Evaluating the Effect of Intercropping Maize (*Zea mays L.*) with Different Lablab (*Lablab purpureus L.*) Cultivars on Yield, Soil Water Content and Soil Nitrogen in Dry Environments of Limpopo Province using APSIM Model

by

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Student number: 14001552

Dissertation submitted in fulfilment of the degree of

Master of Science (MSc) in Agriculture (Soil Science)

at the

FACULTY OF SCIENCE, ENGINEERING AND AGRICULTURE

DEPARTMENT OF PLANT AND SOIL SCIENCES

UNIVERSITY OF VENDA

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2023

DECLARATION

I, **Rebotile Sophy Thaba**, student number:14001552, hereby declare that this Dissertation for Master of Science in Agriculture (Soil Science) submitted to the Department of Plant and Soil Sciences, Faculty of Science, Engineering and Agriculture, University of Venda has not been previously submitted for any degree at this or any other university or institution. Any reference to work done by any other person or institute or any material obtained from other sources have been duly cited and referenced.

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CONFERENCE CONTRIBUTION OF THE DISSERTATION

Thaba, R.S., Odhiambo, J.J.O., and Brancho-Mujica, G. Influence of maize-lablab intercropping on soil mineral nitrogen and soil water content. Combined Congress 2023, 23 – 26 February, Future Africa campus, University of Pretoria, South Africa. Pp 196.

ACKNOWLEDGEMENT

I would like to give my sincere gratitude to the following for making the research project a success:

My main supervisor Prof JJO Odhiambo and co-supervisor Dr G Bracho-Mujica for their guidance with APSIM, support and encouragement throughout the project.

The University of Venda and University of Limpopo farm workers for assistance with land preparation.

The South African Limpopo Landscape Network (SALLnet) Project for assistance with APSIM model and financial support.

The National Research Foundation (NRF) (Innovation Scholarship) and the Research Publication Committee (RPC) at the University of Venda for their financial support.

Mashishi S, Sigwavhulimu NT, Raphole SE, Thaba MJ and Thaba TC for their tested and unbroken support with field work and data collection.

My family for emotional support and financial assistance throughout the project.

DEDICATION

I dedicate this work to my parents, Matsobane Johannes Thaba and Tetsoane Christina Thaba who have been nothing but inspiring and supportive.

ABSTRACT

Smallholder maize production systems are characterized by continuous maize monoculture production, which often leads to soil degradation, nutrient depletion and increased risk of pests and diseases. The cropping system is characterized by low yields that continue to decline due to soil degradation and increased temperatures coupled with poor rains. The integration of drought tolerant crops, such as lablab, into predominantly maize monoculture systems presents a better alternative to maize monoculture. Lablab is native to Africa but remains overlooked in many countries including South Africa, due to lack of information and access to seeds. Crop models, such as APSIM, are useful decision-making tools for investigating crop adaptability to various climates, management, and cropping systems. The objective of this study was therefore to assess the performance of maize and lablab under sole and intercropping systems and to evaluate the capability of APSIM to simulate crop yields in dry environments of Limpopo province, South Africa.

Field experiments were conducted at the University of Limpopo Experimental Farm (Syferkuil) (2018/2019) and at University of Venda Experimental Farm (Univen) (2018/2019 and 2019/2020). Treatments consisted of maize cultivar (DKC-2147) and three lablab cultivars (DL-1002, Rongai (brown) and Q-6880B) planted as sole crops and intercrops. The treatments were laid out in a randomized complete block design with three replicates. Maize and lablab dry biomass (roots and shoots) and grain yield were assessed. Biomass was evaluated at respective flowering and harvest maturity dates for lablab and maize. Harvest index (HI) and land equivalent ratio (LER) were determined from shoot biomass and grain yield collected at harvest maturity. Soil mineral nitrogen (SMN) and soil water content (SWC) were determined at different maize growth stages. Biomass and grain yield of maize-lablab intercrops was evaluated using APSIM and observed data collected from the field experiments. Data obtained was subjected to analysis of variance using the general linear model procedure of Statistix software version 10.0. Means were compared using critical values of comparison at a 5% level of significance.

Intercropping maize with lablab reduced maize roots biomass at Syferkuil by 10% and increased shoots biomass and grain yield by 17% and 19% at Univen in 2018/2019 and 2019/2020, respectively. Lablab cultivars had no effect on LER in both sites. DL-1002 and Rongai had roots and shoots biomass of 117-143% and 212-250%, respectively, greater than Q-6880B at flowering. Cropping system significantly affected lablab grain yield, root and shoot biomass at flowering and harvest, and HI. Intercropping reduced roots biomass, shoots biomass, grain yield and HI of lablab cultivars by over 50% compared to monocropping. Cropping system was highly influential on SMN and SWC, and the highest concentration of SMN was observed in maize monocropping at flowering and, lablab monocropping and maize/lablab intercrops at harvest. Generally, the levels of SMN were greatest in the topsoil depth (0-15 cm). Maize-lablab intercropping had no effect on SWC at both sites. Sole lablab increased SWC by over 13% across locations. Contrary to SMN, SWC was highest at lower soil depth (30-60 cm). APSIM model accurately simulated maize grain yield and shoot biomass. However, the model had difficulties in simulating lablab grain yield and shoot biomass, with overestimations and underestimations of 4-132% and -49.9-98.6% for biomass and grain yield, respectively, across the sites. The highest overestimations were observed for maize-lablab intercropping.

The results of this study showed that intercropping maize with lablab has the potential to sustain maize yields with minimal inputs. Intercropping significantly reduced lablab yields at both locations, however, the biomass and grain yields obtained improved overall productivity of the intercropping system. Results of SMN and SWC support the potential of lablab use to improve soil N and conserve SWC. APSIM was able to simulate maize shoots biomass and grain yield but highly overestimated and underestimated lablab shoots biomass and grain yield. This suggests limited capacity of APSIM-lablab to simulate lablab biomass and grain yield under rainfed conditions in the dry areas of Limpopo province, thus the need for further research. Overall, intercropping maize with lablab showed positive results in maintaining and increasing maize yields over time at Univen, demonstrating that maize-lablab intercropping is a viable system to integrate into maize cropping systems to improve maize yields and land productivity in Limpopo province.

Key words: Intercropping, maize, soil water, APSIM, intercropping, lablab, nitrogen

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LIST OF ABBREVIATIONS AND ACRONYMS

°C	Degrees Celsius
APSIM	Agricultural production systems simulator
BC	Before Christ
BD	Bulk Density
BFAP	Bureau of Food Agriculture Policy
BNF	Biological nitrogen fixation
C	Carbon
Ca	Calcium
CEC	Cation Exchange Capacity
cm	Centimetre
CV	Coefficient of variation
CVC	Critical value of comparison
DAFF	Department of Agriculture, Forestry and Fisheries
DL	DL-1002
FAO	Food and Agriculture Organization
FERTASA	Fertilizer Association of South Africa
GWC	Gravimetric water content
H_2O	Water
HI	Harvest index
K	Potassium
LDA	Limpopo Department of Agriculture
LER	Land equivalent ratio
M	Maize
m	meter
Mg	Magnesium
mm	Millimetres
N	Nitrogen
Na	Sodium
NH_4^+	Ammonium ion
NO_3^{-1}	Nitrate ion
NRC	National Research Council

P	Phosphorus
Q	Q-6880B
R	Rongai
R^2	Coefficient of determination
RMSE	Root mean square error
SALLnet	South African Limpopo Landscape Network
SMN	Soil mineral nitrogen
SWC	Soil water content
USA	United States of America

CHAPTER 1: INTRODUCTION

1.1 Background

Maize (*Zea mays L*.) is one of the most produced cereals in the world, accounting for more than half of South Africa's total cropping area (Maize Trust, 2017). Maize is a summer cereal, largely grown in semiarid areas of the country, and it is highly vulnerable to changes in rainfall and temperature (du Plessis, 2003). Maize is grown globally under different climate conditions; however, maize has less drought tolerance than sunflower and sorghum (FERTASA, 2016). Rainfed maize cultivation in South Africa is often linked to soil degradation that results from continuous soil tillage, lack of fallow periods and mono-cropping. Climate variation, soil fertility, and quality seeds are key components to sustainable maize production in rainfed production systems, which is key to food security. Bureau of Food and Agriculture Policy (BFAP) (2007) reported that, the expected decrease in precipitation is likely to have consequential influence on South African agriculture since a substantial part of the country is semi-arid.

Cereal grains such as maize provide the human population with more nutrient sustenance than any other food type (Ranum *et al*., 2014). Maize is the most widely produced cereal in the world, accounting for 43% of the worldwide production. Maize is one of the highly significant cereal crops in global agriculture economy (Haarhoff *et al*., 2020), as food and fodder. Various species of maize are cultivated world-wide, which are commonly differentiated from one another by colour. Colours of kernels vary vastly, from black, red, yellow to white (Ranum *et al*., 2014). Maize production is spread across South Africa, in different soil and climate conditions and cropping systems. The most common maize cropping system is monocropping, followed by intercropping. Maize is usually sown in intercrop systems with a variety of leguminous crop species such as cowpea, chickpea, mungbean, groundnut and lablab (Mongare *et al*., 2020). Lablab (*Lablab purpureus L*.) is amongst the most diversified legume varieties with multiple uses, high grain yield and biomass production potential (Maass *et al*., 2010); however, its use remains minimal in majority of the countries in Africa (Nord *et al*., 2020), including Southern Africa.

Lablab is a dual-purpose leguminous crop, traditionally cultivated for grain for consumption by humans, feed for animals, or as an organic fertilizer (Hassan *et al*., 2014). Lablab has outstanding qualities such as tolerance to high temperatures and drought that enables the crop to protect the soil, serve as food and feed over extended dry spells long after many crops have dried up (Nord *et al*., 2020). Lablab is widely spread across many African countries; however, the crop is not amongst the main cultivated crops in the continent (Maass *et al*., 2010), and as such its use and part in human nutrition continue to lessen. In many African countries, lablab is largely used within intercrop systems (Dahmardeh *et al*., 2010; Mthembu *et al*., 2018) to increase cereal yields and in mixed crop-livestock (Madzonga and Mogotsi, 2014) farming systems to provide and improve forage quality and quantity (Hassan *et al*., 2014). Lablab is a crop suitable to be grown primarily in a tropical environment, but it can adapt to an extensive range of altitudes, rainfall, and temperatures. The crop has deep tap roots that allow the plant to recycle unavailable minerals from lower depths to the top of the soil (Kabirizi *et al*., 2005). Diversity among lablab species determines the crops' growth and yield potential in varying climates. The use of different lablab cultivars will determine which cultivars are best suited to the semi-arid environments of Limpopo province, thus aiding in designing optimal maize-lablab intercropping systems.

Intercropping is a viable agronomic practice used by farmers to stabilize crop production and provide insurance against erratic weather conditions characterized by rain-fed agriculture (Sheoran *et al*., 2010; Chepkemoi et al., 2019; Karuku et al., 2019; Namoi et al., 2014; Kizito et al., 2018; Mbayaki and Karuku, 2021), thus minimizing risks to farmers' profits and providing a measure of proof against total crop failure (Seran and Brintha, 2010). Intercropping is a form of mixed cropping system described as an act of planting multiple crop species in the same field at the same time (Mukhala *et al*., 1999). This cropping system provides socio-economic, ecological, and biological advantages over monocropping. Sheoran *et al*. (2010) found that, spacing between crops and planting density in intercrop systems plays a crucial role in balancing the competition between intercropped plants and ultimately their overall performance. However, competition for resources can be minimized by appropriate crop management and conscientious crop cultivar selection and crop combinations.

Intercropping of legume and cereal crops is an age-old practice dating back to ancient civilization (Seran and Brintha, 2010) and is still utilized among rural smallholder farmers. Cereal-legume intercropping systems are frequently used for the intention of reducing costs for nitrogen-based fertilizers, thus improving and maintaining productivity and profitability of farms (Nndwambi *et al*., 2016; Kizito *et al*., 2017; Chepkemoi *et al*., 2014). Many maize-legume intercropping field experiments have been previously reported by several authors, such as maize-pigeonpea intercrop (Madembo *et al*., 2020; Kizito *et al*., 2017; 2018), maize-cowpea intercrop (Punyalue *et al*., 2018a), maize-lablab intercrop (Mthembu *et al*., 2018), maize-bean intercrop (Wafula *et al*., 2022). Intercropping of cereal and legume crops is a good practice of lessening soil erosion and maintaining crop production (Dwivedi *et al*., 2015; Mumo *et al*., 2022). An added advantage of cereal-legume intercropping is the leaves of legumes that act as covers resulting in reduction of soil moisture losses, weed emergence and soil temperatures (Haarhoff *et al*., 2020). The dynamics of intercropping and their effect of crop yields can be evaluated through crop models. Crop models such as APSIM are capable of predicting future crop yields (Chimonyo *et al*., 2020); and this is vital in rainfed agriculture as farmers can use these models to simulate crop yields under varying environments and management to better manage their farms and maximize crop yields.

Agricultural Production Systems Simulator (APSIM) was developed by the Agricultural Production Systems Research Unit in Australia (Keating *et al*., 2003; Muli *et al*., 2015) in response to a need for modelling tools that can provide accurate predictions of crop production. APSIM can be used to simulate parameters such as crop yields, soil nitrogen, soil moisture and weeds in simple monoculture systems and complex intercropping systems. Ncube *et al*. (2009) reported that APSIM accurately predicted biomass and grain yield of sorghum in a grain-legume system. APSIM model was able to satisfactorily predict groundnut biomass in a trial carried out at Makhado by Hoffmann *et al*. (2018). There is extensive documentation and description of the APSIM framework, which has been evaluated with observations and simulations under a wide variety of conditions (Keating *et al*., 2003). However, majority of the research studies have been concentrated on single crop sequences (Ncube *et al*., 2009), as such there is a need to investigate the reliability of the APSIM model in multiple cropping systems.

1.2 Problem statement

The declining maize yields in smallholder cropping systems in dry areas of Limpopo province of South Africa are worsening food insecurity in the province and the country at large. Climate change is one of the major factors contributing to reduced yields in rainfed agriculture. Climate change has led to a decrease in rainfall, while increasing temperatures and occurrences of extreme weather patterns, that have led to water scarcity, soil loss and decrease in soil fertility. The impacts of climate change together with the rapidly increasing human population is causing a consequential decline in arable agricultural land while increasing the pressure to meet basic human demands for food. With reduction in arable land, farmers are forced to cultivate crops continuously on very small plots without resting them. Lack of inputs and continuous farming by smallholder farmers has resulted in land degradation and poor soil health that is not sufficient to supply required nutrients and support crop growth. Maize is considered as a main crop under production by majority of the smallholder farmers in the province. Farmers are faced with problems of land size, soil fertility decline, and soil moisture deficits. These creates a need to develop cropping systems that can sustainably increase and maintain maize yields under the diverse conditions of dryland farming.

1.3 Justification

Maize is a staple food in South Africa, and as such, high productivity of the crop is critical to mitigation of food insecurity. Intercropping maize with lablab is a viable option to improving land productivity in smallholder farms. However, problems of low and declining soil fertility and limited soil moisture associated with a vast of smallholder agricultural production areas in Limpopo province may compromise the efficiency of the system. Smallholder agricultural systems generally depend on rain as a source of moisture for their crops; however, rainfall is becoming more and more variable with poor distribution. Lablab has been noted to produce substantial quantities of biomass that creates large canopy covers that can reduce soil temperatures and conserve soil moisture. However, literature on the use of the crop in intercropping under rainfed conditions especially in dry areas in the province is still minimal. Therefore, more studies are required to develop mixed maize/lablab cropping systems that can deal with the problems associated with climate change faced by smallholder farmers. The Agricultural Production Systems Simulator (APSIM) can be utilized to develop intensive agricultural systems that optimizes the crop, land and water productivity. The study aimed to provide practical information that will encourage farmers to integrate lablab within their predominantly maize monoculture cropping systems.

1.4 Objectives

1.4.1 Overall objective

The main aim of the study was to determine the productivity of maize/lablab intercropping and its effect on soil water dynamics and soil mineral nitrogen levels.

1.4.2 Specific objectives

i. To determine the effect of intercropping maize with lablab on:
  - Biomass and grain yield of maize and lablab
  - Harvest index (HI%) and land equivalent ratio (LER)
  - Soil water content
  - Soil mineral nitrogen

ii. To validate the ability of APSIM model to accurately simulate biomass and grain yields under maize and lablab intercropping systems.

1.5 Hypotheses

i. Intercropping of maize with different lablab cultivars will:

- Improve biomass and grain yield of maize and lablab
- Affect HI and LER.
- Affect soil water content.
- Affect soil mineral nitrogen.

ii. APSIM model accurately predicts maize and lablab biomass and grain yields under maize and lablab intercropping system.

CHAPTER 2: LITERATURE REVIEW

2.1 Maize

Origin, cultivation, and utilization

Maize (*Zea mays* L.) is a cereal crop that belongs to the Fabaceae family. It is believed that maize was initially domesticated in Southern Mexico approximately 7000 to 10000 years ago (Tollenaar and Dwyer, 1999). It is the most domesticated and cultivated crop globally (Food and Agriculture Organization (FAO), 2010), with China, USA, Mexico and Brazil being the world's largest producers. Maize is important to food security for majority of vulnerable people in developing countries (Bruinsma, 2009). FAO (2010) estimated that 30% of sub-Saharan Africa's agricultural lands producing cereals are planted with maize, whereas 19% are planted in West Africa, 21% planted in Eastern Africa, and a major 61% and 65% in Central Africa and Southern Africa, respectively. At present, South Africa is the largest maize producing country in Africa (Price Waterhouse Coopers (PWC), 2021), producing both white and yellow maize varieties. White maize is mainly cultivated for the purpose of human consumption, and yellow pigmented maize is largely utilized in the production of fodder for livestock (VIB, 2017). Maize makes up a dominant part the diet and nutrition of many countries in the African continent, including South Africa (DAFF, 2012). Maize is the primary food source for over 300 million individuals in Africa alone. The crop serves as a nutritious food source that has approximately 72% starch, 10% protein and 4% fat (Ranum *et al*., 2014).

The consumption of maize varies widely from region to region. In most developing countries, maize is consumed as food (FAO, 2003) directly or processed into a range of products that include maize flour and maize meal, while in many developed countries, maize is used as fodder, fed to the animals as green crop, dry forage, silage or grain (Ranum *et al*., 2014). An ideal growing environment for maize is a deep soil that drains well, in regions with temperatures between 18-32°C. The crop can grow optimally in areas with annual precipitation within the range of 230 to 4,100 mm (VIB, 2017). The North-West, Free State, Mpumalanga, and KwaZulu-Natal provinces are the major maize producing areas in South Africa (Maize Trust, 2017). By the end of 2018, an approximate 2.6 million hectares of agricultural land in South Africa was assigned to maize production (Haarhoff et al., 2020). The large land allocation to maize production demonstrates the importance of the crop in the country.

Maize is the most significant grain crop in South Africa, especially in Limpopo province where over 80% of the province is classified as rural (Limpopo Department of Agriculture (LDA), 2012). Limpopo province is located in the northern parts of South Africa; and covers an area of approximately 12.3 million hectares. It is one of the country's top agricultural regions known for producing livestock, fruits, vegetables, cereals, and tea. Although maize only makes up 4% of Limpopo's total agricultural income, it is the most important dry land crop in the province.

A large portion of the Limpopo province has infertile soils that commonly have nitrogen and phosphorus deficiencies, that cause crop production limitations and yield reductions (Whitbread and Ayisi, 2004). EcoAfrica (2015) reported that over 60% of Limpopo’s maize areas are credited to smallholder farmers whose yields are restrained by droughts, declining soil fertility, recurring weed and pest infestations, and unavailability of agricultural inputs. As such, there is a need to design viable, environmentally friendly strategies that will increase maize yields to mitigate food insecurity in Limpopo province. A promising strategy is the use and integration of legumes into maize cropping systems.

2.2 Lablab

Origin, cultivation and utilization

Lablab (*Lablab purpureus* L.) is an ancient crop, dating back to 1800 BC (Fuller, 2003). It belongs in the Leguminosae family, along with legumes such as cowpea, chickpea, groundnut and soybean, among many others. As a result of minimal research work and developments on lablab, there is limited understanding on the origination and diversification of the crop. However, there is a general believe that lablab is native to Asia or Africa (Pengelly and Maass, 2001; Robotham and Chapman, 2015). Lablab is currently underutilized globally, with cultivation mainly concentrated in Asian countries such India and China and some parts of Africa (Maass *et al*., 2010). In African, the crop has been cultivated and spread throughout the tropical and subtropical countries in the continent (Aganga and Tswenyane, 2003). However, lablab still remains a forgotten and neglected legume crop in the continent. Like many legume species, lablab can be grown in monoculture, crop rotations or intercropped with cereals or vegetables. Its versatility and adaptation to varying environments, makes the crop a desirable option.

Lablab is generally a summer growing, annual or short perennial crop species with twinning, creeping or bushy growth patterns (Salim *et al*., 2013) but due to its adaptability, it can be planted in a wide range of climate conditions, and this characteristic increases the crop’s potential use in the future (Robotham and Chapman, 2015). Additionally, lablab can be cultivated under varying soil types, from deep sands to heavy clay soil with average fertility (Nath, 1976). Madzonga and Mogotsi (2014) reported that lablab can tolerate pH across a range of 4.5-7.5, provided that drainage is good. Once established, lablab is tolerant to drought conditions and high temperatures between 18˚C and 30˚C. Generally, lablab can grow optimally in areas that receive rainfall amount ranging between 200-2500 mm (Murphy and Collucci, 1999). The crop can be used as a vegetable for human consumption, as a forage for livestock, and it can also be used as a cover crop in soil conservation (Kimani *et al*., 2012). Different lablab genotypes are preferred for different uses (Robotham and Chapman, 2015). Genotypes with long pods are normally used as a vegetable while those with a higher drought tolerance are used for fodder (Pengelly and Maass, 2001). Lablab adaptation and productivity is to a large extent also influenced by crop variety (Nord *et al*., 2020).

