PRODUCTIVITY AND PHYSIOLOGICAL RESPONSES OF WINTER ANNUAL FORAGE LEGUMES TO PLANTING DATE AND SHORT-TERM ROTATION WITH FORAGE SORGHUM FOR SHEEP PRODUCTION UNDER NO-TILL SYSTEM IN LIMPOPO PROVINCE

by

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THESIS
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DECLARATION

I, Lesego Minah Motshekga, declare that the thesis titled **Productivity and physiological responses of winter annual legumes to planting date and short-term rotation with forage sorghum for sheep production under a no-till system in Limpopo Province**, which I hereby submit for the degree of Doctor of Philosophy in Agriculture (Plant Production) is my own work and that all the sources that I have used or quoted have been indicated and acknowledged using complete references and that this work has not been submitted before for any other degree at any other institution.

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Full names   Date

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I dedicate this work to my late mother-Mrs Naume Bodibe, my father, my husband and our sons, mother-in-law and siblings from the Bodibe and Motshekga families.

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A	Photosynthetic rate
ADF	Acid detergent fibre
ANOVA	Analysis of variance
AOAC	Association of Official Analytical Chemists
APAP	Agricultural Policy Action Plan
APSIM	Agricultural Production System Simulator Model
Ci	Sub-stomatal CO_2
CSA	Climate-smart agriculture
Cm	Centimetre
CP	Crude protein
CO_2	Carbon dioxide
CV	Coefficient of variation
DAFF	Department of Agriculture, Forestry and Fisheries
DAP	Days after planting
DM	Dry matter
°C	Degree Celsius
E	Transpiration rate
FAO	Food and Agriculture Organization
GHG	Greenhouse gas
Gs	Stomatal conductance
G	Gram
Ha	Hectare
ha^{-1}	per hectare
IPCC	Intergovernmental Panel on Climate Change
Kg	Kilogram
LSD	Least significant difference
m	Meter
mg	Milligram

mg/kg	Milligram per kilogram
mm	Millimetre
mmol $m^{-2}s^{-1}$	Millimole per square meter per second
$molm^{-2}$ s^{-1}	Mole per square meter per second
mmol m^{-2} s^{-1}	Micromole per square meter per second
μmol mol^{-1}	Micromole per mole
N	Nitrogen
NDF	Neutral detergent fibre
NDP	National Development Plan
NDVI	Normalized difference vegetation index
Ns	Not significant
P	Phosphorus
ppm	parts per million
%	Percent
SE	Standard error
SPAD	Soil and Plant Analysis Development
SSA	Sub-Saharan Africa
Tn	Minimum temperature
Tx	Maximum temperature
UN	United Nations
WUE	Water use efficiency

PUBLICATIONS DURING CANDIDATURE

Articles in preparation from the thesis

Motshekga, L.M., Ayisi, K.K., Isselstein, J. and Ndleve, S. Production practices of communal and smallholder sheep farmers of Limpopo Province: Does it contribute to feed gaps?

Motshekga, L.M., Ayisi, K.K., Isselstein, J. and Ndleve, S. Drivers and barriers to adoption of on-farm forage legume production by communal and smallholder sheep farmers to address feed gaps in Limpopo Province**.**

Motshekga, L.M., Ayisi, K.K., Isselstein, J. and Ndleve, S. Physiological traits and productivity of annual clover and vetch cultivars as influenced by planting date and harvesting stage in a semi-arid environment.

THESIS STRUCTURE

CHAPTER 1

General introduction

This chapter addresses the background on winter feed-gap challenges experienced by sheep farmers in the Limpopo province and the potential of integrating winter annual forage legumes and forage sorghum for sustainable fodder production. Furthermore, the section presents the problem statement, motivation, aim, objectives and hypotheses of the study.

CHAPTER 2

Literature review

This chapter reviews existing literature on the winter feed gap challenges in sheep production, planting date effects on annual clover, vetch and forage sorghum growth, physiology, productivity and nutritive value, Nitrogen rates and residual N effects on forage sorghum productivity, Forage sorghum N-nutrition simulations using APSIM.

CHAPTER 3

Farmer survey of sheep production systems

This chapter presents a survey outcomes on sheep production practices and challenges and furthermore assess the factors affecting the adoption of on-farm forage legume production by sheep farmers in addressing winter feed gaps in the Limpopo province.

CHAPTER 4

Physiology and productivity of winter annual forage legumes

This chapter investigates leaf gaseous exchange, biomass production, biological nitrogen fixation and nutritive value of no-till winter annual vetch and clover cultivars under different planting dates for climate change adaptation.

CHAPTER 5

Winter annual forage legume-sorghum short-term rotation: Empirical and APSIM simulation information.

This chapter examines the growth and nutritive value of forage sorghum, planted after the winter annual forage legumes in combination with nitrogen rates in a short-term rotation. The simulation focused on the performance of Agricultural Production System Simulator Model (APSIM)-grain sorghum module in simulating forage sorgum under nitrogen rates.

CHAPTER 6

General conclusions and Recommendations

This chapter presents overall conclusion of the study mainly focusing on chapters 3-5 and recommendations for future research.

