0.0045
System	1	216.09	216.09	3.36	0.072
Cultivar*System	3	381.05625	127.01875	1.98	0.1279

Appendix 4.20 ANOVA of grain sorghum seed weight per head (SWH) at Ofcolaco in 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	204417.873	68139.291	23.14	<.0001
System	1	8295.0492	8295.0492	2.82	0.0989
Cultivar*System	3	14426.1542	4808.7181	1.63	0.1921

Appendix 4.21 ANOVA of grain sorghum yield (GY) at Ofcolaco in 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	15728225.66	5242741.89	12.06	<.0001
System	1	947417.67	947417.67	2.18	0.1454
Cultivar*System	3	3419182.87	1139727.62	2.62	0.0595

Appendix 4.22 ANOVA of grain sorghum harvest index (HI) at Ofcolaco in 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	601.8427781	200.6142594	4.83	0.0046
System	1	34.500717	34.500717	0.83	0.3658
Cultivar*System	3	90.7880504	30.2626835	0.73	0.5389

Appendix 4.23 ANOVA of grain sorghum Head length (HL) at Ofcolaco in 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	8.97911458	2.99303819	0.37	0.7756
System	1	14.72640625	14.72640625	1.82	0.1832
Cultivar*System	3	17.07980903	5.69326968	0.7	0.5548

Appendix 4.24 ANOVA of grain sorghum head weight (HW) at Ofcolaco in 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	909.857964	303.285988	1.45	0.2392
System	1	3467.983025	3467.983025	16.53	0.0002
Cultivar*System	3	886.443867	295.481289	1.41	0.2498

Appendix 4.25 ANOVA of grain sorghum shelled head weight (SHW) at Ofcolaco in 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	391.6058854	130.5352951	23.76	<.0001
System	1	5.660434	5.660434	1.03	0.3145
Cultivar*System	3	24.711441	8.237147	1.5	0.2247

Appendix 4.26 ANOVA of grain sorghum 1000 seed weight (1000SW) at Ofcolaco in 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	6893.95375	2297.984583	1.26	0.2955
System	1	2425.5625	2425.5625	1.33	0.2529
Cultivar*System	3	4652.23875	1550.74625	0.85	0.4708

Appendix 4.27 ANOVA of grain sorghum seed weight per head (SWH) at Ofcolaco in 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	7253.98591	2417.9953	1.28	0.2906
System	1	24636.40284	24636.40284	13.03	0.0007
Cultivar*System	3	2222.63779	740.87926	0.39	0.7594

Appendix 4.28 ANOVA of grain sorghum yield (GY) at Ofcolaco in 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	975404.784	325134.928	2.98	0.0391
System	1	1598449.027	1598449.027	14.64	0.0003
Cultivar*System	3	397484.094	132494.698	1.21	0.3132

Appendix 4.29 ANOVA of grain sorghum harvest index (HI) at Ofcolaco in 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Cultivar	3	509.7306357	169.9102119	2.1	0.1104
System	1	102.0003788	102.0003788	1.26	0.2662
Cultivar*System	3	149.5095211	49.836507	0.62	0.6073

Appendix 4.30 ANOVA of cowpea 100 seed weight (100SW) at Syferkuil during 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Density	1	5.359225	5.359225	9.03	0.004
System	5	4.174375	0.834875	1.41	0.2364
Density*System	3	8.08495	2.694983	4.54	0.0065

Appendix 4.31 ANOVA of cowpea pod weight per plot (PWP) at Syferkuil during 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Density	1	67275.39	67275.39	9.17	0.0038
System	5	450146.5	90029.3	12.27	<.0001
Density*System	3	0	0	0	1

Appendix 4.32 ANOVA of cowpea grain yield (GY) at Syferkuil during 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Density	1	12218294	12218294	80.18	<.0001
System	5	17010462	3402092	22.33	<.0001
Density*System	3	0	0	0	1

Appendix 4.33 ANOVA of cowpea 100 seed weight (100SW) at Syferkuil during 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Density	1	0.001914	0.001914	0	0.9501
System	5	26.13918	5.227836	10.78	<.0001
Density*System	3	3.221917	1.073972	2.22	0.0968

Appendix 4.34 ANOVA of cowpea pod weight per plot (PWP) at Syferkuil during 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Density	1	13393567	13393567	18.83	<.0001
System	5	1.08E+08	21695009	30.51	<.0001
Density*System	3	0	0	0	1

Appendix 4.35 ANOVA of cowpea grain yield (GY) at Syferkuil during 2020/21 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Density	1	7712192	7712192	29.58	<.0001
System	5	37196240	7439248	28.53	<.0001
Density*System	3	0	0	0	1

Appendix 4.36 ANOVA of cowpea 100 seed weight (100SW) at Ofcolaco during 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Density	1	0.218556	0.218556	0.43	0.5149
System	5	2.570194	0.514039	1.01	0.4205
Density*System	3	1.228994	0.409665	0.81	0.4964

Appendix 4.37 ANOVA of cowpea pod weight per plot (PWP) at Ofcolaco during 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Density	1	1.3E+08	1.3E+08	95.14	<.0001
System	5	1.76E+08	35190051	25.71	<.0001
Density*System	3	0	0	0	1

Appendix 4.38 ANOVA of cowpea grain yield (GY) at Ofcolaco during 2018/19 cropping season.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Density	1	60329741	60329741	92.05	<.0001
System	5	83813101	16762620	25.58	<.0001
Density*System	3	0	0	0	1