Lablab's tolerance to drought and poor soil fertility makes it a good candidate for cultivation in the Limpopo Province and has the potential to be incorporated into maize monoculture systems. Maluleke *et al*. (2004) conducted preliminary studies on lablab that indicated the crop has prolific growth characteristics and, if not well managed, could severely suppress maize growth and yields in an intercropping system. Beyond all its uses for food and fodder, lablab can be used advantageously to provide organic matter and fix atmospheric nitrogen in association with rhizobia, thereby improving subsequent crop yields in a cheap and environmentally friendly manner. According to Pengelly and Maass (2001), lablab has the potential of playing a significant part in transforming cropping systems of southern Africa, which are characterized by semi-arid climate conditions. Due to the capability of the crop to produce food grain and large biomass under severe conditions of water stress and soil infertility, lablab can be an important crop in smallholder farming systems relying on rainfall. However, more studies should be conducted to develop valuable information in understanding its genetic diversity and extensive use as food, fodder, and a supplier of nitrogen through biological N_2 fixation (BNF).

Legume plants such as lablab have the capability of forming symbiotic relationships with a group of bacteria within the soil called rhizobia (Hungria *et al*., 2015), that have the potential to fix nitrogen gas from the atmosphere and convert it to plant available nitrogen forms in the soil (Duchene, 2017). The BNF process provides an economical and sustainable method through which farmers can reduce the use of external inorganic nitrogen fertilizers (Massawe *et al*., 2016 and Abd-All *et al*., 2017), while improving quality and quantity of yields (Rahman, 2013). Suboptimal soil conditions such as high temperatures, salinity, inadequate moisture content, high or low pH, and nutrient deficiency, can severely affect formation of nodules and nitrogen fixation (Abd-All *et al*., 2017 and Hungria *et al*., 2015). Lablab has the potential to produce substantial quantities of nitrogen to meet its growth requirements and leave residual nitrogen in the soil to be used by subsequent crops (Massawe *et al*., 2016). Seran and Brintha (2010) reported minimal competition for nitrogen resources when lablab was intercropped with maize.

2.3 Intercropping

Intercropping is an old practice of cultivating more than one crop species in one area at the same time (Maitra *et al*., 2021). In an intercrop system, resources such as soil water, nutrients and light, are used efficiently to maximize crop production. This ancient agricultural practice has been utilized in past years to achieve agricultural goals (Seran and Brintha, 2010). Intercropping is a common practice applied in sustainable agriculture, playing a significant role in improving productivity and stability of yields (Alizadeh *et al*., 2010). Intercropping is practiced across many African countries, with different crop combinations; however, maize is the common crop (Mukhala *et al*., 1999). Crops with varying root systems and leaf type and size; are able to harmlessly use light, nutrients and water more efficiently than crops of the same species with similar roots and leaves (Seran and Brintha, 2010). An added advantage of intercropping is the reduction in pests and diseases and in cases where there is already infestation, reduction in the spread of pests and diseases (Gebru, 2015). Intercropping can preserve soil moisture, increase crop production and improve soil nitrogen concentrations. But these benefits are dependent on crop combinations and management factors. However, velvet bean roots only incorporated plots had the lowest yields among cover crop residue combinations, a fact attributed to the allellopathetic nature of velvet bean roots (Karuku *et al*., 2014). It has been reported by other workers that some plant roots exert allelopathic effect on tomatoes by producing “allelochemicals” that suppress tomato growth and yields (Igue *et al*, 2006; Wang *et al*., 2003; Karuku *et al*., 2014). However, incorporation of aboveground material from velvet bean probably counteracted the allelopathic effects leading to the observed yields in velvet bean above and below ground biomass (Karuku *et al*., 2014).

2.3.1 Effect of maize-lablab intercropping on soil water content

The presence of soil moisture in the soil is one of the major factors that determine the production-potential of a cereal-legume intercropping system (Maitra *et al*., 2021). Intercropping is a water conserving agricultural practice, especially in water scarce regions. This is because the high leaf area of crops can conserve water by acting as cover crops (Ghanbari *et al*., 2010), thus reducing water evaporation. A review paper by Seran and Brintha (2010) showed that intercropping improved water use efficiency when compared to monocultures. Crops of different species have varying root lengths and as such they are able to take up soil moisture at varying soil depths. Hu *et al*. (2015) reported that maize-wheat intercropping integrated with mulching preserved more soil water than wheat and maize monocrops. Once established, lablab’s root system has the capacity to penetrate water sources as far as 2 m deep into the soil, allowing vigorous plant development to continue after the rains have ended (National Research Council (NRC), 2006). However, this is also influenced by the texture of the soil the crop is growing in.

Nndwambi *et al*. (2016) reported that moisture stress is expected to have a negative impact on cereal-legume intercropping in dry land areas of Limpopo province, as a major portion of the smallholder farmers that practice intercropping in the province often work on small lands in low rainfall areas. Xu *et al*. (2009) cited by Brooker *et al*. (2015) reported that intercropping often increases water availability in water limited regions because it improves uptake of water across the soil profile through complementary root distribution between the intercrops. Water is a major limiting factor of crop production, affecting plant vigour and nutrient uptake by plants. Therefore, there is a need to investigate and understand the dynamics of soil water content under maize-lablab intercropping system to improve resource use under diverse rainfed environments.

2.3.2 Effect of maize-lablab intercropping on nitrogen content

Agricultural practices which mix maize with legume species can decrease the quantity of nutrients taken up by plants from the soil when compared to sole maize (Seran and Brintha, 2010). Due to varying root systems, plants are able to use nutrients from varying soil depths. Lablab has extensive tap roots that are capable of penetrating lower soil depths to access macronutrients such as nitrate and micronutrients such as boron, that are susceptible to leaching. Legumes have the capability to fix nitrogen gas on the atmosphere, as such there is reduced competition for nitrogen resources with maize. Nitrogen is an essential nutrient important for plants’ development and growth (Massawe *et al*., 2016). A study conducted by Dahmardeh *et al*. (2010) found that nitrogen, potassium and phosphorus concentrations in the soil were higher in maize-cowpea intercrop than maize monocrop treatments.

Lablab as a component in an intercrop system can be used to add organic matter through decomposition and mineralization of lablab residues (Mousavi and Eskandari, 2011) and fix atmospheric nitrogen to forms that the plants can readily use, thereby improving soil fertility and yields of crops in a cheap and agriculturally sustainable way (NRC, 2006). Intercropping maize with lablab can help improve and maintain soil’s fertility by adding nitrogen fixed by lablab (Duchene *et a*l., 2017). Lablab can produce substantial quantities of biomass that is rich in nitrogen (Mthembu *et al*., 2018). Lablab residues have low C:N ratios, as such they can decompose and mineralize quickly, becoming available for other crops. A study by Amosse *et al*. (2014) found that lablab had high quantities of nitrogen in the aboveground biomass. As such, further studies should be conducted to investigate the interaction and benefits of intercropping maize with different lablab cultivars on soil nitrogen to improve its adaptation and adoption in Limpopo province.

2.3.3 Effect of maize-lablab intercropping on dry matter and yield production

Intercropping is a commonly practiced agricultural system used in sustainable agriculture, and it plays a crucial part in improving and maintaining crop yields (Mousavi and Eskandari, 2011). Intercropping allows farmers to produce more than one crop on the same size of land, thus improving use of resources (Mbanyele *et al*., 2021). Intercropping improves plant diversity and complementarity between crop species within arable cropping systems. Intercropped systems generally produce higher yields than sole cropping in an equal unit area, and the productivity of the system is usually quantified by land equivalent ratio (Cong *et al*., 2014). The greatest complementary effect and largest crop yield advantage occurs when crops in an intercrop are planted at different dates, so their greatest demand for resources occurs at varying intervals during crop development (Dwivedi *et al*., 2015). Masvaya *et al*. (2017) reported higher biomass and grain yields of maize-cowpea intercrop as compared to maize monocrop and a significant yield reduction when maize and cowpea were planted simultaneously.

Legume plants that have the ability to climb, such as lablab, cowpea and velvet bean, may interfere with the physiological development of cereal plants when they are intercropped together (Abraha, 2013), severely reducing crop yield and biomass accumulation. Sheoran *et al*. (2010) found that growth and yield of maize intercropped with blackgram was lower compared to sole maize. Available literature suggests that such reductions in yield might be linked with shading and competition consequences of maize plants and associated legume plants within intercrops (Dwivedi *et al*., 2015, Cong *et al*., 2014). The contradicting literature about the effect of legumes on maize indicate a need for further research to get more insight and understanding on the influence of crop combinations and cultivars, planting time and climate on maize and lablab yields.

2.4. APSIM Model

Agricultural models serve as tools for understanding complicated interactions within cropping systems, with the intention of attaining higher crop productivity and achieving environmental aims (Archontoulis *et al*., 2014). One popular and widely used agricultural model is APSIM. APSIM (Agricultural Production System Simulator) is a model that has been widely tested and used in southern parts of Africa (Ncube *et al*., 2009; Whitbread *et al*., 2010; Hoffmann *et al*., 2018). APSIM is a process-based model, that simulates plant growth, development and crop yields under different soil and climate conditions. APSIM is popularly used for the model's capability to cope with complicated interactions between the crop, climate, soil fertility, and residue management on farms (Keating *et al*., 2000). The model can simulate soil moisture, carbon, nitrogen and phosphorus changes and their interactions within the crop and management systems. In a study conducted by Archontoulis *et al*. (2014), APSIM accurately simulated soil moisture and soil nitrogen.

In APSIM the key concept is the central part within the model which is the soil module instead of the crop module, even though crop yield is usually of important interest (McCown et al., 1996). A simulation study conducted by Hoffmann *et al*. (2018) showed that APSIM accurately simulated groundnut biomass, while another study by Robertson *et al*. (2005) found that simulated yields of velvet bean by APSIM were higher than observed yield. Archontoulis *et al*. (2014) outlined that in order for APSIM model to efficiently carryout accurate calibrations and simulations, detailed and dependable datasets are required. Maize is predominately cultivated in smallholder agricultural systems under rainfed conditions that are worsened by input and resource limitations. Reliance of maize production on rainfall as the only source of soil moisture makes maize production vulnerable to climate change and climate variability (Cairns *et al*., 2013). APSIM has the potential to help farmers foresee, prepare, adopt, and deal with the effects of climate variability and change, thus minimizing yield loss risks and improving farm management strategies. Intercropping is a risky agricultural practice that requires more labour and time than monocropping and can easily be affected by rainfall variability. APSIM may be utilized to simulate crop performance using different crops and crop varieties under different management scenarios to help farmers make well informed decisions that have minimal risks.

CHAPTER 3: MATERIAL AND METHODS

3.1 Study area

3.1.1 Site description

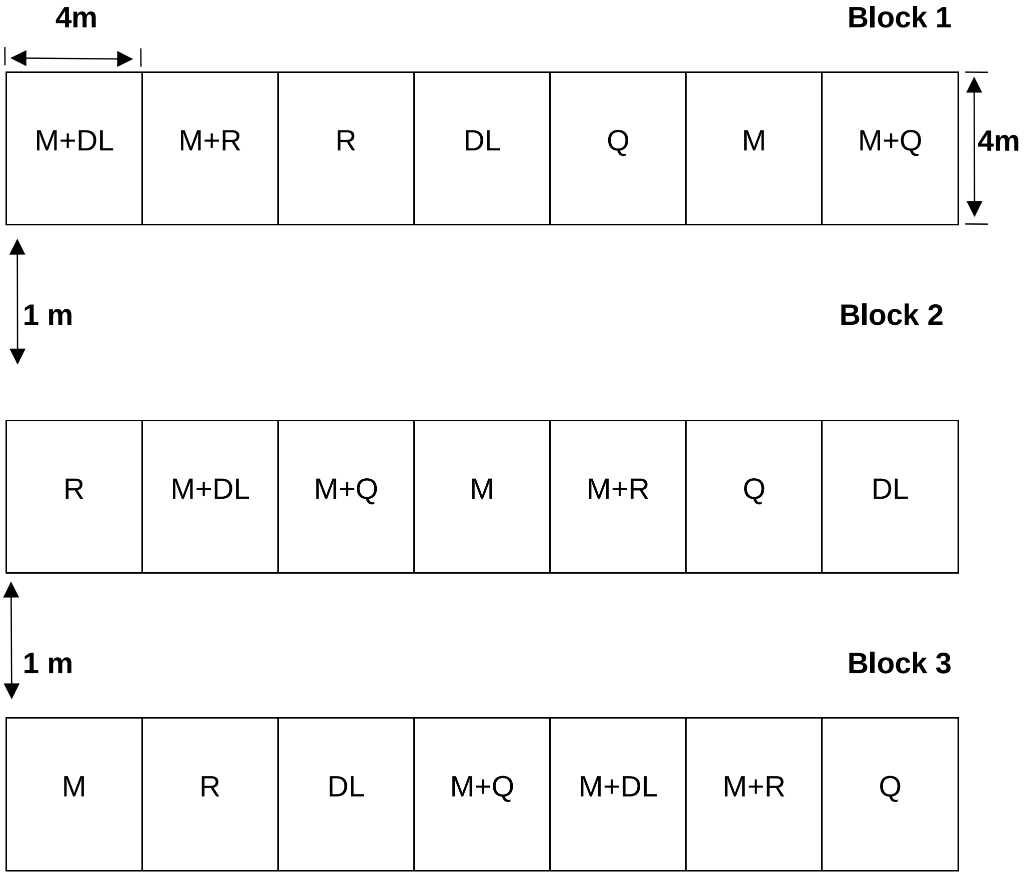
The field experiments were conducted over two consecutive planting seasons (2018/2019 and 2019/2020) in the summer season at the University of Venda Experimental Farm (Univen) located in Thohoyandou and at the University of Limpopo Experimental Farm (Syferkuil) located in Mankweng over one summer planting season in 2018/2019. The experiment was conducted for one season at Syferkuil because the second season failed due to neglect because of the restrictions imposed by the South African government during Covid-19 outbreak. Rainfall is highly seasonal at both locations, with over 80% of the rainfall commonly received between October and March. The areas oftentimes have midseason dry spells at a time of crucial crop growth (FAO, 2009). Univen site receives about 825 mm of rainfall per annum and average temperatures of about 30°C in the summer (FAO, 2009). Syferkuil site generally experiences lower annual mean rainfall of about 491 mm (Rapholo *et al*., 2019) with average temperatures varying between 28°C and 30°C in the summer (Nndwambi *et al*., 2016).

3.1.2 Soils

The soils at Univen are dominated by structureless red clays, that are generally well drained and deep (Mzezewa *et al*., 2010). The soil is slightly acidic with pH of 5-6.5, and generally has a high clay content of about 50-65% (Rapholo *et al*., 2019). They are categorized as Hutton soil form based on the South African System of Soil Classification, which is identical to Rhodic Ferralsols based on the World Reference Base for Soil Resources (WRB) (2006). Syferkuil site is characterized by soils with a high sand content of 60-84%, that are generally sandy clay loam and sandy loam in texture. Similar to soils at Univen, Syferkuil soils are classified as Hutton form. They have a soil pH of 6.0-7.3 and are formed in *in situ* on basalt, sandstone and biotic gneiss; hence the high sand content (Phefadu and Kutu, 2016).

3.2 Experimental set-up and design

The soils were cultivated mechanically using a tractor and the seedbed preparation was completed using a garden fork, spade and hand hoe. Maize variety DKC-2147 along with lablab cultivars DL-1002, Rongai (brown), and Q-6880B were used in the experiments. The cropping systems consisted of sole maize, three sole lablab cultivars, and maize intercropped with each of the lablab cultivars to give a total of 7 treatments. The treatments were laid out in a randomized complete block design (RCBD) with three replications, with each plot measuring 4 m x 4 m with 1 m spacing separating the blocks (Figure 3.1). Two seeds of maize and lablab were planted at a spacing of 80 cm between the rows and 50 cm within the rows. For intercropped plots, lablab cultivars were planted between maize plant rows 28 days after maize sowing. The seedlings were thinned to one plant two weeks after emergence. Superphosphate (10.5% P) and Lime Ammonium Nitrate (28% N) were applied as starter fertilizers at a rate of 50 kg ha^{-1} and 30 kg ha^{-1}, respectively. The plots at Syferkuil were irrigated immediately after sowing to boost seed germination, after which they were rainfed until the final harvest, and plots at Univen were rainfed from sowing to harvest in both seasons. Weeds were controlled using a hand hoe to reduce the competition between the desired crops and weeds for light, water and nutrients. These activities were repeated in 2019/2020 season at Univen. However, cultivation of the soil was carried out using a hand hoe only in the second season to prepare the soil for planting.



Block 1

M+DL	M+R	R	DL	Q	M	M+Q

Block 2

R	M+DL	M+Q	M	M+R	Q	DL

Block 3

M	R	DL	M+Q	M+DL	M+R	Q

Figure 3.1. Experimental field layout

Where**:** **M**-sole maize, **R**-sole Rongai, **DL**-sole DL-1002, **Q**-sole Q-6880B, **+**-shows intercropping combination between crop species

3.3 Soil sampling for characterization of the experimental site

At each experimental site, soil samples were collected randomly using an auger at depths of 0-15 cm, 15-30 cm, and 30-60 cm before planting. The samples were mixed thoroughly and composited, and a subsample was obtained from the composite and stored in a freezer for the determination of soil mineral nitrogen (Table 3.1). The remaining soil sample was air-dried and passed through a 2 mm sieve for the determination of selected physical and chemical soil properties. The soil parameters included soil pH, CEC, texture, organic carbon, total P, Ca, Mg, K and Na (Table 3.2). Soil mineral nitrogen was determined using colorimetric method following the procedure outlined by Sattolo *et al*. (2016), pH (H_2O) was measured using pH meter (1:2.5 soil to water ratio), Ammonium acetate extraction procedure was used to determine CEC and exchangeable cations (Mg, Ca, Na, and K) as described by Peech (1965). Soil organic carbon was determined using the Walkley-Black method (Nelson and Sommers, 1982). Bray-1 method was used to determine available phosphorus (Bray and Kurtz, 1945). Soil texture was determined using hydrometer method following a procedure described by Bouyoucous (1962). Additional soil samples were collected at similar soil depths to determine initial soil water content following the gravimetric method as described by Black *et al*. (1965)

Table 3.1. Initial bulk density (BD), NO_3^-, NH_4^+ and soil water content (SWC)

		Soil characteristics			
Site	**Depth (cm)**	**BD ($g\ cm^{-3}$)**	**NO_3^- ($mg\ kg^{-1}$)**	**NH_4^+ ($mg\ kg^{-1}$)**	**SWC ($g\ g^{-1}$)**
Univen	0-15	1.22	21.85	13.10	0.16
	15-30	1.25	37.90	15.80	0.18
	30-60	1.34	34.05	14.47	0.21
Syferkuil	0-15	1.40	12.52	9.92	0.10
	15-30	1.45	11.15	16.44	0.11
	30-60	1.52	11.15	12.29	0.15

Table 3.2. Selected initial physical and chemical properties of soils at the experimental sites

	Experimental site	
Soil properties	**Univen**	**Syferkuil**
Physical properties		
Clay (%)	61	20
Silt (%)	18	21
Sand (%)	21	59
Textural class	Clay	Sandy clay loam
Chemical properties		
pH (KCl)	5.92	6.76
EC	28.83	65.12
SOC (%)	1.42	0.82
P (mg kg^{-1})	11.23	15.47
Exchangeable cations (mg kg^{-1})		
K	65	72
Na	140	130
Mg	271	389
Ca	724	633
CEC ($cmol_{(+)}$ kg^{-1})	24.21	19.03

3.4 Data collection

3.4.1 Soil water content

Soil water content (SWC) was determined across four maize growth stages, at V10 (vegetative stage-cob development), VT (tasselling), R3 (grain filling) and R6 (physiological maturity). Soil samples were collected from the depths of 0-15, 15-30 and 30-60 cm at both experimental sites between rows of plants in the middle of each plot. Collected soil samples were placed into plastic bags and stored in a cooler box while in the field to minimize moisture losses through evaporation. Soil water content was determined using the gravimetric water content method (GWC) (Black *et al*., 1965). Samples were transferred into tins that were weighed and tared before adding soil. The samples were oven dried at a temperature of 105°C for 24-48 hours, until there was no difference between any two consecutive measurements of the weight of the dry soil sample.

$$GWC = \frac{weight\ of\ wet\ soil - weight\ of\ dry\ soil}{weight\ of\ dry\ soil}$$ (Black *et al*., 1965)……………………1

3.4.2 Soil mineral nitrogen (NH_4^+ and NO_3^-)

Soil mineral nitrogen (SMN) was determined by the colorimetric method following the procedure by Sattolo *et al*. (2016). Soil samples for the determination of SMN were collected at maize flowering and harvest maturity. The samples were collected across the soil profile from 0-15, 15-30 and 30-60 cm depths in the first cropping season and at a depth of 0-15 and 30-60 cm in the second season. All the samples were collected from the middle of each plot. Collected samples were transferred into plastic bags and placed into a cooler box with ice to keep the samples cool while in the field. The samples were stored in a freezer at a temperature of 4°C until they were ready to be analysed.

3.4.3 Crop biomass, grain yield, and harvest index

3.4.3.1 Maize

At flowering and harvest maturity, biomass was determined by randomly selecting four and nine healthy maize crops from each plot at flowering and harvest maturity stages, respectively. The selected plants were uprooted from the soil by loosening the soil around the maize roots using a garden fork. The excess soil adhering to the roots was extracted by gently shaking the plants and rinsing the roots with tap water. Each plant was separated into aboveground (shoots) and belowground (roots) biomass using a garden shears. Collected samples were dried in an oven at a temperature of 65°C until completely dry and the biomass weight was constant.

Grain yield was determined by extracting all maize ears attached to the maize stalks of the plants harvested at harvest maturity. The ears were dehusked, dried and the seeds removed manually by hand. To determine grain yield, the harvested maize seeds were weighed. Harvest index (HI) was determined by calculating the ratio of grain yield to aboveground biomass yield using Eq.2.

$$HI\ (\%) = \frac{grain\ yield\ (kg/ha)}{biomass\ yield\ (kg/ha)} \quad \text{(Rapholo } et\ al\text{., 2019)……………………..2}$$

3.4.3.2 Lablab

Similar to maize, biomass for each lablab cultivar was determined at their respective flowering (50% flowering) and harvest maturity stages. Four plants per plot were collected at flowering, while at harvest maturity, nine plants were collected for each lablab cultivar from within the central rows. The harvested plants were cut into two parts, aboveground (shoots) and belowground (roots) using garden shears. The roots were rinsed with tap water to get rid of any attached soil particles. The samples were placed into paper bags and dried in an oven at a temperature of 65°C to a constant weight. The oven-dried biomass was weighed using a weighing balance of ±0.01 precision.