GENERAL ABSTRACT

Livestock has evolved to serve as the foundation and backbone of human well-being, and it is an important component of South Africa's agricultural sector. The small stock such as sheep (*Ovis aries*) in Limpopo province has remained a significant and multifunctional livelihood strategy for the majority of the rural and resource-poor people. Factors such as population growth, urbanization, rising per capita income and changes in consumer tastes and preferences are all contributing to gradual increases in livestock product consumption and demand. According to the 2019 Abstract of Agricultural Statistics, South Africa is an importer of sheep and sheep products. If the sheep production industry in the province could pursue this opportunity and realize its full production potential then increased production could stimulate economic growth and development, particularly from the communal and smallholder sector. Objective one of the study seeks to describe the demographic and socio-economic characteristics of communal and smallholder sheep farmers, identify sheep feeding practices and describe the constraints that hinder the sustainable productive growth of communal and smallholder sheep systems.

Data were collected from one hundred and twenty (120) sheep farmers using a structured questionnaire across three agro-ecological zones of Limpopo province. Results revealed that overall, the majority of sheep farmers were males (78%) and farmers were above 60 years old (48%). Mean sheep flock size differed significantly between communal (24.74) and smallholder (62.36) farmers. Indigenous crossbreeds were the dominant breed kept by communal (86%) and smallholder (77%) farmers. The majority of communal and smallholder farmers (90% and 96%, respectively) reared their sheep under an extensive system with rangelands as the main source of feed. As a result, they experience a critical feed gap during June and September, the mid-winter to early spring until the first rains. The findings of the study revealed that feed shortages and diseases were ranked as the first and second production constraints by sheep farmers in both the production systems. In rangeland-dependent feeding systems, insufficient feed to meet animal demands create a feed gap, which is a critical factor that limits sheep productivity and causes land degradation through overgrazing. Improved forages have been widely advocated as a critical step toward resolving this challenge. However, the adoption and utilization of improved technologies such as on-farm forage legume production by these farmers have been very low, contributing to the province's low sheep productivity. An extension of objective one of this study used primary data which was collected from a sample of 120 sheep farmers to determine the factors that influence the adoption of on-farm forage legume production and the perceived barriers to adoption by communal and smallholder sheep farmers in the Limpopo province. A Probit regression model and Principal Component Analysis (PCA) were used to analyze the data. The study revealed that the adoption of on-farm forage production by communal and smallholder sheep farmers is influenced by several factors, including gender, farming experience, knowledge of forage legume production, source of income, membership in farmer associations, access to extension services and farm size. Farmer perceived barriers to adoption of on-farm forage legume production identified by this study were low institutional support, lack of resources, lack of knowledge, shortage of water and objectives of the farmer. It is therefore recommended that intensive and high-quality extension support in partnership with industry associations and stakeholders is required for communal and smallholder farmers to improve forage technology awareness, training and promote on-farm forage production to transform communal and smallholder sheep feeding practices.

In the face of climate change, identifying forage species with a high potential to mitigate winter feed gap challenges under more variable climatic conditions is critical. Trifolium and Vicia species are forage legumes well known for producing high-quality forage, particularly protein, which is deficient in the majority of feed resources used for sheep feeding during the winter season. Climate change-induced stresses from rising temperatures, which these winter annual forage legumes are likely to face, necessitate agronomic and breeding approaches to improve their adaptability. Lack of knowledge on how these climate change mitigation approaches influence the productivity of winter annual forage legumes in the Pietersburg Plateau of Limpopo province prompted objective two of this study. A three-year field experiment laid in a split-split plot design with four replications was conducted to measure the effects of planting date, cultivar and harvest stage on the physiological traits associated with biomass production, forage quality, nodulation activity and nutritive value of annual clover and vetch species. The results showed that the planting date and harvest stage had a significant effect on leaf gaseous exchange and biomass production. A non-significant effect of planting date on nutritive value was observed. Intercellular CO_2 concentration, transpiration rate, stomatal conductance, instantaneous water use efficiency and intrinsic water use efficiency in cultivars increased with delayed planting, while a decrease in photosynthetic rate, shoot DM, root DM and nodule DM was observed. Overall among the cultivars, Resal, Alex, Elite, Laser and Dr Baumans showed more consistency in terms of leaf gaseous exchange, biomass production and quality traits under planting date 1 and varying harvest stages.