To determine grain yield, all the pods attached to the nine lablab plants collected at harvest maturity were removed by hand. The pods were air dried, and hand threshed to extract the seeds. Seeds that were rotten or damaged by insects were discarded. The collected seeds were weighed to determine lablab grain yield. Harvest index was determined by using the Eq.2 stated above.

3.4.4 Land equivalent ratio

Land equivalent ratio (LER) was used to evaluate the efficiency of the maize-lablab intercropping system compared to sole cropping (Gebru, 2015). LER is the ratio of land required by sole crops to produce the same yields as that of the intercrops under the same management (Mthembu *et al*., 2018). LER is defined as:

$$LER = \frac{Yim}{Ysm} + \frac{Yilb}{Yslb} \quad \text{(Nord \textit{et al}., 2020)……………………..……..3}$$

Where Y*im* and Y*ilb* are the intercrop yields for maize and lablab and Y*sm* and Y*slb* are sole planted yields of maize and lablab, respectively. Maize and lablab are generally cultivated for grain and fodder, thus two LERs were calculated to evaluate the grain yield and production of fodder in the intercropping systems.

3.4.5 APSIM

3.4.5.1 Model calibration

The APSIM (version 7.10 r4219) was set up for the two seasons (2018/2019 and 2019/2020). APSIM model was calibrated using field experimental data, management parameters, site-specific soil data, and daily climate data for 2018/2019 cropping season. The climate data was collected for the two sites from 2018-2020 from the Agricultural Research Council data base (Table 3.3 and Table 3.4). Climate parameters used include solar radiation, minimum and maximum temperatures, and rainfall. The daily weather data was computed, and the file converted into APSIM model format (.met). Soil water parameters, organic carbon parameters, soil nitrogen parameters and management parameters were inputted into the model (Table 3.1). Existing maize cultivars in the model were selected as they were grouped as early maturing maize varieties while only one lablab cultivar existed within the model. For calibration, the cultivar coefficients of each selected cultivar were modified using field-observed data to best represent the new cultivars and they were given new cultivar names.

3.4.5.2 Model testing and validation

The suitability of the APSIM model was assessed by comparing the simulated values with the observed values and two statistical indices, namely root mean square error (RMSE) and coefficient of determination (R^2). The R^2 reflects the consistency between the simulated values and the observed value. The closer the value of R^2 to 1, the better the simulation effect of the model (Zhou *et al*., 2022). RMSE reflects the relative error between the simulated values and observed values. The smaller the RMSE, the better the accuracy of the model (Zhou *et al*., 2022). The RMSE and R^2 were determined using the Eq.4 and Eq.5 below:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Yi-Xi)^2}{N}}$$ (Berghuijs *et al*., 2021)……………………………4

$$R^2 = \frac{\sum_{i=1}^{N}(\mathrm{Yi}-\bar{\mathrm{Y}})^2}{\sum_{i=1}^{N}(Xi-\bar{X})^2}$$ (Seyoum *et al*., 2018)……………………………….5

Where Y_i is the simulated values, X_i is the observed values, $\bar{Y}$ is the simulated average value, $\bar{X}$ is the observed average value, N is the number of samples.

Table 3.3. Maximum and minimum (°C) average monthly temperatures at Univen and Syferkuil during 2018/2019 and 2019/202 seasons.

Location	**Univen**				**Syferkuil**	
Season	**2018/2019**		**2019/2020**		**2018/2019**	
Month	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
October	28.9	13.7	32.5	16.8	27.2	10.3
November	30.6	16.4	32.9	19.0	24.8	14.0
December	33.8	19.7	31.3	18.4	30.5	16.9
January	32.9	20.0	31.6	20.1	28.9	16.8
February	31.6	19.7	30.1	19.1	29.4	16.8
March	31.5	19.3	30.8	17.5	29.0	15.8
April	29.1	16.8	28.3	15.4	26.2	12.1
May	28.7	11.3	27.8	10.8	25.6	6.1
June	26.3	9.6	24.8	9.0	22.9	3.0
July	28.3	8.8	24.6	7.7	24.0	1.2
August	29.5	11.9	26.8	10.9	26.3	7.7
September	29.9	12.7	27.0	13.7	27.3	8.1

Table 3.4. Average monthly rainfall (mm) at Univen and Syferkuil during 2018/2019 and 2019/2020 seasons.

Location	**Univen**		**Syferkuil**
Season	**2018/2019**	**2019/2020**	**2018/2019**
Month		**Rainfall** (mm)	
October	22.5	0	0.24
November	84	201.83	1.22
December	129.4	120.23	1.77
January	204.9	242.06	5.05
February	320.1	407.92	1.17
March	31.1	25.39	1.33
April	26.4	69.09	0.65
May	3.5	0.76	0
June	0.2	8.63	0
July	0	2.7	0
August	0	50.4	0
September	0	57.9	0.06

3.5 Statistical analysis

Data collected from season 1 and 2 at Univen and from season 1 at Syferkuil for maize yield and yield components was subjected to a one-way analysis of variance using the general linear model procedure of Statistix software version 10.0. Lablab yield and yield components, soil mineral nitrogen and soil water content were subjected to a two-way analysis of variance using the same statistical model stated above. Means were compared using critical value of comparison (CVC) at a 5% level of significance.

CHAPTER 4: EFFECT OF MAIZE-LABLAB INTERCROPPING ON MAIZE BIOMASS, GRAIN YIELD, HARVEST INDEX AND LAND EQUIVALENT RATIO

4.1 Introduction

Maize is amongst the major cereal crops cultivated across the African continent, which is used as a feed grain and serves as food for a large proportion of the African population (Maize Trust, 2017). Kornher (2018) reported maize as the third most primary agricultural product globally after rice and wheat. However, a recent research by Erenstein *et al.* (2022) showed an increase in maize production globally, with maize being the highest produced cereal followed by wheat and rice. The field areas used for maize production in South Africa covers approximately 2.8 million hectares and represents 70% of all summer crops (FERTASA, 2016). Due to its geographical adaptability, maize can successfully be cultivated under varying climate conditions (Erenstein *et al*., 2022). White maize is generally cultivated to provide humans with food while yellow maize is predominately cultivated for animal feeds. In South Africa, maize serves as a source of staple food, more especially for the poor communities, as such increasing the production and yield of the crop is crucial to securing food security.

One third of global maize production occurs in low-income areas, contributing less than 15% to the global production. Smallholder farming in low-income areas are characterized by low crop yields associated with insufficient utilization of farm resources such as irrigation, pesticides and fertilizers (Cammarano *et al.,* 2020). Smallholder farmers greatly rely on rain as the main source of water, thus limiting their production. Smallholder systems are managed with unsustainable practices such as intensive soil till and continuous maize monoculture which have led to depletion of soli nutrients (Haarhoff *et al.,* 2020). Despite soil degradation and nutrient depletion maize yields have continued to increase because of genetically modified maize hybrids that are tolerant to drought (Cammarano *et al*., 2020). Even though there has been an improvement in maize yields globally over the past decade (Erenstein *et al*., 2022), smallholder maize cultivation in rural areas has been experiencing yield declines. As such, there is a need to practice maize cultivation in cropping systems that will help increase soil fertility and lessen soil degradation which are the primary contributors to crop failure after moisture deficits.

One possible strategy of addressing the problem of soil degradation, nutrient depletion and poor maize yields is maize-legume intercropping. Intercropping is an act of cultivating multiple crops at the same time and within the same field (Duchene *et al*., 2017). Intercropping is often practiced on smallholder farms to improve food security, food diversity and minimize the risks associated with total crop losses (Seran and Brintha, 2010). Intercropping of maize with French beans resulted in higher maize yields than maize monocrop (Hugar and Palled, 2008).

Additionally, a research study conducted by Brooker *et al*. (2015) found that intercropping under low-yielding environments increased yield stability through the reduction of diseases and pests. Intercropping maize with grain legume crops not only offers the yield advantage per unit area over sole cropping (Yin *et al*., 2020), but can also protect the soil from erosion and can help with nutrient cycling.

One important legume that can be intercropped with maize is lablab. Although not as common in South Africa as Bambara groundnut, and cowpea, the addition of lablab into maize dominated systems may be a viable strategy to reducing soil degradation, adding nitrogen and improving crop yields. Limpopo Province is a predominately semi-arid/arid region characterized by soils with poor fertility, and lablab as a legume has the potential to fix atmospheric nitrogen. This can improve nitrogen levels in the soil which can ultimately benefit the maize crop. Lablab can produce large amounts of biomass (Mthembu *et al*., 2018), making it a good surface cover. This ability of the crop to cover the soil gives lablab an added advantage of protecting the soil from erosion and improving moisture preservation. There has been reported evidence of the benefits of maize-lablab intercropping (Punyalue *et al*., 2018a; Massawe *et al*., 2016). However, majority of the studies were focusing on one cultivar, Rongai. As such, there is a need investigate more cultivars under diverse environments to better understand their suitability and maximize their benefits for farmers. The objective of the study was to investigate the impact of intercropping maize with varying lablab cultivars on maize roots and shoots biomass and grain yield in two different environments.

4.2 Materials and methods

Full experimental details are given in chapter 3, but a brief summary is given below. Field experiments were conducted at two experimental sites during the summer of 2018/2019 and 2019/2020 at the University of Venda Experimental Farm (Univen) and during the 2018/2019 summer at the University of Limpopo Experimental Farm (Syferkuil). The experiments consisted of sole maize (DKC-2147), sole lablab (DL-1002, Rongai (brown) and Q-6880B), and three intercropping systems where maize was intercropped with each lablab cultivar. Each lablab cultivar was planted 28 days after maize planting within the intercropped plots. The treatments were laid out in a randomized complete block design with three replications. Starter nitrogen and phosphorus were applied at a rate of 30 kg N ha^{-1} and 50 kg P ha^{-1}, respectively, at planting. Biomass was collected at approximately 50% maize flowering and at harvest maturity. Grain yield was determined from the plants collected for biomass at harvest maturity. All data collected was subjected to a one-way ANOVA using the Statistix software version

10.0. Comparison of means was done using the critical value of comparison (CVC) method at a 5% level of significance.

4.3 Results

4.3.1 Maize shoot and root biomass at flowering

Intercropping maize with different lablab cultivars had no significant effect on root and shoot biomass at flowering in 2018/2019 and 2019/2020 seasons at Univen and 2018/2019 season at Syferkuil (Table 4.1). Although not significantly different, root biomass was the lowest under maize monocropping at Univen and Syferkuil. In 2018/2019 cropping season the greatest shoot biomass (3094.1 kg ha^{-1}) was recorded in maize monocropping at Univen, while maize+Q-6880B had the highest shoot biomass (3571.4 kg ha^{-1}) in 2019/2020 season. At Syferkuil, the greatest biomass of shoots (2381.7 kg ha^{-1}) was in maize+Rongai intercropping system. Generally, Syferkuil site demonstrated minimal variation in root and shoot biomass across cropping systems relative to Univen in 2018/2019 season.

4.3.2 Maize root and shoot biomass at harvest maturity, grain yield and harvest index (HI)

Maize-lablab intercropping did not influence biomass of roots and shoots, grain yield and HI in 2018/2019 but significantly affected shoot biomass and grain yield in 2019/2020 season at Univen (Table 4.2). Shoot biomass of maize was greatest under maize+Q-6880B at Univen in 2018/2019 and 2019/2020 cropping seasons, although only significant in 2019/2020. Lablab cultivars had a comparable effect on maize shoots and grain yield in 2019/2020 at Univen, with maize shoot biomass of (7686.4-7941.6 kg ha^{-1}) and grain yield of (4778.6-4840.0 kg ha^{-1}) across the intercrops. Intercropping maize with lablab only affected maize root biomass at Syferkuil (Table 4.2). Maize monocropping had 10.3-15.7% greater root biomass compared to intercropped maize, while the lowest root biomass was recorded in maize+Rongai at Syferkuil. At Syferkuil, sole maize had the greatest grain yield and root and shoot biomass. Intercropping of maize with varying cultivars of lablab did not affect HI, however, maize + Rongai cropping system had a greater HI compared to maize+DL-1002 and maize+Q-6880B across locations.

4.3.3 Partial maize and lablab biomass LER and total biomass LER

Effect of cropping system on partial maize and lablab biomass LER and total biomass LER was not significant at Univen in 2018/2019 and 2019/2020 season and at Syferkuil in 2018/2019 season (Table 4.3). Although not analysed, there was a noticeable variation in partial biomass LER and total biomass LER across locations. Generally, Syferkuil site had the lowest partial maize and lablab LER biomass and total biomass LER. Partial biomass LER increased across seasons for maize by 6.1-10.4% and for lablab by 17.4-35.9%, while total biomass LER increased by 9.6-17.2% from season 1 to season 2 at Univen.

4.3.4 Partial maize and lablab grain LER and total grain LER

Effect of cropping system on lablab partial grain LER and total grain LER was not significant in 2018/2019 and 2019/2020 at Univen and in 2018/2019 cropping season at Syferkuil (Table 4.4). Partial grain LER of maize and lablab and total grain LER was slightly higher in 2019/2020 season compared to the 2018/2019 cropping season at Univen. Maize+DL-1002 had a greater partial lablab and maize grain LER and total grain LER in the 2018/2019 cropping period. However, in the 2019/2020 cropping season maize+DL-1002 and maize+Q-6880B had comparable partial grain LER and total grain LER. At Syferkuil the partial grain LER of maize and lablab and total grain LER were comparable across all the cropping systems.

Table 4.1. Effect of intercropping maize with different lablab cultivars on maize root and shoot biomass at flowering at Univen in 2018/2019 and 2019/2020 and at Syferkuil in 2018/2019.

Site	**Univen**				**Syferkuil**	
Season	**2018/2019**		**2019/2020**		**2018/2019**	
Treatment	Roots (kg ha^{-1})	Shoots (kg ha^{-1})	Roots (kg ha^{-1})	Shoots (kg ha^{-1})	Roots (kg ha^{-1})	Shoots (kg ha^{-1})
Cropping system						
Sole maize	593.8	3094.1	574.4	2783.5	503.7	2304.9
Maize + DL-1002	619.5	2987.9	731.6	3328.1	528.9	2367.8
Maize + Rongai	624.6	2833.8	742.4	3388.5	530.4	2381.7
Maize + Q-6880B	633.0	2644.2	690.9	3571.4	513.9	2337.3
CVC	212.0	1247.2	184.77	907.65	132.84	907
P-value						
Cropping system	ns	ns	ns	ns	ns	ns
CV (%)	12.14	15.26	9.54	9.82	9.05	13.66

Means without letters are not significantly different, CVC-Critical value of comparison, CV-Coefficient of variation

Table 4.2. Effect of intercropping maize with different lablab cultivars on maize root and shoot biomass at harvest maturity, grain yield and harvest index (HI) at Univen during 2018/2019 and 2019/2020 season and at Syferkuil in 2018/2019 cropping season.

Site	**Univen**								**Syferkuil**			
Season	**2018/2019**				**2019/2020**				**2018/2019**			
Treatment	Roots (kgha^{-1})	Shoots (kgha^{-1})	Grain yield (kgha^{-1})	Harvest Index (%)	Roots (kgha^{-1})	Shoots (kgha^{-1})	Grain yield (kgha^{-1})	Harvest Index (%)	Roots (kgha^{-1})	Shoots (kgha^{-1})	Grain yield (kgha^{-1})	Harvest Index (%)
Cropping system												
Sole maize	724.5	7292.8	4341.4	59.8	931.8	6590.0b	4012.1b	60.9	778.1a	5391.7	3310.6	61.9
Maize + DL-1002	842.7	8034.0	4682.3	58.5	1169.7	7686.4a	4778.6a	62.2	705.3ab	4680.3	2881.3	61.6
Maize + Rongai	726.4	7725.8	4562.0	59.2	1113.3	7720.9a	4819.3a	62.4	672.8b	4824.8	3008.5	62.7
Maize + Q-6880B	776.3	8337.5	4303.2	51.7	1090.3	7941.6a	4840.1a	61.0	691.2ab	4933.3	2989.0	60.5
CVC	275.83	1123.10	1088.40	19.51	537.86	642.02	705.06	7.66	97.65	2217.4	1060.9	11.99
P-value												
Cropping system	ns	ns	ns	ns	ns	***	*	ns	*	ns	ns	ns
CV (%)	12.71	5.06	8.61	12.05	17.67	3.03	5.41	4.4	4.85	15.82	12.31	6.87

Means followed by the same letter are not significantly different, *** (P<0.001), ** (P<0.01) and * (P<0.05), CV-Coefficient of variation, CVC-Critical value of comparison

Table 4.3. Effect of intercropping maize with different lablab cultivars on partial maize and lablab biomass LER and total biomass LER at Univen during 2018/2019 and 2019/2020 seasons and at Syferkuil in 2018/2019 cropping season.

Location	**Univen**						**Syferkuil**		
Season	**2018/2019**			**2019/2020**			**2018/2019**		
Treatment	**$PLER_{lablab}$**	**$PLER_{maize}$**	**TotalLER**	**$PLER_{lablab}$**	**$PLER_{maize}$**	**TotalLER**	**$PLER_{lablab}$**	**$PLER_{maize}$**	**TotalLER**
Cropping system									
Maize + DL-1002	0.46	1.10	1.56	0.54	1.17	1.71	0.31	0.90	1.21
Maize +Rongai	0.39	1.06	1.45	0.53	1.17	1.70	0.34	0.95	1.29
Maize + Q-6880B	0.50	1.14	1.64	0.62	1.21	1.83	0.49	0.96	1.44
CVC	0.33	0.16	0.33	0.11	0.08	0.14	0.41	0.29	0.31
P-value									
Cropping system	ns	ns	ns	ns	ns	ns	ns	ns	ns
CV (%)	25.68	5.08	7.28	6.6	2.29	2.84	37.05	10.79	8.22

Means without letters are not significantly different, CV-Coefficient of variation, CVC-Critical value of comparison

Table 4.4. Effect of intercropping maize with different lablab cultivars on partial maize and lablab grain LER and total grain LER at Univen during 2018/2019 and 2019/2020 seasons and at Syferkuil in 2018/2019 cropping season.

Location	**Univen**						**Syferkuil**		
Season	**2018/2019**			**2019/2020**			**2018/2019**		
Treatment	**PLER$_{lablab}$**	**PLER$_{maize}$**	**TotalLER**	**PLER$_{lablab}$**	**PLER$_{maize}$**	**TotalLER**	**PLER$_{lablab}$**	**PLER$_{maize}$**	**TotalLER**
Cropping system									
Maize + DL-1002	0.27	1.07	1.35	0.32	1.19	1.52	0.24	0.96	1.20
Maize + Rongai	0.16	1.05	1.21	0.28	1.20	1.49	0.22	0.98	1.21
Maize + Q-6880B	0.20	0.99	1.20	0.31	1.21	1.52	0.21	0.99	1.20
CVC	0.19	0.29	0.42	0.06	0.19	0.20	0.21	0.35	0.41
P-value									
Cropping system	ns	ns	ns	ns	ns	ns	ns	ns	ns
CV(%)	30.70	9.59	11.50	6.48	5.47	4.60	32.37	12.19	11.69

Means without letters are not significantly different, CV-Coefficient of variation, CVC-Critical value of comparison

4.4 Discussion

Compared to 2018/2019, intercropping maize with lablab had a significant impact on maize shoots at harvest and grain yield at Univen in 2019/2020 but had no significant impact on shoots and grain yield at harvest at Syferkuil and Univen. The lack of significance at Syferkuil may be attributed to the soil type found on the farm, that is characteristically dominated by sandy to sandy loam soils (Phefadu and Kutu, 2016) that has low fertility and water holding capacity. The high sand content may have caused high water losses through percolation, given that the rainfall amount during that season was below average thus depriving the crops of moisture. This process also facilitates leaching, which is major pathway of nitrogen losses in the soil. Nitrogen is an important nutrient that aids in the development of maize as it affects photosynthesis. The nonsignificant effect of maize/lablab intercropping at Univen may have been due to the clay-rich soils of the area that are known to be fertile and have good water holding capacity. The fertile soils at Univen may have been able to supply nutrients and moisture to maize under both monocropping and intercropping without compromising biomass and grain yield.

A study by Rapholo *et al*. (2019) conducted at the University of Venda Experimental Farm reported that maize biomass and grain yield was similar under sole maize and maize/lablab intercropping, supporting the findings of this study. However, results of this study are contradicted by Madembo *et al*. (2020) who reported that legume crops (cowpea, lablab and pigeonpea) partially suppressed biomass and grain yield of maize in intercropping. They reported that the results were likely due to increased competition for resources between the legumes and maize. Despite the lack of influence of intercropping on maize yields in 2018/2019 season the Total-LER values demonstrated a yield advantage of intercrops for both biomass and grain yield. Total-LER was greater than 1 across all the intercrops. This suggests improved productivity in the intercrops than maize monoculture in absorbing and utilizing water and nutrients, especially immobile nutrients like phosphorus and potassium (Gebru, 2015).

The competition for resources between intercrop species is influenced by crop requirements, crop characteristics such as roots and spacing which determines plant population (Kiwia *et al*., 2019). Competition between maize and lablab exists aboveground and belowground, for soil moisture, light, and nutrient sources (Maitra *et al.*, 2021). Planting crops that have varying roots in an intercrop allows for a better exploitation of larger soil volume, and this also results in increased access to nutrients that are relatively immobile within the soil profile (Gebru, 2015). The differences in maize and lablab roots may have created complementary conditions that resulted in low competition for soil resources. Intercropping crops that have varying roots is important because it improves resource use efficiency as nutrients and moisture are taken up from different soil depths, thus minimizing competition. A study by Rapholo *et al*. (2019)

found significantly lower maize grain yield when lablab and maize were sown at the same time. In the current study, the competition between maize and lablab was reduced by planting lablab 28 days after maize sowing. Perennial crops such as lablab have an extensive root system which has a high ability to effectively loosen and aerate soils, thus improving water storage and absorption (Duchene *et al*, 2017).

Contrary to the first cropping season, maize grain yield was higher in intercropped systems than that in sole cropping system in the second season at Univen. These results demonstrate that maize yields may have been affected as a subsequent crop in the successive season (Amosse *et al*., 2014), as the plots intercropped in the previous season are the same ones used in season two. This is most likely because of residual nutrients released which could have been enhanced and set free for plant uptake during the previous season residue decomposition (Massawe *et al*, 2016). This effect may have been enhanced by the late maturing lablab varieties, that continued to grow and add mulch long after maize was harvested. Harvesting lablab later than maize also provides the soil with protection from erosion during winter when normally the fields would be left fallow and bare. As result, this may have long term effects as lablab could provide more biomass that can act as mulch and leaf litter that protects and covers the soil, and this may improve nutrient levels in the soil from decomposition of lablab litter (Madembo *et al*., 2020). A study by de Quadros *et al*. (2019) showed that maize-lablab intercropping, and lablab-maize rotations significantly affected soil chemical properties (organic carbon and nitrogen) that led to increased microbial communities and activity in lablab cropping systems. In the same study, it was also found that lablab planting in intercropping positively correlated with nitrogen, organic carbon and exchangeable cations. These results are a probable explanation for the increased maize yields in the second season at Univen. Maize is a heavy feeder and returns little nutrients back to soil resulting in nutrient depletion over time. Continuous maize cultivation without fertilizer inputs can lead to yield reductions (Haarhoff *et al*., 2020), and this was shown in this study by the poor biomass and grain yield production of maize under maize monoculture in the second season.

Similar to findings in this study, Mthembu *et al.* (2018) found that intercropping maize with lablab yielded nonsignificant results for biomass and grain yield of maize in the first cropping season, however, showed tremendous improvements in intercrop systems in the subsequent years relative to maize monocropping. Punyalue *et al*. (2018a) reported that lablab residues effectively suppressed weeds during the second season, which allowed maize to be sown without tillage. These findings agree with the observations made in the current study. Although not measured, there was a notable reduction (field observation) in weed emergence in intercropped systems. Weeds tend to have a negative effect on crop production as they increase the competitiveness of the cropping system for soil resources amongst the crops

(Haarhoff *et al*., 2020). Reducing weed occurrence preserves the nutrients from residues for the subsequent cultivation, thus reducing supplemental fertilization. Preservation and recycling of nutrients in maize-lablab intercropping may also explain the increased biomass and grain yield in intercropped plots. Punyalue *et al*. (2018a) reported improvement in soil physical properties from the build-up of organic matter which affected rainfall infiltration. Improved water infiltration is especially important at the Univen site where the soil is predominately clay. The mulch from lablab contributed in moisture preservation by reducing soil temperatures and increasing aeration, and as such, improving moisture and nutrient uptake by maize.

Similar to a study of Mthembu *et al*. (2018), intercropping had no significant effect on grain and biomass yields of maize in the first season. The results in this study are contradicted by Massawe *et al* (2016) who observed increased maize biomass and grain yield results in maize-lablab and maize-common bean intercropping systems in all cropping seasons. In another study, maize-lablab intercropping was found to be superior, resulting in the highest maize residue yield and grain yield when compared to maize-rice bean, maize-mung bean, and maize-cowpea cropping systems (Punyalue *et al*., 2018a). The authors attributed the high maize yield components and grain yield to the nitrogen that was biologically fixed by lablab, that was significantly higher than the other legumes, which was released for the uptake and use by maize. The contradiction in the first cropping season may be because nitrogen and phosphorus fertilizers were applied at planting in all the cropping systems, thus making up for the nitrogen that may have been fixed by lablab in the intercropping systems. Overall, the study showed that maize/lablab can be a viable strategy to improve maize yields over time with minimal inputs, as significant results were only observed from the second season.

4.5 Conclusion and recommendations

Intercropping maize with different lablab cultivars influenced maize biomass and grain yield; however, this effect was only evident in the subsequent season at Univen. The use of different cultivars had no significant effect on maize grain yield, biomass, HI and LER in both sites. Regardless of the nonsignificant impact of maize-lablab intercrops on grain yield and biomass in the first cropping season, LER still showed that intercropping is a better cropping option than maize monocropping. As such, by utilizing intercropping farmers can attain optimal yields of maize, and an extra harvest from lablab. This not only offers farmers an economic advantage of selling two products but may also lessen costs of feeds for livestock farmers that could use lablab as fodder. Although intercropping offers a yield advantage over monocropping, it is important for farmers to use appropriate planting densities and crop mixtures coupled with appropriate agricultural implementations such as weeding and controlling pests timely, to sustain the cropping system. South African rainfed maize production is under diverse climate conditions and soil types, which brings about numerous advantages and disadvantages. Use of complex cropping systems through increased introduction of diverse crops could increase resource use efficiency and may also offer tools to overcome the disadvantages faced within continuous maize systems. It is recommended that further studies should be carried out that utilize lablab cultivars that are more diverse from one another to fully explore the potential benefits and advantages and disadvantages of the system. This is vital as it would provide critical information that could be used by farmers to make well informed decisions that are specific to their environments and needs.

CHAPTER 5: EFFECT OF LABLAB CULTIVARS AND CROPPING SYSTEM ON BIOMASS, GRAIN YIELD AND HARVEST INDEX OF LABLAB

5.1 Introduction

Provinces that are predominately rural in South Africa, such as Limpopo province, have high levels of poverty. Many households in such areas depend on agriculture as their source of income and food (FAO, 2015). Common agricultural activities in rural areas include the production of fruits, vegetables, grains, livestock, and poultry farming. Smallholder farming is commonly characterized by poor yields (Baiphethi and Jacobs, 2009), largely because of lack of farm resources such as fertilizers, quality seeds and adequate water sources. As a result, South Africa has experienced a decline in the proportion of smallholder farms (Baiphethi and Jacobs, 2009). South Africa is a relatively food secure country when compared to the rest of the continent. However, the country is still lagging behind with regards to food security at the household level. For South Africa to achieve and maintain food security there must be an increase in agricultural output. Increasing production in smallholder farming systems has the potential to ameliorate food insecurity in poor communities in rural and urban regions through increased supply of food within the communities, thus reducing food prices.

Crop production and agricultural productivity in smallholder farming systems can be increased through the application of sustainable land intensification (Maitra *et al*., 2021; Chepkemoi *et al*., 2014; Liavoga *et al*., 2014; Namoi *et al*., 2014). The use and integration of legumes within farming systems is a feasible strategy for improving agricultural productivity with limited external resources (Gebru, 2015; Kizito *et al*., 2017; 2018 and 2022). Legumes commonly cultivated in Southern Africa include cowpea, pigeon pea, groundnut, bambara, mung bean and soybeans. While these legumes form a vital part of traditional cropping systems, lablab offers better advantages under rainfed conditions. Lablab has been found to be more drought tolerant than most legumes including cowpea and groundnut (Maass *et al*., 2010), making it an ideal crop for the semi-arid areas of Limpopo province. Similarly to majority of legumes, lablab has the potential to fix atmospheric nitrogen with the assistance of nitrogen-fixing bacteria into inorganic forms that can be used by plants. This protein rich legume is commonly cultivated for fodder and food in many countries (Maass *et al*., 2010), and has the added benefits of protecting fields against soil erosion, reducing incidence of weeds in the farm and adding organic carbon to the soil through leaf shedding.

The cultivation of lablab is well investigated in India, Kenya, Nigeria, Ethiopia and Tanzania and thus far, reports on the growth and yield of lablab under varying soils and climates have yielded positive results (Ewansiha *et al*., 2017; Maluleke *et al*., 2004; Madzonga and Mogotsi, 2014). However, utilization of lablab in smallholder cropping systems remains low in the

Southern parts of Africa with majority of the farmers favouring legumes such a cowpea, groundnut, bambara, and mung bean. The limited research that is available on lablab in South Africa has largely been centred on the Rongai cultivar (Maluleke *et al*., 2004; Rapholo *et al*., 2019). There are three main lablab cultivars widely cultivated, Rongai, Highworth and Endurance. However, there are over 4000 landraces of lablab grown globally (Devaraj, 2016). Therefore, there is a need to further study and better understand the performance of varying cultivars of lablab in different cropping systems in order to identify suitable cultivars that will meet the production needs of the farmers in different regions of Limpopo province.

Lablab can be grown as a sole component or cultivated in mixed farming systems, the common one being intercropping. Intercropping is a multiple cropping system that involves planting more than one crop in the same field in proximity (Brooker *et al*, 2015). The crops utilized in intercropping can be cultivated simultaneous or at separate times during the cropping season (Rapholo *et al*., 2019). Lablab is usually intercropped with cereal crops like sorghum (Kahsay *et al*., 2021), maize (Rapholo *et al*., 2019), and vegetables such as potatoes (Nyawade *et al*., 2020a). Intercropping of maize with legumes is the most commonly practiced type of mixed farming involving lablab in Africa (Kiwia *et al*, 2019) largely because maize is a staple grain for many countries in the continent. Intercropping maize with lablab increases crop output on limited land, maximises the potential of available resources and minimizes the spread of pests and diseases within the farm. The degree of success in intercropping depends largely on the compatibility of the crop species and crop cultivars used, such that the competition for resources between the crops does not limit the primary crop. Lablab's versatility and adaptability make it an ideal option for the harsh semi-arid areas where agriculture is mostly practiced under rainfed conditions by smallholder farmers. The aim of the study was to assess the performance of different lablab cultivars in varying cropping systems across different environments.

5.2 Materials and methods

Full experimental details are given in chapter 3, but a brief summary is given below. The performance of lablab cultivars was assessed in two field experiments which were conducted at the University of Venda Experimental Farm (Univen) during 2018/2019 and 2019/2020 seasons and one field experiment conducted at the University of Limpopo Experimental Farm (Syferkuil) during 2018/2019 season. The experiment was laid out using a randomized complete block design in a factorial arrangement with three replications. Three lablab cultivars, DL-1002, Rongai (brown), and Q-6880B were planted in two cropping systems as sole and intercropped with maize cultivar DKC-2147. Intercropped lablab was planted between the rows of maize plants 28 days after maize sowing. Biomass at flowering was collected at approximately 50% flowering of each lablab cultivar. Biomass was also collected at harvest maturity and pods attached to the plants harvested were collected to measure grain yield at maturity. Data collected was subjected to a two-way ANOVA using Statistix model 10.0 software and Tukey's critical value for comparison was used to compare the treatment means at 5% level of probability.

5.3 Results

5.3.1 Root and shoot biomass of lablab at flowering at Univen and Syferkuil

The lablab cultivars had a significant effect on lablab root and shoot biomass at Univen and Syferkuil sites (Table 5.1). The lowest root and shoot biomass were observed for cultivar Q-6880B at both locations, recording 59-61% and 54-57% less roots and 68-69% and 72-73% less shoots biomass than cultivar DL-1002 and Rongai at Univen and Syferkuil sites, respectively (Table 5.1). Although a similar trend was observed for lablab root and shoot biomass across the locations, Univen yielded 66-76% and 55-82% greater root and shoot biomass, respectively, than Syferkuil.

The Cropping system had a significant effect on lablab root and shoot biomass at flowering at both sites. The lablab root and shoot biomass were found to be highest in sole cropping than intercropped (Table 5.1). Intercropping reduced root and shoot biomass of lablab by between 74-80%, 52-86%, respectively, across the locations. The interaction between cropping system and lablab cultivars was nonsignificant for lablab shoot biomass at flowering at Univen. However, a significant interaction was observed for root biomass (Figure 5.1). Cultivar Q-6880B had the lowest root biomass in both sole and intercropped plots at Univen. At Syferkuil, the interactive effect of lablab cultivar and cropping system was significant for both root and shoot biomass (Figure 5.2). Cultivar Q-6880B yielded the lowest root and shoot biomass under both monocropping and intercropping systems. Generally, root and shoot biomass were greater at the Univen than Syferkuil site.

Table 5.1. Effect of lablab cultivars and cropping system on roots and shoot biomass of lablab at flowering at Univen and Syferkuil in 2018/2019 season.

Season	**2018/2019**			
Location	**Univen**		**Syferkuil**	
Treatment	**Roots**	**Shoots**	**Roots**	**Shoots**
Cultivar				
DL-1002	1050.4a	2700.0a	555.2a	1659.8a
Rongai	1010.9a	2770.4a	596.0a	1778.2a
Q-6880B	415.1b	863.3b	255.7b	473.1b
CVC	109.71	841.93	125.07	126.86
Cropping system (CS)				
Mono-cropping	1312.5a	2851.9a	782.3a	2278.5a
Intercropping	341.1b	1370.5b	155.7b	328.9b
CVC	72.78	558.48	82.96	84.15
Cultivar*cropping system				
Sole DL-1002	1644.4a	3530.9	936.3a	2915.5a
Sole Rongai	1616.5a	3897.4	967.4a	3102.1a
Sole Q-6880B	676.5b	1127.5	443.1b	818.0b
Maize + DL-1002	464.3c	1869.1	174.0c	404.2c
Maize + Rongai	405.3c	1643.3	224.6bc	454.4c
Maize + Q-6880B	153.7d	599.1	68.3c	128.1d
CVC	196.05	1504.5	223.48	226.69
P-value				
Cultivar	****	***	****	****
Cropping system	****	***	****	****
Cultivar*cropping system	****	ns	**	****
CV (%)	8.38	25.17	16.83	8.33

Means followed by the same letter are not significantly different, CVC-critical value of comparison, CV-coefficient of variation, ****(P<0.0001), ***(P<0.001), **(P<0.01), *(P<0.05), ns-not significant

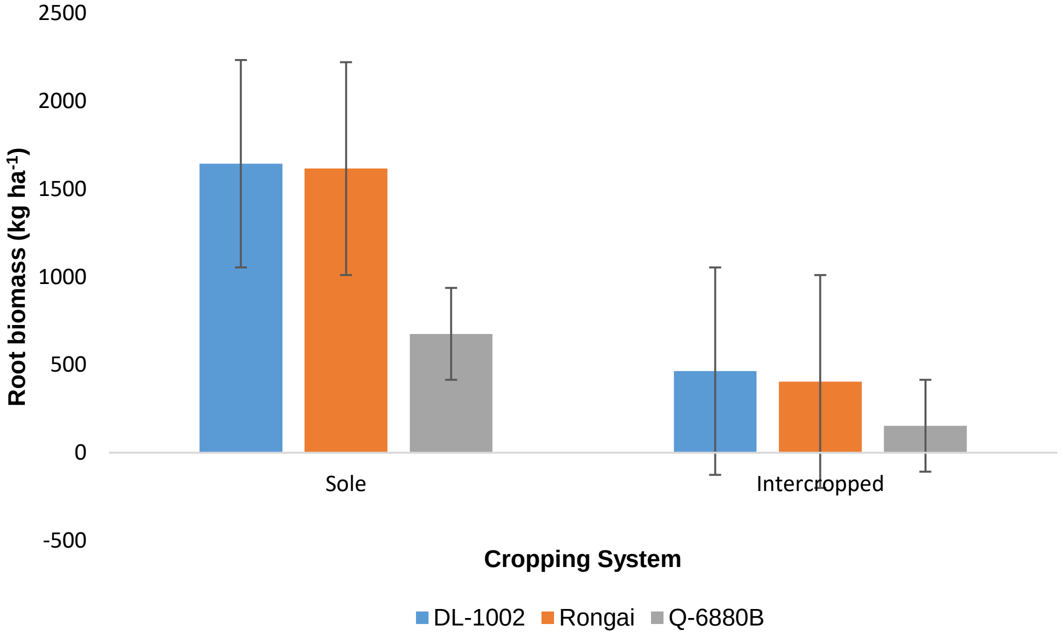


Figure 5.1 Interactive effect of cropping system and lablab cultivars on lablab roots biomass at Univen at flowering in 2018/2019 season.

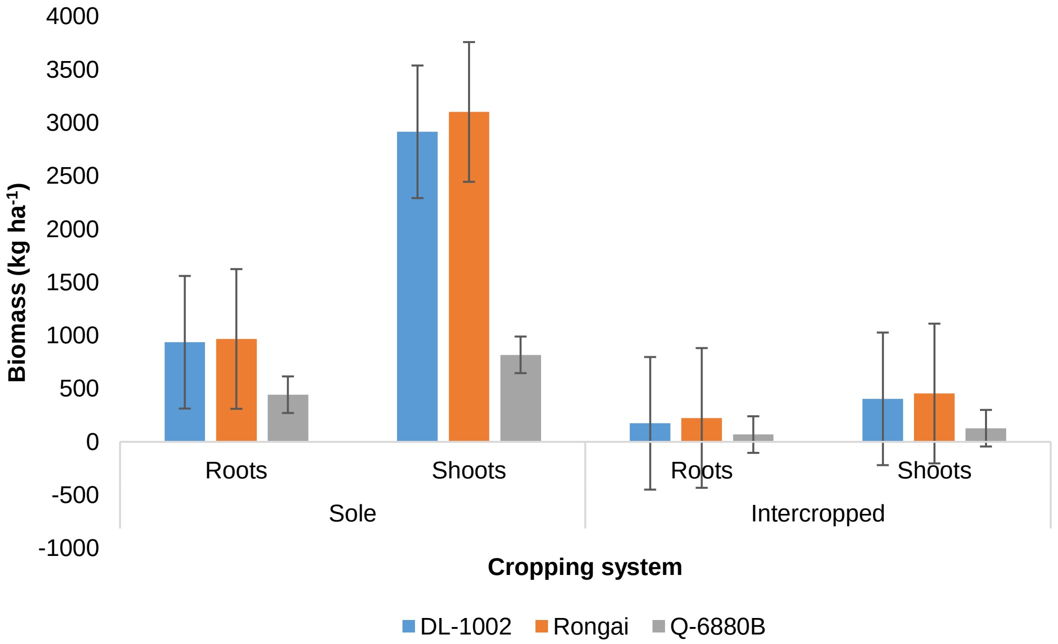


Figure 5.2 Interactive effect of cropping system and lablab cultivars on lablab roots and shoots biomass at flowering at Syferkuil in 2018/2019 cropping season.

5.3.2 Root biomass, shoot biomass, grain yield and harvest index (HI) of lablab at harvest maturity

5.3.2.1 Root and shoot biomass of lablab at harvest maturity at Univen

The lablab cultivars had no significant influence on root biomass at harvest during the 2018/2019 and 2019/2020 seasons. However, the lablab cultivars significantly affected shoot biomass at harvest in the 2019/2020 season (Table 5.2). The late flowering lablab cultivars, DL-1002 and Rongai, had the highest shoot biomass compared to the early flowering variety Q-6880B. Cultivar Q-6880B produced between 10-12% less shoot biomass compared to DL-1002 and Rongai. The root and shoot biomass increased drastically in the second season when compared to the first season. The effect of cropping system was highly significant on root and shoot biomass at harvest for both 2018/2019 and 2019/2020 cropping seasons. Lablab monocropping yielded higher root and shoot biomass than intercropped lablab crop. Root and shoot biomass of lablab in monoculture were between 43-45% and 44-56%, respectively, higher than in intercropping. The interactive effect of lablab cultivars and cropping system had no significant impact on root and shoot biomass in the first cropping season (2018/2019). The interaction of lablab cultivars and cropping system did however influence shoot biomass in 2019/2020 cropping season (Figure 5.3). Cultivar Rongai and DL-1002 had the greatest shoot biomass at harvest under sole cropping system. However, in maize-lablab intercropping system the cultivars had comparable shoot biomass yield.

5.3.2.2 Grain yield and harvest index (HI) of lablab at Univen

The lablab cultivars had a nonsignificant effect on grain yield and harvest index in 2018/2019 and 2019/2020 seasons (Table 5.2). There was a small increase in lablab grain yield in the second season while HI experienced a decrease in the second season, compared to the first cropping season. The cropping system significantly affected HI and grain yield of lablab in 2018/2019 and 2019/2020 seasons. Harvest index and grain yield of lablab were the highest in lablab monoculture than in intercropping. Harvest index and grain yield of lablab were between 70-74% and 42-45%, respectively, higher in monocropping than intercropping. The interaction of lablab cultivars and cropping system had a nonsignificant effect on HI and grain yield in 2018/2019 and 2019/2020 cropping seasons.

5.3.2.3 Root and shoot biomass of lablab at harvest maturity at Syferkuil

The lablab cultivars had no significant effect on root and shoot biomass at Syferkuil in 2018/2019 (Table 5.3) season at harvest maturity. Root and shoot biomass of lablab were significantly affected by cropping system (Table 5.3). Intercropping maize with lablab reduced HI, grain yield, shoot and root biomass of lablab. There was 68% and 64% decline in root and shoots biomass of lablab, respectively, of intercropped lablab when compared to sole planting. The interactive effect of cropping system and lablab cultivars had no significant effect on shoot biomass at Syferkuil. However, cropping system and lablab cultivars had a significant interactive effect on lablab root biomass at harvest (Figure 5.4). Cultivars DL-1002, Rongai and Q-6880B had similar root biomass under maize-lablab intercropping system. However, in sole lablab cropping system cultivar Q-6880B had significantly lower root biomass compared to DL-1002 and Rongai. Cultivars DL-1002 and Rongai had 29% and 37% greater biomass, respectively, than that of Q-6880B.

5.3.2.4 Grain yield and harvest index (HI) of lablab at Syferkuil

Lablab cultivars had a nonsignificant effect on grain yield and HI of lablab (Table 5.3). Cropping system significantly affected grain yield and harvest index of lablab in 2018/2019. Intercropping of maize-lablab reduced grain yield and HI of lablab by 78% and 36%, respectively, relative to lablab monocropping. The interactive effect of lablab cultivars and cropping system was nonsignificant for grain and harvest index.

Table 5.2. Effect of lablab cultivar and cropping system on root biomass (kg ha^{-1}), shoot biomass (kg ha^{-1}), grain yield (kg ha^{-1}) and harvest index (HI) (%) at Univen in 2018/19 and 2019/20 seasons.

Location	**Univen**							
Season	**2018/2019**				**2019/2020**			
Treatments	**Roots**	**Shoots**	**Grain**	**HI (%)**	**Roots**	**Shoots**	**Grain**	**HI (%)**
Cultivar								
DL-1002	897.8	3693.6	1487.2	39.9	1342.8	4575.6a	1546.5	31.4
Rongai	849.9	3633.9	1507.9	35.3	1337.0	4654.7a	1753.0	34.5
Q-6880	957.1	3688.0	1452.1	35.3	1266.3	4090.8b	1515.5	34.3
CVC	277.41	1026.60	550.63	17.39	182.92	411.84	244.48	4.69
Cropping system (CS)								
Mono-cropping	1149.3a	5108.1a	2358.9a	46.7a	1696.5a	5686.8a	2465.1a	43.5a
Intercropping	653.9b	2235.6b	466.9b	26.9b	934.2b	3193.9b	745.0b	23.3b
CVC	184.02	680.95	327.73	11.53	121.71	274.03	162.67	3.12
Cultivar*CS								
Sole DL-1002	1146.1ab	5093.0a	1965.7a	38.7ab	1715.5a	5926.3a	2339.7a	39.5a
Sole Rongai	1052.8abc	5291.4a	2611.2a	50.6a	1733.7a	6083.1a	2735.5a	45.1a
Sole Q-6880	1249.0a	4939.9a	2499.8a	51.6a	1640.3a	5051.0b	2319.9a	45.9a
Intercropped DL-1002	649.5c	2294.3b	521.7b	23.3b	970.2b	3224.8c	753.3b	23.4b
Intercropped Rongai	647.1c	1976.3b	404.5b	20.1b	940.2b	3226.3c	770.6b	23.9b
Intercropped Q-6880	665.2bc	2436.2b	474.6b	19.5b	892.3b	3130.7c	711.2b	22.7b
CVC	495.71	1834.40	882.84	23.83	324.85	731.38	434.17	8.33
P-value								
Cultivar	ns	ns	ns	ns	ns	**	ns	ns
Cropping system	***	****	****	**	****	****	****	****
Cultivar*CS	ns	ns	ns	ns	ns	*	ns	ns
CV (%)	19.42	17.65	22.07	24.86	9.00	6.01	9.86	9.08

Means followed by the same letter are not significantly different, CVC-critical value of comparison, CV-coefficient of variation, ****(P<0.0001), ***(P<0.001), **(P<0.01), *(P<0.05), ns-not significant

Table 5.3. Effect of lablab cultivars and cropping system on root biomass (kg ha^{-1}), shoot biomass (kg ha^{-1}), grain yield (kg ha^{-1}) and harvest index (HI) (%) at Syferkuil in 2018/19 season.

Location	**Syferkuil**			
Season	**2018/2019**			
Treatments	**Roots**	**Shoots**	**Grain**	**HI (%)**
Cultivar				
DL-1002	494.6	2498.3	395.1	14.7
Rongai	473.5	2517.6	372.8	13.3
Q-6880	399.8	2057.5	390.3	20.2
CVC	109.79	777.98	169.66	15.29
Cropping system				
Mono-cropping	690.0a	3472.6a	633.7a	18.17a
Intercropping	222.1b	1243.0b	138.5b	11.6b
CVC	72.83	516.06	112.54	3.00
Cultivar*CS				
Sole DL-1002	776.1a	3807.6	640.2	16.6
Sole Rongai	728.8ab	3795.1	617.1	16.1
Sole Q-6880	565.2b	2815.3	643.6	23.5
Intercropped DL-1002	213.6c	1189.0	150.0	12.7
Intercropped Rongai	218.1c	1240.2	128.5	11.3
Intercropped Q-6880	234.4c	1299.7	136.9	10.8
CVC	196.18	1390.2	303.16	8.08
P-value				
Cultivar	ns	ns	ns	ns
Cropping system	***	****	****	***
Cultivar*CS	*	ns	ns	ns
CV (%)	15.19	20.83	27.74	18.82

Means followed by the same letter are not significantly different, CVC-critical value of comparison, CV-coefficient of variation, ****(P<0.0001), ***(P<0.001), **(P<0.01), *(P<0.05), ns-not significant.

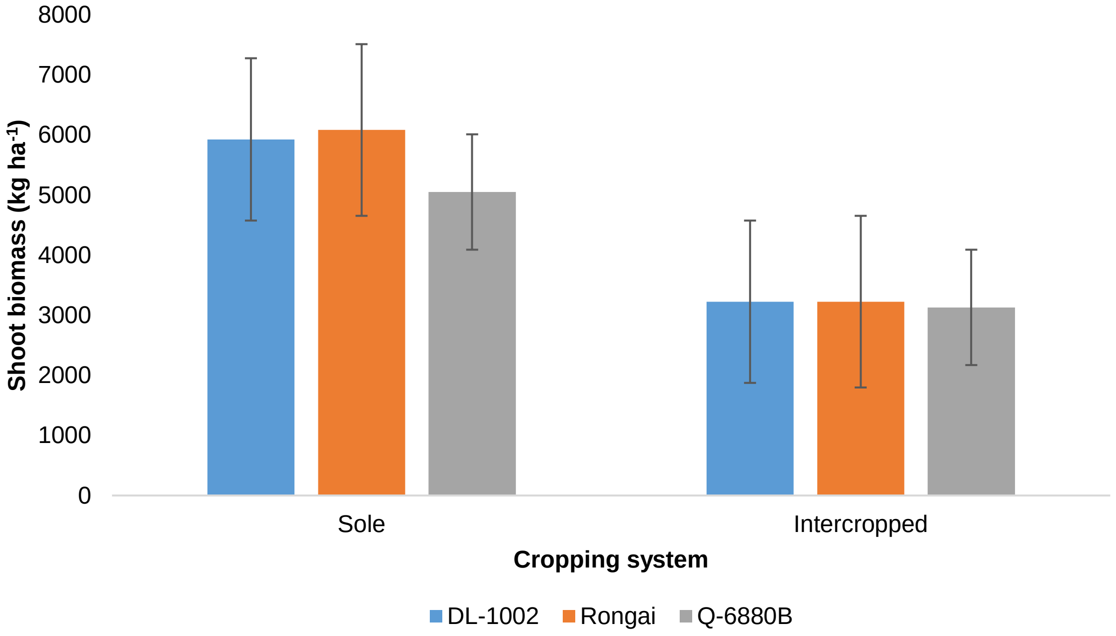


Figure 5.3 Interactive effect of lablab cultivars and cropping system on shoot biomass of lablab at harvest in 2019/2020 at Univen.

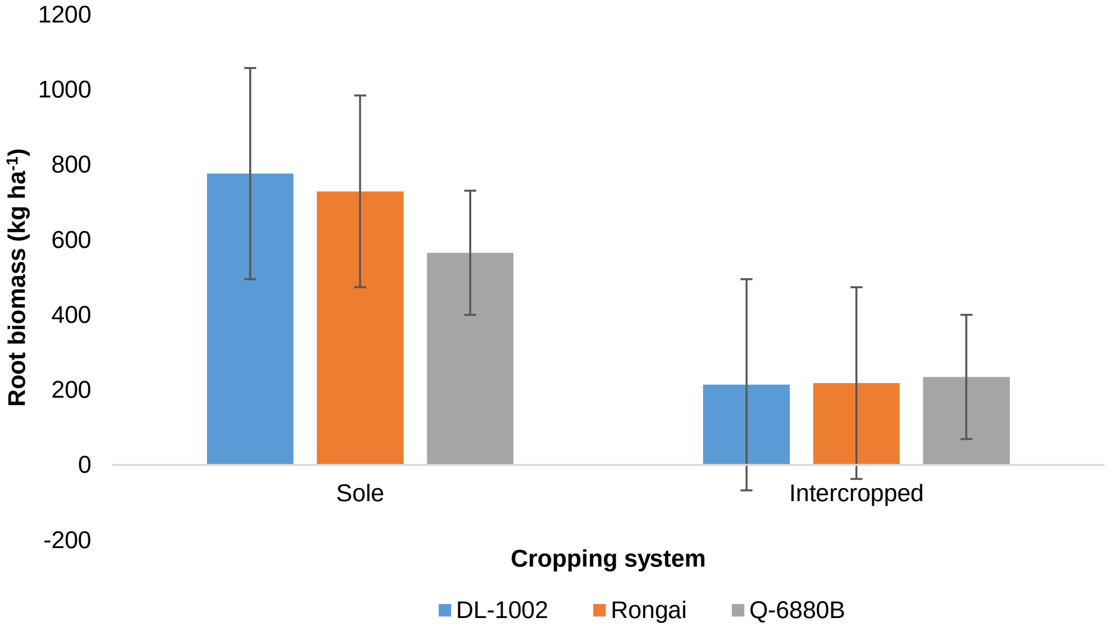


Figure 5.4 The interactive effect of lablab cultivars and cropping system interaction on root biomass of lablab at harvest at Syferkuil in 2018/2019.

5.4 Discussion

Root and shoot biomass produced at Univen was greater than that harvested at Syferkuil. Root and shoot biomass of lablab was significantly superior for DL-1002 and Rongai compared to Q-6880B at Univen and Syferkuil. Q-6880B is an upright bushy early flowering cultivar characterized by poor biomass accumulation (Nord *et al*., 2020). DL-1002 and Rongai are late flowering varieties that were able to grow and accumulate biomass after cultivar Q-6880B had flowered. This phenological trait of Q-6880B may be the explanation for the significant differences in biomass at flowering stage. These findings are in accord with Nord *et al*. (2020) and Wangila *et al*. (2021) who reported that early flowering lablab varieties had the lowest biomass at flowering across different environments. However, at harvest, lablab cultivars only had a significant effect on shoot biomass at Univen in 2019/2020 season. DL-1002 and Rongai had comparable biomass yields across locations, sampling stage and seasons at Univen. Similar results were reported by Wangila *et al*. (2021) with DL-1002 and black Rongai producing similar biomass yields. The comparable biomass at Univen in the first season may be because Q-6880B had multiple pod abortions. Contrary to Nord *et al*. (2020) who reported Q-6880B as a short season variety, the cultivar did not undergo senescence but remained green and flowered again. The observed pod abortions may have been due to a combination of heat stress and infestation from pod suckers. This observation is consistent with Grotelüschen *et al*. (2014) who reported that Q-6880B is susceptible to pests and diseases.

At Syferkuil, cultivar Q-6880B did not experience pod abortions and was successfully harvested in March. The quick growth and early harvest of Q6880B at Syferkuil could mean that the cultivar is more suited for the cooler environment of Syferkuil than Univen, where it had multiple flowering incidents and abortions. However, this observation is contradicted by Nord *et al*. (2020) who reported that due to the ability of cultivar Q-6880B to produce grain yield under stressful heat conditions, the cultivar might be suitable as a heat tolerant variety. Lablab root and shoot biomass across cultivars was not significantly different at Syferkuil at harvest. The results may have been due to the early onset of senescence in DL-1002 and Rongai in response to moisture and heat stress as the experiment was rainfed. Many studies have reported lablab as a high biomass producing crop, with biomass ranging between 3.59-7.22 t ha^{-1} under varying environments and management (Hassan *et al*., 2014, Wangila *et al*., 2021). Current study demonstrated average biomass (2815.3-3807.6 kg ha^{-1}) under sole cropping and below average biomass values (1189.0-1240.2 kg ha^{-1}) for all three cultivars under intercropping at Syferkuil and this could be due to a combination of pest, temperature and water stress. However, at Univen, lablab had above average biomass under sole lablab (4939.9-5291.4 kg ha^{-1}) in 2018/2019 and (5051.0-6083.1 kg ha^{-1}) in 2019/2020, which may be due to the high soil fertility (Table 3.1 and 3.2) and rainfall (Table 3.4) received in the area as compared to Syferkuil. Hassan *et al*. (2014) indicated that variation in soil moisture content, plant population, climate and soil type are factors that can result in biomass fluctuations. Nord *et al*. (2020) also reported lower biomass yields in areas with low rainfall. In this study the pods were left in the field until they lost approximately 50% or more moisture before they were harvested, and during this period lablab cultivars lost consequential amounts of biomass due to insufficient soil moisture to support the plants.

There were no significant differences in grain yield and harvest index (HI) across locations in 2018/2019 season and at Univen in 2019/2020 season. Although not significantly different, Rongai had the greatest grain yield at Univen in both seasons. The indifferences in grain yield may be due to genetics, environment and management practices that would have affected the performance of the cultivars. These results are contradicted by Nord *et al*. (2020) who reported that cultivar Q6880B was the best performing variety in terms of grain production. The poor grain yields at Syferkuil (128.5-643.6 kg ha^{-1}) across cropping systems are in line with the poor biomass yields, relative to grain yield at Univen (404.5-2611.2 kg ha^{-1}); and may have been because of low soil fertility (Table 3.2) and early moisture stress conditions (Table 3.4) that set-in at grain filling stage. Nord *et al*. (2020) reported low to nil grain yields across different lablab accessions at site TPRI (Tropical Pesticides Research Institute farm) for two seasons, demonstrating the effect of environment on the performance of lablab.

The low harvest index percentage at Syferkuil was due to the poor grain production from all three cultivars while at Univen the high harvest index was due to the biomass reduction. Contrarily, Rapholo *et al*. (2019) found that Univen had lower lablab HI when compared to Syferkuil. Ewansiha *et al*. (2017) reported that intercropping lablab with maize reduced lablab mean HI while lablab cultivars had no significant effect on HI. Harvest index is determined by interactions between genotypes, environment and crop management. Harvest index can vary widely depending on the time for sampling and the extent of leaf fall before reaching the full maturity, especially in the case of indeterminate varieties. Cultivar DL-1002 and Rongai are indeterminate varieties, while Q-6880B is a semi-determinate variety. Indeterminate varieties can have different plants of the same cultivar growing in the same area displaying varying growth stages, flowering, grain filling, and harvest maturity. This characteristic makes it difficult to determine the time for plant sampling and harvesting grain.

Cropping system significantly influenced shoots, roots, grain yield and harvest index in both sites. Intercropped lablab produced less than 50% of shoots, roots, grain yield and harvest index recorded in sole lablab at Syferkuil and Univen. Although, there was a noticeable increase of biomass of intercropped lablab in the second season at Univen. Other authors have reported similar dry matter and grain yield reduction of lablab in intercropping relative to sole crops (Mbanyele *et al*., 2021, Massawe *et al*., 2016). Contrarily, Redae and Tekie (2020) observed an increase in biomass and grain yields of lablab under maize-lablab intercropping when lablab was sown 10 days after emergence of maize. In this study, lablab was integrated into maize plots 28 days after maize planting, and this may have put lablab at a disadvantage since maize had already established itself. The reduction in lablab biomass and grain yield may have been influenced by the oppression experienced by lablab from maize as a result of the differences in growth stages. The maize cultivar used in this study is an early maturing variety that had reached a significant height when lablab was planted 28 days after maize planting. This made the competition for moisture, nutrients and light more favourable for maize, leaving lablab to struggle to acquire resources. A similar observation was made by Redae and Tekie (2020) who reported reduction in biomass and grain yield of lablab when lablab was intercropped 20 days after maize emergence.

Competition between maize and lablab exists belowground for space, soil moisture and nutrients and aboveground for light (Duchene *et al*., 2017). Reduction of crop yields is likely to occur when competition for resources between intercrops is extreme (Kiwia *et al*., 2019). Maize as a tall plant suppressed the growth of lablab by shading the crop, thus limiting its access to sunlight. Sunlight is a vital factor of photosynthesis; a process used by plants to transform light energy into chemical energy that powers the plant's metabolic activities (Nyawade *et al*., 2020a). To lessen the shading effect caused by maize, lablab climbed and intertwined with maize to get better access to sunlight. This observation was more evident for DL-1002 and Rongai and because of their trailing and twining growth habit, the lablab cultivars were able to continue growing and accumulating biomass after maize harvest (Wangila *et al*, 2021). However, the biomass and grain yield variation were still pronounced between intercropped and sole lablab systems. The competitiveness within an intercrop system for light, soil moisture and nutrients between maize and intercrop component can be lessened by a well thought crop selection. These includes crop species and cultivars, crop maturity and planting time (Maitra *et al*., 2021).

Interaction of cropping system and cultivars was significant for roots and shoots at flowering at both locations and shoot biomass in 2019/2020 season at Univen. While at Syferkuil a significant effect of interaction between lablab cultivars and cropping system was observed for roots in 2018/2019 season at harvest. Q6880B produced the lowest shoot biomass at harvest at Univen and this may have been due to Q-6880B typically being an upright variety that does not accumulate biomass as much as DL-1002 and Rongai. Wangila *et al*. (2021) outlines that upright lablab varieties tend to lower biomass because of few branches and thus minimal foliage. As an early maturing variety, cultivar Q-6880B was the first to undergo senescence at Univen. Although cultivar Q-6880B had significantly lower biomass in sole cropping, it had comparable yields under intercropping systems. These results suggest that Q-6880B might have been more suitable for intercropping than DL-1002 and Rongai, especially at Syferkuil. This is because the cultivar can grow and be harvested early before there is moisture stress, an important trait for farmers that rely only on rainfall as a source of moisture.

Generally, Univen portrayed greater lablab root and shoot biomass, grain yield, HI and LER (Table 5.2) than at Syferkuil (Table 5.3). The variation between sites may be due to environmental variability and contrasting soil textures. Hassan *et al*. (2014) reported fluctuations in lablab dry matter due to variation in environmental variability and planting density per plot. Univen has relatively more fertile clay soils while Syferkuil is characterized by sandy loam textured soils with low fertility. As such, the high yields and yield components at Univen may be because of the highly fertile soils that supported rigorous growth of lablab.

5.5 Conclusion and recommendations

The early maturing semi-determinate Q-6880B cultivar is advantageous over DL-1002 and Rongai because it creates an opportunity for farmers to harvest multiple times, given that temperature and soil moisture conditions remain suitable. The early senescence of DL-1002 and Rongai at Syferkuil makes them unsuitable for cultivation in the area, unless supplemental irrigation is possible. This is because they require a much longer period to grow, develop and reproduce, and their reproductive phase coincides with the colder and much drier winter season. Lablab has been reported to be susceptible to frost and as such, the May/June temperatures characteristic of Syferkuil may not be ideal for the late maturing cultivars. The results in this study demonstrated that lablab can successfully be sown in Limpopo province, however, in an area such as Syferkuil, additional management (fertilization) may be required to improve yields. Supplemental irrigation may also improve the yields of lablab especially under intercropping system in both locations. While at Univen, no cultivar had an advantage over another. However, with improved pest and disease management, cultivar Q-6880B could be a better suited variety for grain production as farmers would be able to harvest multiple times before the end of the rains in winter. Cultivars DL-1002 and Rongai would be more suitable for forage or dual-purpose, and this is because the late maturing capability of the cultivars gives farmers a chance to harvest the leaves and stems numerous times to feed their livestock. The study demonstrated that lablab performance is highly influenced by environmental variability, making early maturing varieties the best agronomic choice for farmers that rely on rainfall. Further studies should be conducted to assess the nutritive content of the forage and grain of the cultivars to make better informed decisions and recommendations for animal feeding and human consumption.

CHAPTER 6. EFFECT OF MAIZE-LABLAB INTERCROPPING ON SOIL MINERAL NITROGEN (NH_4^+ AND NO_3^-) AND SOIL WATER CONTENT

6.1 Introduction

Continuous cultivation without replenishment has gradually led to the depletion of nitrogen levels from the soils and this now presents a major threat to crop production (Massawe *et al*., 2016). Nitrogen is a very important and abundant plant nutrient, next to carbon, hydrogen, and oxygen. The primary function of nitrogen is to supply amino acids to plants, and it also serves as a vital component of compounds such as enzymes, pigments, and polymers. Crop production is heavily limited by nitrogen deficiency in soil, as the deficiency is likely to lead to plant disorders (Amosse *et al*., 2014). Growth reduction and loss of green pigmentations are common consequences of nitrogen deficiency in plants, and this affects photosynthesis and ultimately crop yields.

Application of nitrogen-containing inorganic and organic fertilizers can be used to improve nitrogen levels in the soil. The use of inorganic nitrogen fertilizers can drastically improve crop growth and yields. A large portion of the world's population relies on the use of nitrogen fertilizers to achieve satisfactory crop yields (Duchene *et al*., 2017), especially for cereals like wheat, rice, barley and maize. Maize is among the three major nitrogen demanding crops on a global scale. Application of inorganic nitrogen fertilizers to increasing nitrogen levels in the soil is critical to improving maize growth and yields (Whitbread and Ayisi, 2004). However, the continued use of nitrogen fertilizers has resulted in increased soil acidification, disturbance of important microbial communities and population, and contamination of ground water (Nyawade *et al*., 2020b). The continued impact of nitrogen fertilizers on the soil and environment require development and transformation of cropping systems that can address the problem of nitrogen deficiency in soil. Possible strategies include introduction of legumes into farming practices in the form of rotational farming, green manuring and intercropping. One such legume that can be included in maize cropping systems is lablab.

The natural ability of legume crops to obtain nitrogen through BNF with the assistance of compatible rhizobia strains is the main justification for the addition of the crops into crop fields (Duchene *et al*., 2017). The additional nitrogen from BNF is typically expected to prevent competition between the legumes and other crops within the intercrop for nitrogen uptake and to make considerable amounts of nitrogen available for the next crop (Duchene *et al*., 2017). Legumes added in an intercrop can result in increased nitrogen content, storing up to 40-100 kg N ha^{-1} in the aboveground parts of plants (Amosse *et al*., 2014). The authors also reported increased maize yields by up to 30% when maize was planted as a subsequent crop.

However, adding legumes into maize cropping systems can pose a challenge of competition for soil water.

Resource poor maize farmers that are forced to depend solely on rain as a source of moisture for their crops face major difficulties because of climate change (Chimonyo *et al*., 2020). Erratic and poorly distributed rainfall and extremely high temperatures pose a threat to food security in rainfed farming regions of Southern Africa (Mbanyele *et al*., 2021). Occurrence of frequent dry spells throughout the season worsen the situation, negatively affecting crop production. This calls for a need to assess and create sustainable practices within rainfed agriculture that promote infiltration, soil water retention and conserve soil water for longer periods.

Recently, the practice of intercropping has gradually lessened as a result of increase in resource shortages in water scarce regions (Yin *et al*., 2020). Intercropping is a commonly practiced form of land intensification method, which serves as an option for smallholder and subsistence farmers in rainfed cropping systems. However, significant yield losses and total crop failure are possible because of resource limitations that are worsened by competition between the crops (Mbanyele *et al*., 2021). Crop selection in intercropping is vital to the success of the system. Water use by crops in an intercrop varies considerably, depending on the soil and climate conditions and crop species used in the system (Maitra *et al*., 2021). Crop selection, planting space, and planting time are important factors that influence the efficiency of water usage in an intercrop (Yin *et al*., 2020). Crops grown in intercropping need to be complementary to one another, to further reduce competition between them. The amount of water required by maize is influenced by the duration of growth and development, planting density and expansion of canopy (du Plessis, 2003).

Soil water content is one of the mechanisms that producers use for better decision making. The absence or presence of underground moisture plays a determining role in the risk of planting (FERTASA, 2016). A relatively small quantity of stored water, in addition to rainfall during the active growing season can make a significant contribution towards lowering production risks (Yin *et al*., 2020). The pattern of crop-water requirements is of agronomic and economic importance, particularly in water scarce areas (Nhamo *et al*., 2018). The improved water productivity and crop yields observed under conservation agriculture practices in South Africa have largely been in crop rotations of maize and legumes, with a few studies on intercrops (Mbanyele *et al*., 2021). While the performance of these practices has been evaluated in the past, there is still a continuing need to experiment with their derivatives. The study evaluated the interactive effect of maize/lablab intercropping and soil depth in different agricultural climates on soil mineral nitrogen and soil water content.

6.2 Materials and methods

Full experimental details are given in chapter 3, but a brief summary is given below. Two field experiments were conducted at the University of Venda Experimental Farm (Univen) in 2018/2019 and 2019/2020 cropping seasons and one field experiment at the University of Limpopo Experimental Farm (Syferkuil) in 2018/2019 cropping season. The trials were laid out in a randomized complete block design and replicated three times. Maize cultivar DKC-2147 and three lablab cultivars; DL-1002, Rongai (brown), and Q-6880B, were used in the experiment. The maize and lablab cultivars were sown in sole stands and in intercropping, with each lablab cultivar sown between the rows of maize 28 days after maize planting. Each sole maize and lablab plots consisted of six rows with 80 cm spacing between the rows and 50 cm between plants in rows. An amount of 30 kg N ha^{-1} was applied at planting as starter nitrogen and 50 kg P ha^{-1} was applied as basal phosphorus for the phosphorus deficient soils of Univen and Syferkuil. Soil samples for the determination of mineral nitrogen were collected before planting, at maize flowering and maize harvest. Samples were collected from 0-15, 15-30 and 30-60 cm depth in the first season and from 0-15 and 30-60 cm depth in the second season. Soil samples for the determination of soil water content were collected from 0-15, 15-30 and 30-60cm depths at V10 (cob development), VT (tasselling), R3 (grain filling) and R6 (physiological maturity) maize growth stages across sites and seasons. Soil water content was determined using the gravimetric water content method. Data obtained was subjected to ANOVA using the Statistix 10.0. Significant differences between treatment means were compared using critical value of difference (CVD) of means at 5% level.

6.3 Results

6.3.1 Effect of cropping system and sampling depth on soil mineral nitrogen

6.3.1.1 Soil mineral nitrogen at Univen

Cropping system significantly influenced levels of NO_3^- and NH_4^+ at maize flowering and harvest at Univen in 2018/2019 (Table 6.1) but only had a significant influence at harvest in 2019/2020 (Table 6.2). The NO_3^- and NH_4^+ at maize flowering and harvest was lower than at the initial characterization (Table 3.1). Lablab cultivars had a comparable effect on NO_3^- and NH_4^+ in both sole and intercropped systems in both seasons. Generally, sole maize plots had the highest levels of NO_3^- and NH_4^+ at flowering while maize-lablab intercropped plots had the lowest levels of NO_3^- and NH_4^+ in 2018/2019 (Table 6.1). Maize sole recorded between 17-31% NO_3^- and 4-26% NH_4^+ levels higher than sole lablab and maize-lablab intercrops. However, at harvest maize sole had the lowest levels of NO_3^- and NH_4^+ while sole lablab had the highest levels of NO_3^- and NH_4^+ (Table 6.2). In 2019/2020 season, sole Rongai and sole

DL-1002 had the highest levels of NO_3^- and NH_4^+ at harvest. At harvest in 2018/2019, NO_3^- and NH_4^+ under maize-lablab increased by at least 38% and 29%, respectively, when compared to sole maize. However, in 2019/2020, only maize+DL-1002 had a significant increase in NO_3^-, while maize+Rongai and maize+Q-6880B significantly influenced NH_4^+ at harvest. Generally, soil NO_3^- and NH_4^+ increased from flowering to harvest across all cropping systems except for sole maize that experienced a decline in both NO_3^- and NH_4^+.

Soil sampling depth had a significant effect on soil NO_3^- at both flowering and harvest in 2018/2019 (Table 6.1) and 2019/2020 (Table 6.2). At both sampling stages, levels of NO_3^- decreased with increasing soil depth in 2018/2019, but in 2019/2020, NO_3^- increased with increasing depth at flowering. In 2018/2019, the 0-15 cm depth had the highest levels of NO_3^- at flowering and harvest by between 12-23% and 14-26%, respectively, when compared to 15-30 and 30-60 sampling depth. There were no significant differences in NH_4^+ levels in 2018/2019 across the sampling depths at flowering and harvest. However, in 2019/2020, the 30-60 cm depth had significantly lower levels of NH_4^+ at harvest.

The interaction between cropping system and sampling depth had no significant effect on NH_4^+ at flowering and NO_3^- and NH_4^+ at harvest maturity in 2018/2019 (Table 6.1) and NO_3^- and NH_4^+ in 2019/2020 at flowering and harvest (Table 6.2). However, the interactive effect of cropping system and sampling depth was significant for NO_3^- at flowering in 2018/2019. NO_3^- levels were the highest in sole maize at 0-15 and 15-30 cm depths while at 30-60 cm depth, sole Q-6880B had the highest NO_3^- levels (Figure 6.1). The lowest NO_3^- levels at 0-15, 15-30 and 30-60 cm were observed under maize-Rongai, maize-Q-6880B and sole DL-1002 respectively. In sole maize, sole DL-1002, sole Rongai, maize+DL-1002 and maize+Rongai, NO_3^- levels decreased along the sampling depth, from 0-15 cm to 30-60 cm. Sole Q-6880B and intercropped maize+Q-6880B had the opposite trend, with NO_3^- levels increasing with increasing soil depth.

6.3.1.2 Soil mineral nitrogen at Syferkuil

Significant differences were observed across the cropping systems at Syferkuil for NO_3^- and NH_4^+ at flowering and harvest (Table 6.1). At flowering, sole maize and sole lablab cultivars had the highest NO_3^- levels, ranging between 37.5-122.6% compared to intercropped systems. Intercropping maize with lablab significantly reduced NH_4^+ in maize+DL-1002 and maize+Rongai at flowering by 43.3% and 138.9%, respectively, relative to sole maize. In contrast intercropping maize with lablab improved levels of NH_4^+ in maize-Q-6880B at flowering by 83.7% relative to maize monocropping. At maize harvest, cropping system was highly significant for NO_3^- and NH_4^+ (Table 6.1). Maize-lablab intercropping significantly improved NO_3^- and NH_4^+ when compared to maize monocropping. Sole Q-6880 demonstrated the highest levels of NO_3^- and NH_4^+. Sole lablab and maize+lablab intercropping had at least 96.6% and 112.1% more NO_3^- and NH_4^+, respectively, higher than sole maize.

Soil sampling depth had no effect on NO_3^- at harvest and NH_4^+ at flowering and harvest. However, soil sampling depth affected NO_3^- at flowering (Table 6.1). NO_3^- levels were significantly greater by 24.1% at a depth of 0-15 compared to 30-60 cm depth which had the lowest level of NO_3^-. Generally, NO_3^- and NH_4^+ were the highest in the upper soil depth of 0-15 cm. NO_3^- and NH_4^+ peaked at maize harvest at all the sampling depths.

The two-way interaction between cropping system and sampling depth significantly affected NO_3^- at flowering but had no effect on NH_4^+ at flowering (Table 6.1). The effect of cropping system and sampling depth interaction was also not significant on NO_3^- and NH_4^+ at maize harvest. At flowering maize + Q-6880B had the lowest levels of NO_3^- at 0-15, 15-30 and 30-60 cm depth (Figure 6.2). Highest level of NO_3^- was observed under sole Rongai at a depth of 0-15. Sole maize had higher NO_3^- levels across all sampling depths when compared to all intercropped cropping systems.

Table 6.1. Effect of cropping system and sampling depth on soil mineral nitrogen (NO_3^- and NH_4^+) during 2018/2019 planting season at Univen and Syferkuil.

Season	**2018/2019**							
Location	**Univen**				**Syferkuil**			
Sampling stage	**Flowering**		**Harvest**		**Flowering**		**Harvest**	
Treatment	**NO_3^-**	**NH_4^+**	**NO_3^-**	**NH_4^+**	**NO_3^-**	**NH_4^+**	**NO_3^-**	**NH_4^+**
Cropping system (CS)								
Sole maize	16.0a	11.0a	10.1b	8.0b	5.5ab	4.3b	2.9d	3.3b
Sole DL-1002	12.6ab	9.3abc	17.5a	10.8a	6.2a	8.5a	9.0ab	7.0a
Sole Rongai	13.2ab	8.9bc	19.9a	10.1a	6.9a	8.5a	9.4ab	9.1a
Sole Q-6880B	13.3ab	10.6ab	17.3a	11.6a	6.4a	8.6a	11.3a	9.9a
Maize + DL-1002	11.5b	8.7bc	16.2a	11.3a	3.4c	3.0bc	9.0ab	8.4a
Maize +Rongai	11.0b	8.1c	16.2a	11.6a	4.0bc	1.8c	7.9bc	8.7a
Maize + Q-6880B	11.6b	8.3c	16.6a	11.3a	3.1c	7.9a	5.7cd	8.2a
CVC	3.39	2.15	4.67	1.90	1.87	2.25	2.95	3.19
Sampling depth (SD)								
0-15	14.4a	9.3	18.7a	10.3	5.8a	6.0	8.3	8.5
15-30	12.7b	9.2	16.1b	11.2	5.0ab	6.1	8.1	7.5
30-60	11.1b	9.3	13.9b	10.5	4.4b	6.1	7.1	7.4
CVC	1.74	1.10	2.40	0.97	0.96	1.16	1.52	1.64
P-value								
Cropping system	***	***	****	***	****	***	****	****
Sampling depth	****	ns	****	ns	***	ns	ns	ns
CS*SD	**	ns	Ns	ns	**	ns	ns	ns
CV (%)	18.22	15.83	19.69	12.16	26.56	25.64	25.70	27.94

Means followed by the same letter are not significantly different, ****(P<0.0001), ***(P<0.001), **(P<0.01) and *(P<0.05), ns-not significant, CV-coefficient of variation, CVC-critical value of comparison

Table 6.2. Effect of cropping system and sampling depth on soil mineral nitrogen (NO_3^- and NH_4^+) (mg kg^{-1}) during 2019/220 planting season at Univen.

Location	**Univen**			
Season	**2019/2020**			
Sampling time	**Flowering**		**Harvest**	
Treatment	**NO3-**	**NH4+**	**NO3-**	**NH4+**
Cropping system (CS)				
Maize	10.1	1.9	3.1b	1.9b
DL-1002	8.8	2.2	17.1a	12.5a
Rongai	10.3	2.0	16.0a	10.4a
Q-6880	9.5	1.9	13.6ab	8.9ab
Maize + DL-1002	7.1	1.8	14.3a	9.2ab
Maize +Rongai	5.0	1.6	12.8ab	10.1a
Maize + Q-6880	7.0	1.6	10.1ab	10.9a
CVC	6.93	1.27	10.70	7.82
Sampling depth (SD)				
0-15	6.0b	1.9	15.2a	10.9a
30-60	10.5a	1.8	9.6b	7.4b
CVC	2.38	0.44	3.68	2.69
P-value				
Cropping system	ns	ns	**	***
Sampling depth	***	ns	**	*
CS*SD	ns	ns	ns	ns
CV (%)	45.71	37.05	46.83	46.29

Means followed by the same letter are not significantly different, ****(P<0.0001), ***(P<0.001), **(P<0.01) and *(P<0.05), ns-not significant, CV-coefficient of variation, CVC-critical value of comparison

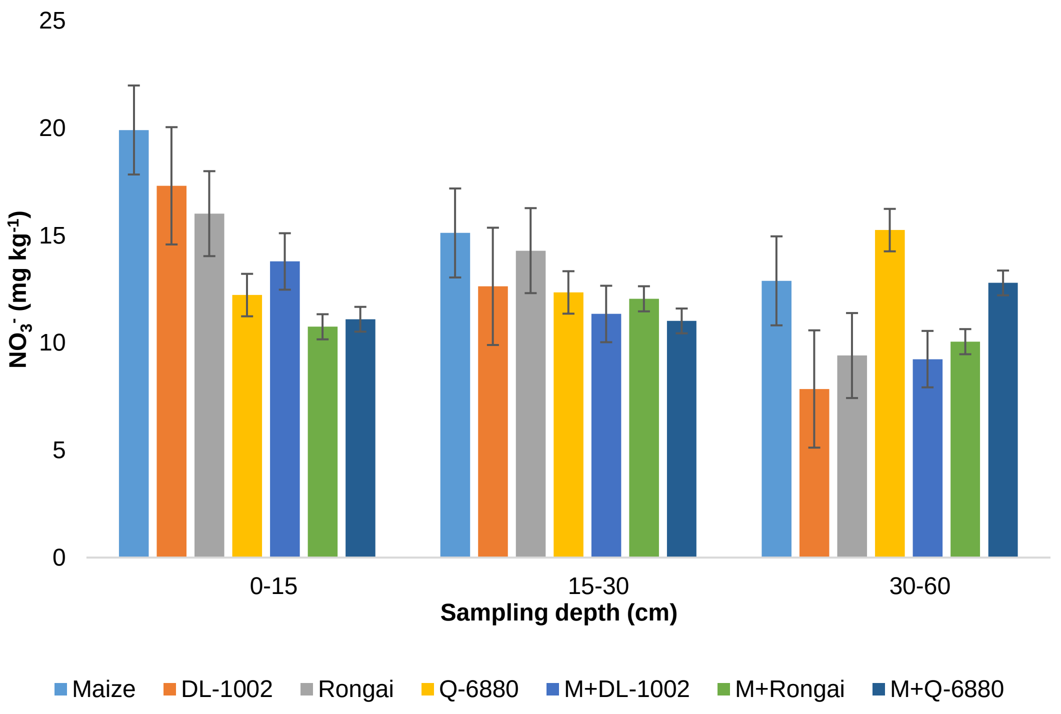


Figure 6.1 Interactive effect of cropping system and sampling depth on NO_3^- at flowering in 2018/2019 season at Univen.

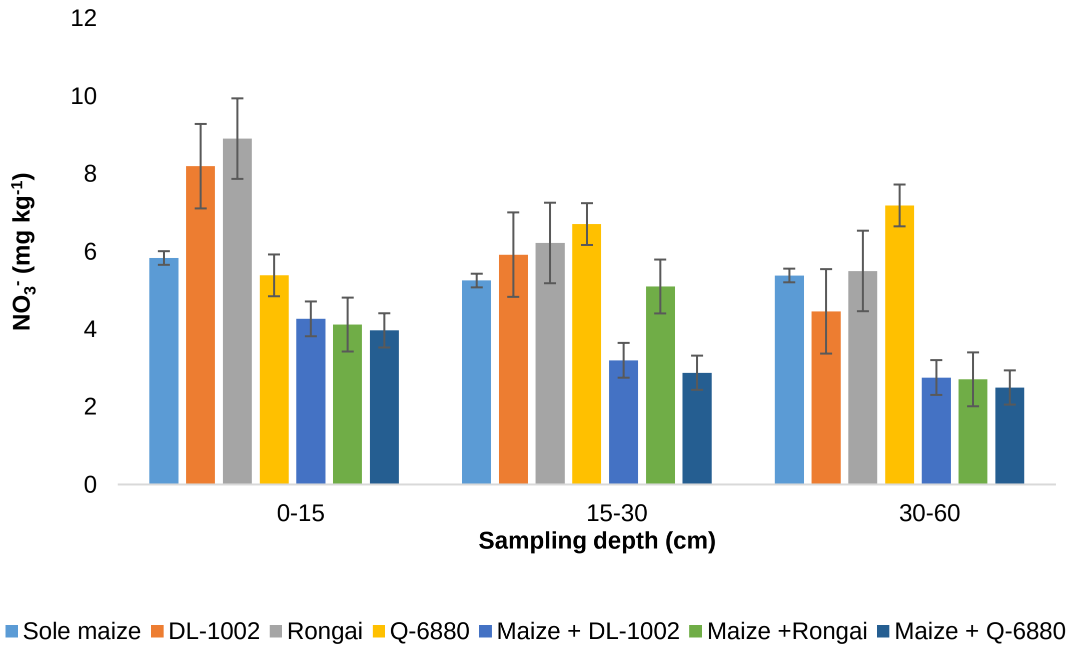


Figure 6.2 The interactive effect of cropping system and sampling depth on NO_3^- at flowering at Syferkuil in 2018/2019.

6.3.2 Effect of cropping system and sampling depth on soil water content

6.3.2.1 Soil water content at Univen

The effect of cropping system and soil sampling depth varied across seasons and stage of sampling (Table 6.3). However, the interactive effect of cropping system and sampling depth was not significant for soil water content across all growth stages in 2018/2019 and 2019/2020 season. Cropping system had no significant effect on soil water content at V10 in 2018/2019 season. Similarly, cropping system did not affect soil water content in 2019/2020 at V10 and VT stages. Intercropping maize with different lablab cultivars did not influence soil water content across all crop growth stages in both seasons. However, lablab monocropping showed a significant increase in water levels in the late growth stages of maize at R3 and R6 in both seasons and at VT in the first cropping season (Table 6.3). In 2018/2019 season increase in soil water content in sole lablab plots ranged from 14% to 17% at VT, 24% to 26% at R3, and 32% to 35% at R6 compared to sole maize and maize/lablab intercrops. A similar trend was observed in 2019/2020 season, with 20-24% and 14-18% increase in water content under sole lablab cropping at R3 and R6 stages respectively, relative to maize monocropping.

Soil water content varied across soil depths at R3 and R6 in 2018/2019 season. Soil sampling depth significantly affected soil water content at V10, VT and R3 stages in the 2019/2020 season (Table 6.3). Generally, the greatest soil water content was observed at a depth of 30-60 cm in both seasons. The greatest variation in water content was in 2019/2020 season at V10 maize growth stage, with a difference of 41.4% and 22.7%, respectively, compared to 0-15 and 15-30 cm depth.

6.3.2.2 Soil water content at Syferkuil

Soil water content was significantly affected by cropping system at R3 and R6 growth stages (Table 6.4). Maize monocropping had similar soil water content to maize+DL-1002, maize+Rongai and maize+Q-6880 across all growth stages and sole Q-6880B at R3 stage. Generally, sole lablab cropping systems had significantly higher soil water content, however, at R6 stage Q-6880, monocropping had significantly lower water content than sole Rongai. At R6, sole Rongai had 8.3% and 21.9% greater water content relative to sole DL-1002 and sole Q-6880B, respectively.

Soil sampling depths significantly influenced soil water content at VT, R3 and R6 crop growth stages (Table 6.4). Soil water content was the highest at 30-60 cm depth. The 0-15 and 15-30 cm depths had similar soil water content at all growth stages, but at R3, 0-15 cm depth had significantly lower water content than 15-30 cm depth. The interaction of cropping system and sampling depth had a significant effect on soil water content at R6 (Table 6.4). Sole DL-1002, sole Q-6880 and sole Rongai cropping systems had the greatest water content at all soil depths; however, DL-1002 and Rongai had a greater effect on soil moisture than Q-6880B at 30-60 cm depth (Figure 6.3). The lowest soil water content was observed under maize+DL-1002 and maize+Q-6880B at 0-15 cm and under maize+DL-1002 and sole maize at 15-30 and 30-60 cm depths.

Table 6.3. Effect of cropping system and sampling depth on soil water content (%) at Univen in 2018/2019 and 2019/2020 planting seasons.

Location	**Univen**							
Season	**2018/2019**				**2019/2020**			
Sampling stage	**V10**	**VT**	**R3**	**R6**	**V10**	**VT**	**R3**	**R6**
Treatment	**Soil water content (%)**				**Soil water content (%)**			
Cropping system (CS)								
Sole maize	22.7	18.5b	15.6b	11.6b	22.3	21.4	20.8b	17.7b
Sole DL-1002	23.1	21.5a	19.7a	15.7a	26.6	21.5	24.9a	20.8a
Sole Rongai	22.1	21.3a	19.5a	15.5a	25.3	22.2	25.8a	20.6a
Sole Q-6880B	22.7	20.9a	19.3a	15.3a	27.1	21.4	24.5a	20.2a
Maize + DL-1002	21.9	18.9b	15.8b	11.8b	23.1	22.1	21.0b	18.2b
Maize +Rongai	22.0	18.7b	16.4b	12.4b	27.7	21.9	21.6b	18.0b
Maize + Q-6880B	22.0	18.4b	16.8b	12.8b	22.6	21.8	22.0b	17.7b
CVC	1.93	1.68	1.86	1.21	8.84	1.28	1.88	1.69
Sampling depth (SD)								
0-15	21.9	19.6	17.0b	13.0b	21.0b	21.1b	22.3b	18.9
15-30	22.2	19.6	17.2b	13.2b	24.2b	21.0b	22.4b	18.9
30-60	22.8	20.0	18.4a	14.5a	29.7a	23.1a	23.7a	19.2
CVC	0.99	0.86	0.95	0.80	4.54	0.66	0.96	0.87
P-value								
Cropping system	ns	***	***	***	ns	ns	**	***
Sampling depth	ns	ns	**	**	***	**	***	ns
CS*SD	ns	ns	ns	ns	ns	ns	ns	ns
CV (%)	5.90	5.80	7.25	9.39	24.27	4.01	5.59	6.09

V10 (cob development), VT (tasselling), R3 (grain filling) and R6 (physiological maturity) stages, means followed by the same letter are not significantly different, ***(P<0.001), **(P<0.01), *(P<0.05), ns-not significant, CV-coefficient of variation, CVC-critical value of comparison

Table 6.4. Effect of cropping system and sampling depth on soil water content (%) at Syferkuil in 2018/2019 planting season.

Location	**Syferkuil**			
Season	**2018/2019**			
Sampling stage	**V10**	**VT**	**R3**	**R6**
Treatment	**Soil water content (%)**			
Cropping system (CS)				
Sole maize	25.9	9.4	5.1bc	4.7c
Sole DL-1002	25.5	9.5	5.9a	7.2ab
Sole Rongai	24.5	10.2	6.0a	7.8a
Sole Q-6880B	25.8	9.4	5.9ab	6.4b
Maize + DL-1002	25.9	10.1	5.0c	4.2c
Maize +Rongai	25.1	9.9	5.1bc	4.6c
Maize + Q-6880B	25.8	9.8	4.9c	4.5c
CVC	2.15	1.28	0.86	0.46
Sampling depth (SD)				
0-15	24.9	9.1b	4.5c	5.1b
15-30	25.4	9.0b	5.2b	5.5b
30-60	25.7	11.1a	6.6a	6.3a
CVC	1.10	0.66	0.44	0.46
P-value				
Cropping system	ns	ns	***	***
Sampling depth	ns	***	***	**
CS*SD	ns	ns	ns	*
CV (%)	5.80	8.95	6.23	10.79

V10 (cob development), VT (tasselling), R3 (grain filling) and R6 (physiological maturity) stages, means followed by the same letter are not significantly different, ***(P<0.001), **(P<0.01), *(P<0.05), ns-not significant, CV-coefficient of variation, CVC-critical value of comparison

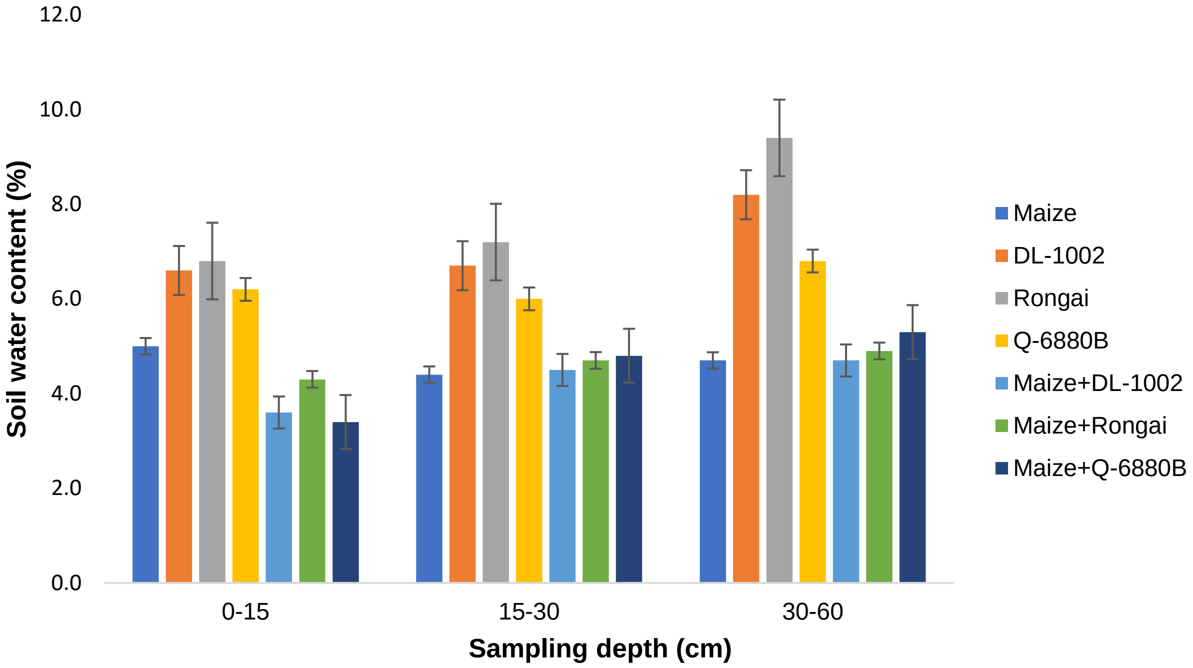


Figure 6.3 Interactive effect of soil sampling depth and cropping system on soil water content at R6 growth stage at Syferkuil in 2018/2019 season.

6.4 Discussion

The effects of intercropping maize with lablab on soil mineral nitrogen and soil water content varied widely across locations and seasons. At flowering, intercropping maize with lablab significantly decreased levels of mineral nitrogen in the soil across all the lablab cultivars in both sites. The observed reduction in mineral nitrogen in maize/lablab intercropping may be attributed to the increased competition and uptake of nitrogen between maize and lablab. These findings are consistent with Nyawade *et al*. (2020b) who found that sole potato had the highest levels of nitrogen compared to potato/legume (lablab and vetch) plots. A maize/pea intercropping study by Zhao *et al*. (2020) demonstrated contrary findings, as they reported that maize/pea intercropping improved nitrogen concentrations at flowering at the highest planting density. These results suggest that nitrogen dynamics within the soil may be influenced by a combination of factors such as type of legume crop species, planting density and crop combinations within the intercrops.

The increased soil mineral nitrogen in sole lablab and maize/lablab at harvest may be due to mineralization of nitrogen rich lablab residues and possibly nitrogen fixation by lablab cultivars. Lablab was reported by Nyawade *et al*. (2020a) to have lower carbon to nitrogen and lignin to nitrogen ratios compared to potato and lima bean. Crop residues with lower carbon to nitrogen and lignin to nitrogen ratios decompose quickly and completely, leading to a release of considerable amounts of nitrogen through mineralization (Mungai *et al*., 2005). Soil mineral nitrogen levels increased considerably from 2018/2019 to 2019/2020 season at harvest at Univen. The explanation for the increase in nitrogen may be because of the lifespan of the lablab cultivars grown with maize. The lablab cultivars continued to grow and mature long after maize was harvested. Similar findings were made by Nyawade *et al*. (2020a) who noted that the canopy of dolichos lablab was extended after potato harvest. This trait makes the lablab cultivars suitable for increasing nitrogen in the soil as they were able to have a prolonged effect on nitrogen mineralization by continuing to supply nitrogen rich organic residues for a longer period. The canopy cover created by the large leaves of lablab is essential for lessening soil loss which is a common pathway of nutrient losses in the topsoil. Punyalue *et a*l. (2018b) reported reduced soil and nitrogen losses of up to 60% in maize/lablab intercropping compared to sole maize. Soil erosion is by far the largest contributor to soil deterioration which generally causes a decline in soil fertility and subsequently crop yields.

Crops obtain nitrogen from soil nitrogen derived from decomposition and mineralization of organic materials, nitrogen derived by biological N_2 fixation by root nodules, and from applied fertilizers. High levels of soil nitrogen have been reported to inhibit symbiotic N_2-fixation (Gai *et al*., 2017). Maitra *et al*. (2021) stated that it is advisable to apply basal nitrogen at planting as cereals are aggressive in nature and their growth could suppress the legumes if nitrogen is insufficient. However, they also outlined that sufficient supply of nitrogen supplied as fertilizer may reduce biological nitrogen fixation by legumes. In this study the soils were amended with 30 kg ha^{-1} of starter, and this may be a probable explanation for the decline of nitrogen at flowering and for the minor improvement at harvest. This is because the experimental soils already had over 20 kg ha^{-1} nitrogen at sowing. Tekulu *et al*. (2020) reported that the application of starter nitrogen combined with phosphorus fertilizer promoted biological nitrogen fixation by groundnut; however, larger nitrogen fertilizer rates (> 15 kg ha^{-1}) inhibited biological nitrogen fixation.

Soil sampling depth showed a significant effect on NO_3^- at Syferkuil at maize flowering, however, NO_3^- was significantly affected by sampling depth at maize flowering and harvest in both seasons at Univen. NO_3^- decreased with increasing soil depth at both sites in 2018/2019 (Table 6.1) and increased with increasing soil depth at flowering at Univen in 2019/2019 (Table 6.2). The higher levels of NO_3^- in the 0-15 cm depth in 2018/2019 may have been influenced by the combination of the initial nitrogen and nitrogen applied at planting as lime ammonium nitrate (LAN). Additionally, the initial NH_4^+ and NH_4^+ added through LAN may have increased NO_3^- through conversion of NH_4^+ through nitrification (Brady and Weil, 2017). The nonsignificant effect of sampling depth on NH_4^+ may have been due to nitrogen uptake by maize and lablab at varying soil depths. While maize has characteristically shallow roots, lablab has an extensive and well-developed rooting system that has the ability to penetrate deeper into the soil. The variation in rooting system allows for a more even nitrogen uptake across the soil profile (Mongare *et al*., 2020) instead of one area by both maize and lablab.

At Univen, the highest levels of mineral nitrogen were observed at a depth of 0-15 cm at flowering and harvest. The nitrogen levels were significantly higher at harvest maturity than flowering for maize/lablab intercropping and sole lablab. This may have been due to the lablab cultivars in the intercrops fixing atmospheric nitrogen, as a reaction to low nitrogen levels in the soil as a result of increased nitrogen uptake by maize to support maize grain filling. The high nitrogen concentration in the 0-15 cm depth at harvest may be due to the mulching effect of lablab. When cultivated, lablab can serve as a living mulch as the crop sheds leaves when it accumulates biomass. Punyalue *et al*. (2018b) reported higher nitrogen concentrations in lablab crops when compared to maize. Incorporation of lablab residues into soil was reported by Mthembu *et al*. (2018) to result in the greatest nitrogen concentrations in the soil relative to vetch and cowpea. These findings allude to the prospect that lablab may be a good source of organic residues to supplement nitrogen in farms. The use of lablab as live mulch or as organic residues may also assist farmers in conserving soil water (Mthembu *et al*., 2018) under rainfed agriculture.

Lablab monocropping system significantly affected soil water content at Univen and Syferkuil sites. The increased soil water content under sole lablab cropping may be as a result of better surface cover by lablab. The results are contradicted by Rapholo *et al*. (2019) who found that soil water content was not significantly different between sole maize, sole lablab and maize-lablab intercropping. The nonsignificant effect of intercropping on soil water content in relation to sole maize may be attributed to the increased water consumption in the intercropping system (Gebru, 2015); however, this may have been counteracted by the increased canopy cover which aided with moisture preservation (Punyalue *et al*., 2018a).

Competition for water between intercrop species is generally a problem in areas that have water limitations (Mbanyele *et al*., 2021). In this study, lablab was intercropped 28 days post maize planting to minimize the competition between maize and lablab. Intercropped lablab growth resulted in canopy overlap that covered the empty spaces in the inter-row spaces of maize thus increasing soil surface cover. These observations are consistent with Nyawade *et al*. (2019) who reported that legume intercropping (lablab and lima bean) with potato increased leaf area index as the legumes rapidly matured. The combination of maize and lablab biomass created a soil cover during the growing season and later as dead mulch, that could have shielded the soil surface from the elements (Punyalue *et al*., 2018b). The increased surface cover may have reduced the raindrop hitting force, thus slowing down the velocity of runoff, especially in the clay rich soils of Univen.

Soil sampling depth significantly affected soil water content at Univen (Table 6.3) and Syferkuil (Table 6.4). The highest soil water content was in the 30-60 cm soil depth in both sites. Soil water content is affected by soil characteristics, vegetation, topography and climate (Brady and Weil, 2017). The increased moisture content in the lower soil depth may be because of water percolation that would result in higher moisture content in the deeper soils depths. Additionally, soil water content may be the lowest at the top depth (0-15 cm) due to moisture losses through evaporation and water uptake by the plants. Although sole maize cropping system uses less soil moisture than intercropping system, the monocropping system is susceptible to higher evapotranspiration moisture losses (Haarhoff *et al*., 2020). This is because maize is a tall plant that has higher sunlight exposure and provides little surface cover. The increased radiation exposure may increase transpiration moisture loss by increasing maize water uptake from the soil (Maitra *et al*., 2021). Utilization of water in intercropped systems is greater than that of monocropping during the entire growing period, however, the differences are generally lower than the mean value of the corresponding water uptake in monocropping (Yin *et al*., 2020).

Sole lablab plots had significantly higher soil moisture content. Sole lablab increased soil moisture content at VT, R3 and R6 at Univen and at R3 and R6 at Syferkuil. The lower soil moisture content in maize/lablab intercrops may have been due to increased water extraction by the two crops. Additionally, the higher soil moisture content in sole lablab may be because lablab is a crop with bushy characteristics that resulted in increased surface cover when compared to sole maize. Vegetation cover of lablab may have also acted as a thermal insulator lowering soil temperatures during the day thus resulting in reduced moisture loss through evaporation (Haarhoff *et al*., 2020 and Nyawade *et al*., 2019). Lablab has the ability to accumulate large biomass that provides shade, and an extensive rooting system that can effectively loosen and aerate the soil; thus improving soil and water conservation (Kabirizi *et al*., 2005).

Soil moisture content directly affects availability of soil mineral nitrogen and mineralization of plant residues (Haarhoff *et al*., 2020). Too much soil moisture causes leaching of essential nutrients, while low moisture content can lead to nutrient losses through volatilization (Nyawade *et al*., 2019). This is a significant process in arid and semi-arid areas that generally have a low and poorly distributed soil cover and experience high temperatures. There is therefore a growing need to provide farmers with practical and sustainable solutions to maintain maize yields under the challenging conditions of climate change while using water more efficiently.

6.5 Conclusion and recommendations

The study showed that introduction of lablab into maize cropping systems is a viable strategy to improving nitrogen and preserving soil moisture. Nitrogen was found to be higher under sole lablab and maize/lablab cropping systems at maize harvest. The delayed benefit of lablab on nitrogen suggests that lablab may be more beneficial to maize as a nitrogen supplier through crop rotation, maize receiving the nitrogen as a subsequent crop. Maize monoculture resulted in low nitrogen and soil water content at maize harvest, highlighting the high demand of maize for nutrients and soil moisture. However, intercropping may pose problems of soil nutrient and water deficits due to the increased demand for water and nutrients by the intercropped crops. Maize-lablab intercropping also showed greater efficiency in water use by producing more grain and biomass than sole maize with equal amounts of resources. These findings suggest the potential of maize-lablab cropping system to ameliorate food security and ultimately the wellbeing of farmers with minimum inputs. However, growing multiple crops at the same time may require additional care and management to efficiently utilize resources and lessen competition between crops. While this study showed the benefits of maize-lablab intercropping over sole maize, further research studies are required to fully exploit the benefits of the cropping system and to better understand belowground dynamics between the intercrops and the link between starter nitrogen with biological nitrogen fixation and nodulation and their effect on grain yield and biomass.

CHAPTER 7: SIMULATING BIOMASS AND GRAIN YIELD OF MAIZE–LABLAB INTERCROP UNDER RAINFED CONDITIONS USING APSIM

7.1 Introduction

Although the food security of South Africa is secure at a national level, food insecurity at a household level remains a problem for the country. This is prominent in poor resource communities where majority of the people rely on rainfed agriculture to support their livelihoods (Nhamo *et al*., 2018). In December 2020 over 9.34 million South Africans were facing severe food insecurity (IPC, 2021). The deteriorating food security is mainly driven by climate variability, high food prices and economic decline (World Bank, 2022). A major source of nutrition for people in rural areas of South Africa is maize. South Africa's primary grain crop, maize, produced nationally across different environmental conditions (du Plessis, 2003). Although national maize production has been increasing steadily, production in rural dryland farming has been decreasing (Masereka *et al*., 2017). Zhou *et al*. (2022) outlined that this is mainly because of the extreme climate conditions that put crop production in semi-arid areas in jeopardy.

Due to climate change and variability, drought episodes and food insecurity are expected to increase, and herd sizes are likely to decline irreversibly, thus intensifying poverty (Masereka *et al*., 2019). The practices of rainfed agriculture need to be better adapted to climate change and climate variability while improving the productivity of smallholder farmers. Increasing concern about climate change and its effect on the environment requires transformation of cropping system (Zhou *et al*., 2022). One possible strategy that farmers can utilize to acclimate to climate variability is the integration of legume grains into maize cropping systems. The legumes can be grown in sole stands, in rotation with maize or intercropped with maize.

Intercropping is an act of planting multiple crop species for a significant duration of their growing period within the same field. Intercropping offers multiple benefits to farmers such as enhancing yield, environmental security, increased income and production sustainability (Maitra *et al*., 2021). Intercropping uses resources more efficiently when crop species are not competing for the same resources during the same period (Duchene *et al*., 2017). Cereal-legume intercropping is a commonly practiced form of intercropping that is used in semi-arid areas. This combination is particularly significant because cereal and legume crops grown in intercropping may be complementary to one another in terms of nitrogen use (Berghuijs *et al*., 2021). Majority of smallholder cropping systems are characterized by maize monocropping, an unsustainable and nutrient demanding practice that usually produces poor yields under rainfed conditions (Haarhoff *et al*., 2020). Although the addition of legumes into maize-dominated cropping systems has the potential to improve overall biomass and grain yield it poses a challenge of competition for soil water and nutrients, creating uncertainties regarding its use in rainfed agriculture.

Due to climate change and climate variability, there has been a change and shift in the duration and time of the growing seasons, and a higher occurrence of droughts and prolonged dry spells (Seyoum *et al*., 2018). This has led to a reduction in agricultural water sources for farmers that rely on rain, causing water scarce regions to become more water strained (Masereka *et al*., 2017). Rainfed agriculture in rural areas is suffering from reduced yields, suggesting that most farmers may be lacking essential risk management skills to cope with the increasing water shortages (Zhou *et al*., 2022). Therefore, there is a necessity to redesign agricultural practices that are currently utilized and to introduce decision supporting models such as the APSIM (Agricultural Production System Simulator) model. The APSIM model may be used to mitigate climate change risks, assist with selection of suitable crop genotypes and appropriate management options for a viable maize production.

APSIM (Agricultural Production System Simulator) is a crop simulating model that considers the link between farm management factors, climate characteristics and soil properties, and the influence of this factors on crop performance (Keating *et al*., 2000). The use of modelling and simulation tools supports the acceleration of research attainments and understanding of cropping systems. With the worsening effects of climate change and climate variability, adapting agronomic responses to changing environments and resources may allow for sustainable intensification over the traditional cropping systems (Chimonyo *et al*., 2020). However, errors in input data distribution during model simulations may create serious complications in the assessment of model performance (Ojeda *et al*., 2021). With the increasing concerns about food security and sustainable agricultural production in rainfed conditions, modelling of intercropping systems is of great importance as it can produce predictions of crop production in association to climate, crop genotypes, soils and management. The study assessed the APSIM model’s ability to accurately simulate observed biomass and grain yield of maize and lablab in monoculture and intercropping system.

7.2 Materials and methods

7.2.1 Experimental setup

Full experimental details are given in chapter 3, but a brief summary is given below. The field experiments were conducted under rainfed conditions at the University of Venda Experimental Farm in Thohoyandou (Univen) and University of Limpopo Experimental Farm in Syferkuil (Syferkuil). The experiment ran for one season at Syferkuil during 2018/2019 cropping season because the second season failed in 2019/2020 due to neglect during Covid-19 restrictions, and it was conducted for two seasons at Univen during 2018/2019 and 2019/2020 cropping seasons. Treatments consisted of one maize cultivar (DKC-2147) and three lablab cultivars (Rongai, DL-1002 and Q-6880B) planted as monocrops and intercrops. Intercropped lablab was sown within the maize plots 28 days after maize planting. To account for variation in the fields the treatments were laid out in a randomized complete block design (RCBD) replicated three times. Nitrogen and phosphorus were applied at a rate of 30 kg ha^{-1} and 50 kg ha^{-1} respectively, at sowing. The fields were managed optimally throughout the study by controlling weeds, diseases and pests as much as possible. Weeds were controlled manually by using hand hoes whenever they emerged until maize reached tasselling stage. Pests were controlled chemically using Cyperthrine. Data collected included crop data, soil and weather conditions which were required for calibrating the cultivar coefficients and to create new maize and lablab varieties.

7.2.2 APSIM model set-up

Soil, management, and crop modules are the main components of the APSIM model. The model simulates soil water and nutrient transfer by dividing the soil environment into soil nitrogen, soil phosphorus, and surface residues. Soil water characteristic parameters include field capacity (mm^{3} mm^{-3}), wilting coefficient and saturated water content of layered soil which were obtained from the APSIM model from the previously classified soils of Univen. Soil water characteristics of Univen and Syferkuil are indicated in Tables 7.1 and 7.2, respectively. Maize lower limits were used for maize simulation while lablab lower limits were created by copying lower limits of cowpea as it was the most comparable crop to lablab. Previously classified soils (Station_UniVenda and Syferkuil) were selected from the APsoil database and edited after analysing soil samples collected from each location. Each soil was used for the simulation of the corresponding experimental site based on the verification that it matched the soil type, depth and soil texture. Initial volumetric soil water and soil mineral nitrogen concentration were set in the simulations. Parameters such as sowing and harvesting crops, input and output, crop cultivars, irrigation and fertilization were set in the management module. The daily weather data required for the model included precipitation, total radiation, and maximum and minimum temperatures. The meteorological data for Univen and Syferkuil used for the simulations were obtained from ARC Institute from weather stations located less than 3 km from the experimental fields. Average monthly temperature and rainfall data for Univen and Syferkuil site are shown in Chapter 3 (Table 3.3 and 3.4).

Table 7.1. Soil chemical and physical properties and initial values at Univen by depth.

Depth (cm)	**0-15**	**15-30**	**30-60**	**60-90**
Bulk density (g/cc)	1.22	1.25	1.34	1.34
SAT (mm/mm)	0.49	0.49	0.49	0.49
DUL (mm/mm)	0.26	0.29	0.29	0.32
Air-Dry weight (mm/mm)	0.06	0.08	0.13	0.13
LL (mm/mm)	0.12	0.13	0.15	0.15
XF (0-1)	1.00	1.00	1.00	1.00
KL (0-1)	0.06	0.06	0.06	0.05
Fbiom (0-1)	0.03	0.02	0.02	0.01
Finert (0-1)	0.50	0.70	0.70	0.90
OC (Total%)	2.42	1.00	0.40	0.40
ph (1:5 water)	5.92	5.92	5.82	5.72

SAT-Saturated volumetric water content, DUL-Drained upper limit, LL-Lower limit, XF-Root exploration factor, KL-Water extraction coefficient, OC-Organic carbon

Table 7.2. Soil chemical and physical properties and initial values at Syferkuil by soil depth.

Depth (cm)	**0-15**	**15-30**	**30-60**	**60-90**
Bulk density (g/cc)	1.45	1.45	1.45	1.45
SAT (mm/mm)	0.40	0.40	0.40	0.40
DUL (mm/mm)	0.15	0.16	0.16	0.16
Air-Dry weight (mm/mm)	0.03	0.03	0.11	0.11
LL (mm/mm)	0.05	0.07	0.11	0.11
XF (0-1)	1.00	1.00	1.00	1.00
KL (0-1)	0.06	0.06	0.06	0.04
Fbiom (0-1)	0.03	0.02	0.02	0.01
Finert (0-1)	0.50	0.50	0.60	0.70
OC (Total%)	0.87	0.87	0.70	0.60
ph (1:5 water)	6.60	7.00	6.90	6.90

SAT-Saturated volumetric water content, DUL-Drained upper limit, LL-Lower limit, XF-Root exploration factor, KL-Water extraction coefficient, OC-Organic carbon

7.2.3 Model calibration

The APSIM-maize and APSIM-lablab models were used to calibrate and test maize (DKC 2147) and three lablab cultivars (DL-1002, Rongai and Q-6880B) using the APSIM-version 7.4 r4219. APSIM-maize and APSIM-lablab were calibrated for maize and the three lablab cultivars with, climate data, management parameters, site-specific soil and field data obtained from the 2018/2019 cropping season; in order to develop cultivar specific parameters. The field data collected included a combination of two measures of biomass, observations of crop phenological development, and a measure of grain yield at harvest maturity, soil water and soil mineral nitrogen. Soil Nitrate-N and ammonium-N concentrations were measured at each site at the start and end of each season.

7.2.4 Modification of maize and lablab genotype-specific parameters

The growth and development of APSIM-maize and APSIM-lablab uses a set of different coefficients to define phenology, crop growth and yield (Table 7.3 and 7.4). The calibration stage aimed to produce functional maize and lablab models by making necessary modifications to the genetic coefficients within the APSIM-maize and APSIM-lablab models to improve the fitness between the observed and predicted data of each crop species and cultivar. Initial coefficients for the lablab cultivars were based on cultivar Highworth and Endurance because they were the only lablab models available in APSIM. While for maize it was based on three maize genotypes namely Hycorn_50, 19_leaf and Pioneer_3153, which were selected because they are classified as early maturing varieties within APSIM and cultivar DKC 2147 which was used in the field experiments is also an early maturing variety. Modifications to genetic coefficients were made using the observed data, and adjustments were made until a point was reached that optimized model agreement with observed values. Model parameterization was conducted step-by-step, which first focused on crop phenology then on biomass partitioning and grain yield.

Table 7.3. Genetic coefficients fitted for APSIM-maize cultivars.

Model parameter	Cultivar		
	_19leaf	hycorn_50	Pioneer_3153
tt_emergence to end juvenile (°C day)	250	280	300
tt_end juvenile to init (°C day)	0	0	0
photoperiod_critical 1 (hours)	12.5	12.5	12.5
photoperiod_critical 2 (hours)	24	20	24
photoperiod_slope (°C/hour-1)	0	0	0
tt_flag to flower (°C day)	50	50	50
tt_flower to start grain fill (°C day)	120	170	120
tt_flower to maturity (°C day)	980	850	980
tt_maturity to ripe (°C day)	1	1	1

Table 7.4. Genetic coefficients fitted for APSIM-lablab cultivars.

	Cultivars	
Parameters	Endurance	Highworth
_hi_increase 1/days	0.03	0.03
_hi_max pot stress	0	0
_hi_max pot	0.2	0.2
cumvd emergence day>0	100	100
tt_emergence (°C day)	500	500
est_days emergence to init (day)	20	20
_tt_end of juvenile (°C day)	600	600
_tt_floral initiation (°C day)	20	20
_tt_flowering (°C day)	100	100
_tt_start grain fill (°C day)	900	900
tt_end grain fill (°C day)	400	400
tt_maturity (°C day)	5	5
_stem weight (g)	15	15
_height (mm)	1200	1200

7.3 Results

7.3.1 Maize

Simulated and observed maize biomass yields at both sites are given in Table 7.5. APSIM model performance to simulate biomass at Univen was very good, especially in 2019/2020 with RMSE values of 575.1 kg ha^{-1} compared to 941.76kg ha^{-1} in 2018/2019 season. The RMSE was 13% and 9% against the lowest recorded maize biomass in 2018/2019 and 2019/2020 seasons, respectively. The RMSE increased with increase in the differences between simulated and observed biomass. In general, biomass of maize under maize-lablab intercrops was underestimated by the model while sole maize was overestimated by APSIM-maize model in both seasons by 16.7% and 14.2%. The decrease in the differences across the seasons may be due to the interaction and errors associated with environment, soil data, and management.

Based on coefficient efficiency value (R^2) of 0.04, biomass simulations were poorer at Univen in 2019/2020 compared to 2018/2019 (0.53) season. However, the differences in biomass between simulated and observed values were lower in 2019/2020. The low R^2 shows that there was little consistency in maize biomass, these consistencies may have been as a result of the interaction of environment, soils, management and other factors that the model does not account for such as pest and weed problems.

At Syferkuil site APSIM model was able to simulate biomass well, with an R^2 value of 0.88 (Table 7.6). There was a high agreement with observed data at Syferkuil, with observed and simulated data showing a similar trend under sole and intercrop systems. Biomass was slightly overestimated in maize monoculture (4.1%) and underestimated under intercrop systems by 10.4%-15.3%, however the differences were deemed acceptable. Syferkuil also had the lowest RMSE value (565.44 kg ha^{-1}) which was 12% against the lowest biomass compared to Univen in 2018/2019 season. As such, the model was better able to reproduce maize biomass at Syferkuil than at Univen in 2018/2019.

The model simulations for grain yield were deemed unsatisfactory at Univen based on the statistical output (R^2). The R^2 was 0.27 and 0.04 in 2018/2019 and 2019/2020 seasons, respectively (Table 7.7). The low R^2 could have been due to the low differences in grain between simulated and observed values under maize monoculture (0.4-6.7%) compared to differences in intercrops (11.3-26.8%). Generally, APSIM model underestimated grain yield in both seasons, with the greatest differences in maize-lablab intercrops. RMSE was observed to be slightly high (646.79-956.42 kg ha^{-1}), with the lower RMSE observed in the second season. The RMSE for grain yield at Univen was 22% and 16% against the lowest observed grain yield in 2018/2019 and 2019/2020 seasons. Based on simulated and observed grain yield values, the RMSE values were considered to be good.

Based on statistical outputs used in the study, APSIM-maize model had higher accuracy simulating grain yield at Syferkuil. The R^2 value was observed to be 0.91 and the RMSE to be 343.44 kg ha^{-1}. The RMSE value was 12% against the lowest grain yield in 2018/2019. The RMSE for grain yield at Syferkuil was 54% lower than that observed at Univen in the first season. Regardless of the high R^2 and low RMSE values, the model slightly overestimated grain yield under monoculture and slightly underestimated it under intercropping systems. There was a 4.8% difference in the average simulated and average observed grain yield at Syferkuil.

Table 7.5. Comparison of simulated and observed aboveground maize biomass at Univen and Syferkuil in 2018/2019 and 2019/2020 seasons.

Location	**Univen**						**Syferkuil**		
Season	**2018/2019**			**2019/2020**			**2018/2019**		
Treatment	**Aboveground biomass**								
Cropping system	Observed (kg ha^{-1})	Simulated (kg ha^{-1})	Differences (%)	Observed (kg ha^{-1})	Simulated (kg ha^{-1})	Differences (%)	Observed (kg ha^{-1})	Simulated (kg ha^{-1})	Differences (%)
Sole maize	7292.8	8510.9	16.7	6590.0	7526.8	14.2	5391.7	5654.2	4.9
Maize + DL-1002	8034.0	7118.4	-11.4	7686.4	7497.6	-2.5	4680.3	4192.2	-10.4
Maize + Rongai	7725.8	7147.2	-7.5	7720.9	8168.7	5.8	4824.8	4191.1	-13.1
Maize + Q-6880B	8337.5	7393.7	-11.3	7941.6	7482.2	-5.7	4933.3	4178.2	-15.3
R^2	0.53			0.04			0.88		
RMSE (kg ha^{-1})	941.76			575.50			565.44		

R^2=coefficient of determination, RMSE= root mean square error

Table 7.6. Comparison of simulated and observed maize grain yield at Univen and Syferkuil in 2018/2019 and 2019/2020 seasons.

Location	**Univen**						**Syferkuil**		
Season	**2018/2019**			**2019/2020**			**2018/2019**		
Treatment	**Grain yield**								
Cropping system	Observed (kg ha^{-1})	Predicted (kg ha^{-1})	Differences (%)	Observed (kg ha^{-1})	Predicted (kg ha^{-1})	Differences (%)	Observed (kg ha^{-1})	Predicted (kg ha^{-1})	Differences (%)
Sole maize	4341.4	4046.4	-6.7	4012.1	4026.3	0.4	3310.6	3705.6	11.9
Maize + DL-1002	4682.3	3426.5	-26.8	4778.6	3988.6	-16.5	2881.3	2644.4	-8.2
Maize + Rongai	4562.0	3429.5	-24.8	4819.3	4274.0	-11.3	3008.5	2644.3	-12.1
Maize + Q-6880B	4303.2	3459.2	-19.6	4840.1	3973.1	-17.9	2989.0	2632.6	-11.9
R^2	0.27			0.04			0.91		
RMSE (kg ha^{-1})	956.42			646.79			343.44		

R^2=coefficient of determination, RMSE= root mean square error

7.3.2 Lablab

Generally, lablab biomass was poorly simulated by APSIM model at Univen during 2018/2019 and 2019/2020 seasons. Although the R^2 value was high (0.92-0.96) in both seasons, the RMSE values were also high (Table 7.7). RMSE was found to be 3073.50 kg ha^{-1} in 2018/2019 and 5115.64 kg ha^{-1} in 2019/2020 cropping season. The RMSE for lablab biomass was 155% and 62% in 2018/2019 for intercropped and sole lablab, respectively. While the RMSE was recorded at 163% and 84% in 2019/2020 for intercropped and mono-cropped lablab, respectively. The model overestimated biomass in both seasons under monocropping and intercropping systems. The large RMSEs are in agreement with the high biomass differences between simulated and observed data. The lowest difference (59.2%) in biomass was in maize+Q-6880B in 2018/2019 season.

Simulation of lablab biomass by APSIM model at Syferkuil was also found to be poor, however, the accuracy was better at Syferkuil as compared to Univen. Despite a 0.97 value of R^2 (Table 7.7), the fitness of the model was concluded as poor because of the large RMSE and high differences in biomass between simulated and observed values. The RMSE for biomass at Syferkuil was found to be 81% and 25% for intercropped and mono-cropped lablab, respectively. As observed at Univen, cultivar Q-6880B had the highest biomass differences in monocropping but had the lowest differences in intercropping at Syferkuil. This observation indicates that the performance of the model may have been influenced by lablab cultivars and soil and climate conditions. Biomass was overestimated by the model across cropping systems, with the largest overestimations found in intercrop systems.

APSIM-lablab model had difficulties reproducing grain yield at Univen in both seasons. The results are reflected by the large RMSE values and high grain yield differences between observed and simulated data (Table 7.8). However, the differences were much lower in lablab monocropping in 2019/2020 season. The RMSE for lablab grain yield was 154% in intercropping and 32% in monocropping in 2018/2019, while in 2019/2020 season the RMSE was 66% and 20% for intercropped and mono-cropped lablab, respectively. Although grain yield increased from season 1 to season 2 at Univen, APSIM still overestimated yield values in maize-lablab intercrops. However, grain yield was underestimated in lablab monoculture. The data showed two cluster groups, resulting in a high R^2, despite the high simulation inaccuracy.

At Syferkuil, APSIM model was unable to accurately reproduce lablab grain yields under maize/lablab intercropping, however the model had better accuracy simulating lablab grain yield under lablab monocropping. The model overestimated the grain yield in both cropping systems, with the largest overestimation observed under maize/lablab intercropping (Table

7.9). Although the R^2 value was high (0.95) the RMSE and percentage differences between observed and simulated data were too high. The RMSE for lablab grain yield at Syferkuil was 183% in intercropping and 38% in monocropping. Syferkuil site had higher RMSE percentages compared to Univen in 2018/2019 season.

Table 7.7. Lablab observed and simulated values for aboveground biomass during 2018/219 and 2019/2020 cropping seasons at Univen and Syferkuil sites.

Location	**Univen**						**Syferkuil**		
Season	**2018/2019**			**2019/2020**			**2018/2019**		
Treatment	**Aboveground biomass**								
Cropping system	Observed (kg ha^{-1})	Simulated (kg ha^{-1})	Differences (%)	Observed (kg ha^{-1})	Simulated (kg ha^{-1})	Differences (%)	Observed (kg ha^{-1})	Simulated (kg ha^{-1})	Differences (%)
Sole DL-1002	5093.0	8789.8	72.6	5926.3	11561.4	95.1	3807.6	5025.5	32.0
Sole Rongai	5291.4	8935.1	68.9	6083.1	11954.3	96.5	3795.1	5037.1	32.7
Sole Q-6880B	4939.0	8918.8	80.6	5051.0	11758.7	132.8	2815.3	3936.6	39.8
Maize + DL-1002	2294.3	4546.4	98.2	3224.8	7412.6	129.9	1189.0	2001.3	68.3
Maize + Rongai	1976.3	4572.9	131.4	3226.3	7503.9	132.6	1240.2	1986.2	60.2
Maize + Q-6880B	2436.2	3879.3	59.2	3130.7	6287.4	100.8	1299.7	1360.0	4.6
R^2	0.96			0.92			0.97		
RMSE (kg ha^{-1})	3073.50			5115.64			957.7		

R^2=coefficient of determination, RMSE= root mean square error

Table 7.8. Observed and simulated values for lablab grain yield during 2018/219 and 2019/2020 cropping seasons at Univen and Syferkuil sites.

Location	**Univen**						**Syferkuil**		
Season	**2018/2019**			**2019/2020**			**2018/2019**		
Treatment	**Grain yield**								
Cropping system	Observed (kg ha^{-1})	Simulated (kg ha^{-1})	Differences (%)	Observed (kg ha^{-1})	Simulated (kg ha^{-1})	Differences (%)	Observed (kg ha^{-1})	Simulated (kg ha^{-1})	Differences (%)
Sole DL-1002	1965.7	1757.9	-10.6	2339.7	2312.3	-1.2	640.2	998.2	55.9
Sole Rongai	2611.2	1787.0	-31.5	2735.5	2390.9	-12.6	617.1	995.5	61.3
Sole Q-6880B	2499.8	1252.7	-49.9	2319.9	2131.3	-8.1	643.2	787.3	22.4
Maize + DL-1002	521.7	643.4	23.3	753.3	1482.5	96.8	150.0	241.9	61.2
Maize + Rongai	404.5	567.1	40.2	770.6	1500.8	94.7	128.5	248.9	93.7
Maize + Q-6880B	474.6	397.3	-16.3	711.2	1012.4	42.4	136.9	272.0	98.6
R^2	0.82			0.90			0.95		
RMSE (kg ha^{-1})	622.49			467.39			235.69		

R^2=coefficient of determination, RMSE= root mean square error

7.4 Discussion

APSIM-maize model mostly required adjustments of the phenological parameters to simulate biomass and grain yield production of maize in Syferkuil and Univen. Maize yield predictions confirmed prior observations that APSIM model is capable of predicting maize responses to different environments and cultivars (Seyoum *et al*., 2018). Results of the current study showed that the APSIM-maize model was able to capture the observed variation in biomass in different cropping systems across the sites, however, biomass was slightly overestimated in sole maize and slightly underestimated in maize/lablab intercrops. Contrary to this study, Chimonyo *et al*. (2020) reported increased maize biomass under maize/bambara and maize/groundnut intercrops. Another contrary study was by Whitbread and Ayisi (2004) who found that simulated biomass was underestimated by APSIM in maize monoculture, but this was only late in the season. However, research studies by Chimonyo *et al*. (2016) (sorghum/cowpea), Nelson *et al*. (2021) (pearl millet/cowpea) and Berghuijs *et al*. (2021) (Wheat/fababean) are in accordance with this study, as they also reported an overestimation of cereal biomass in sole cropping and underestimation in intercropping.

Simulation of maize under monoculture was more accurate for grain yield than biomass at Univen in both seasons. These results are supported by Zhou *et al*. (2022) as they reported high prediction accuracy by APSIM model when maize was grown as sole crop. Similarly, Nelson *et al*. (2021) published that pearl millet grain yield simulation by APSIM had a better fitness to observed data in pearl millet sole crops, however, the accuracy was reduced at a higher planting density. APSIM model was able to capture the improvement in maize grain yield in the second season at Univen, which may have been because of the higher rainfall received in 2019/2020. Comparable findings were made by Seyoum *et al*. (2018) who found significantly higher maize yield during favourable rainy seasons.

Generally, maize grain yield followed a similar trend to biomass except in 2018/2019 season at Univen. Dimes *et al*. (2011) reported similar grain yield levels and grain yield reduction under maize/legume intercropping. However, Dimes *et al*. (2011) also reported that maize model simulated a yield decline of about 42% when maize was intercropped with beans (common bean, soybean, pigeonpea and cowpea), a substantially greater reduction than that estimated in this study (16%). The results obtained showed that APSIM is capable of simulating the influence of crop selection and management on maize biomass and grain yields under different environments, but the overestimations and underestimation also demonstrated that there is room for improving the accuracy of prediction by the model.

Lablab biomass and grain yield production was not captured very well by APSIM across sites despite the high R^2 values. The inability for APSIM to predict biomass and grain yield of lablab accurately was indicated by the high RMSE values when compared to the actual lablab biomass and grain yield. Overestimated biomass by the model negatively affected the accuracy of model prediction. Contrarily, Chimonyo *et al*. (2016) found the model's performance satisfactory in simulating both cereal (sorghum) and legume (cowpea) biomass in monocultures, however, this conclusion was based solely on statistical outputs (R^2 and RMSE). APSIM's inability to accurately reproduce lablab yields was more pronounced in intercropping system. However, this was not a surprising outcome since the model also failed to accurately simulate lablab biomass and grain yield under monocropping. The differences in simulated and observed yields was greatest at Univen for biomass and greatest at Syferkuil for grain. This observation may largely be due to climate differences between the two sites.

Another probable explanation for the overestimation of lablab biomass may be because of the observed early senescence. APSIM model has the ability to initiate leaf senescence due to age, light competition, water stress and frost (Nelson *et al*., 2021). However, in this study APSIM did not simulate the observed senescence. The observed senescence could have been due to high temperatures coupled with low rainfall from April, a period which was associated with flowering for the lablab cultivars in the current study. The inability of APSIM to simulate senescence may be attributed to errors associated with weather data sources. Ojeda *et al*. (2021) explains that most errors in APSIM arise from inconsistencies in data sources. Weather stations at Syferkuil and Univen were compromised and as such, were unable to record data for extensive periods during which the experiments were active.

Additionally, there were multiple pest infestations (aphids, armyworms, blister beetles, monkeys and pod borers) and bacterial brown spotting and rusting, which may have to a degree affected lablab biomass and grain yield. The reduction of biomass and grain yield from direct consumption by the pests could have affected potential observed data. A study by Chimonyo *et al*. (2016) explained that overestimation of cowpea under both monocropping and intercropping may have been as a result of the legume succumbing to other yield reducing factors that were not adequately accounted for by the model. Furthermore, Ojeda *et al.* (2021) reported that inaccurate simulations by APSIM may be due to a combination of errors. This includes lack of documentation or large uncertainty to determine and estimate soil parameters amongst data sources, inaccurate observed yield calculations, and mismatch of soil data available in the model with experimental soil, all which could lead to model inaccuracies. Despite inaccurate lablab yield simulations by APSIM, the model was able to capture intercropping dynamics as both simulated and observed data values indicated yield compromise under intercropping.

Similar to this study, Chimonyo *et al*. (2016) found that APSIM performed poorly in predicting grain yield of cowpea when intercropped with sorghum. Chimonyo *et al*. (2016) further stated that a possible explanation for the cowpea yield overestimation by APSIM may be due to the carry over error brought about by biomass overestimation. A sorghum-cowpea study by Nelson *et al*. (2021) found that APSIM had difficulties in simulating cowpea under intercropping but reproduced satisfactory yields for sorghum. Findings by Chimonyo *et al*. (2016) and Nelson *et al*. (2021) partially contradict the findings of this study since lablab performed poorly in both lablab monoculture and maize/lablab intercropping. However, findings of the current study are consistent with Berghuijs *et al*. (2021) as indicated that APSIM had limited capabilities to reproduce faba bean yields under monoculture and intercrop.

The poorly simulated legume yields under monocropping and/or intercropping systems across different studies suggest a larger influence outside basic environment, soil and management factors. Nelson *et al*. (2021) explained that poor simulations of legume yields may be due to the fact that there has been more emphasis and extensive research placed on cereals (maize, wheat, sorghum etc.) rather than on legumes. For example, legume crops tend to be unstable and highly sensitive to environment and management, which is not necessarily fully captured by process-based crop simulations model in general. APSIM model does not capture the effect of factors such as pests, diseases and extreme weather conditions. These factors may have affected biomass and grain yield of lablab in this study, only one lablab cultivar to worked with for the simulation of three different cultivars. This can lead to cultivars having erroneous crop coefficients that may lead to APSIM overestimating or underestimating crop yields that are not reflected by observed data. However, this may be improved by collecting extensive crop data for the simulations.

7.5 Conclusion and recommendations

The APSIM model successfully simulated maize in different cropping systems under different environments. APSIM was able to also capture the year-to-year trend in lablab biomass and grain yield, but failed to accurately simulate biomass and grain yield levels. APSIM gave reliable simulations for maize biomass and grain yield, and although it had difficulties with lablab yields the model was able to show the effects of intercropping on crop yields. The model can be used to quantify the effect of inter and intra-specific competition between the intercrops, thus leading to higher yields in intercropping than in monocultures. Current results indicate that intercropping maize with different lablab varieties can allow farmers to achieve constant maize yields and increase overall yield potential. However, this may be site specific because intercropping is susceptible to crop yield losses due to moisture stress under low rainfall receiving areas. Model performance can be certainly improved by conducting further calibration and validation of the model with data from the field experiments under non-limiting conditions (optimum conditions), with higher number of biomass sampling points from emergence until harvest, supported by LAI measurements and expanding the number of years of data collection. In addition, as most crop simulations models, there is also a need to test further whether the model is able to capture the effect of extreme weather events on crop performance, especially under rainfed conditions. Regardless of the poor accuracy of the model to simulate lablab, integration of legumes into maize cropping systems is still promoted as important for food production systems and soil conservation. The results obtained simply demonstrate a need for more research. Further studies should test different parameters and aspects of crop interactions, which may provide further insight into the mechanisms driving competition and complementarity in field crops. Understanding this would allow farmers to make well informed decisions and better manage their farms, thus lessening risk losses associated with climate and poor management.

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