Investment in the year-round fodder flow establishment with high-quality forages is important in supporting sustainable sheep production. Forage legume-grass rotation systems are important not only for green fodder production of high crude protein, mineral and vitamin content throughout the year but also for enhanced soil fertility to reduce the nitrogen (N) fertilizer requirements. Accurate estimates of forage yields on the farm are required for fodder flow planning to ensure the seasonal distribution of fodder throughout the year. Objective three of the study was a no-tillage, short-term rotation experiment conducted to determine the growth and nutritive value of forage sorghum, planted after the winter annual forage legumes in combination with nitrogen application and to validate the performance of the APSIM-grain sorghum crop model in simulating forage sorghum growth and biomass production under different N rates. The treatments were planting date (January and February) and N source from inorganic N fertilizer (0 kg N ha$^{-1,}$ 60 kg N ha$^{-1,}$ 120 kg N ha^{-1}, 180 kg N ha^{-1}) and forage legume N residues (Alex, Capello, Dr Baumans, Elite, Hanka, Laser, Linkarus, Opolska, Resal and Timok) arranged in a randomized complete block design with four replicates. The findings of this study showed a significant response of forage sorghum growth and nutritive value to planting date. Delayed planting reduced plant height (11%), stem diameter (18%), LAI (6.7%), chlorophyll content (18%), NDVI (2.5%), photosynthetic rate (38%) and biomass production (8%). Delayed planting further reduced crude protein, acid detergent fiber and N yield. Nitrogen source from inorganic N at 60 kg N ha$^{-1,}$ 120 kg N ha^{-1}, 180 kg N ha^{-1} and residual N from annual clover and vetch cultivars had a significant effect on morphological, physiological, yield and nutritive value parameters of forage sorghum.

Generally, legume N residue effects on all the studied parameters of forage sorghum were similar to the inorganic N fertilizer of 60 kg N ha^{-1}. However, the effects differed widely according to the species and cultivar of the legume. Resal, Laser, Elite Capello and Dr Baumans N residue consistently showed greater effects than other legume residues. They consistently outperformed inorganic 60 kg N ha^{-1} on the most measured parameters. The results confirm that annual clover-forage sorghum and vetch-forage sorghum rotation have huge potential to reduce the cost and negative environmental effects associated with inorganic N use in forage prediction systems. Regarding the evaluation of the potential of the APSIM grain legume model to simulate forage legume DM and plant height, in general, the model performed well and accurately in predicting the shoot dry matter accumulation and plant height under 0 kg N ha^{-1}, 60 kg N ha^{-1} and 120 kg N ha^{-1}. However, it underestimated both these parameters at 180 kg N ha^{-1} implying that the application of N up to 180 kg N ha^{-1} is not necessary. APSIM-grain module was able to accurately predict forage biomass production under N rates up to 120 kg N ha^{-1} and it is therefore considered reliable to support the N nutrition in the forage sorghum fodder production systems.

Keywords: adoption, clover, communal, feed gap, forage sorghum, on-farm forage legume, smallholder, sheep farmers, vetch, planting date

CHAPTER 1: GENERAL INTRODUCTION

1.1 Background of the study

The current global human population is 7.9 billion and this is predicted to reach 8.6 billion in 2030, 9.8 billion in 2050 and 11.2 billion in 2100 (United Nations, 2020). Consequently, the global demand for food, specifically animal protein in the form of meat and milk is expected to increase by 48% in 2050 (FAO, 2017; Delaby *et al*., 2020). Hence, the worldwide adoption of the United Nations 2030 Agenda for Sustainable Development in 2015. The agenda is meant to create a pathway to achieve zero hunger by 2030 through a renewed focus on agricultural development which increases agricultural productivity and incomes of small-scale food producers (United Nations, 2015). Subsequently, the South African response to attain sustainable food security is documented in the key strategic development plans, APAP (Agricultural Policy Action Plan 2015–2019) and the NDP (National Development Plan 2011) which have identified livestock farming as one of the strategies to alleviate rural poverty and improve food security in South Arica.

Livestock has evolved to form the foundation and backbone of human wellbeing, a significant component of the South African agricultural economy (Stroebel *et al*., 2011). Small ruminants such as sheep (*Ovis aries*) are a key resource of great benefit to society, with contributions that extend beyond direct food production to include multipurpose uses that include generating household cash income to improve the socio-economic status of farmers (Herrero *et al*., 2013). Furthermore, sheep are an essential component of heritage, tradition, and cultural festivities as well as religious celebrations (Mahlobo, 2016). Additionally, sheep are prolific animals that have enormous potential in extensive pastoral areas where no alternative farming ventures can be practiced, such as the extensive Karoo and semi-arid regions (Cloete *et al*., 2014). This is mainly due to their genetic (Molotsi *et al*., 2020) and ability to convert low-quality biomass into high-quality nutrient-dense foods (Smith *et al*., 2013a).

Despite the well-acknowledged socio-economic roles played by sheep and the existence of indigenous breeds like BaPedi, Dorper and Meatmaster, which possess adequate fitness traits (Molotsi *et al*., 2017) sheep productivity in Limpopo province is still low. As reported by DAFF (2021), the contribution of Limpopo province to the national sheep industry remains minor, at 1%, indicating that the economic benefits of sheep farming in the province are not yet exploited. A larger population of sheep in the province is in the hands of communal and smallholder farming systems, where sheep are reared under sub-optimal conditions. However, in this system, record keeping is less to non-existing and as a result, it can subjectively be speculated that the sheep population in the communal and smallholder farming systems is under-recorded in the national population. Hence the province reflects its low contribution to the national sheep industry.

Smallholder and communal sheep farmers are faced with a myriad of constraints that limit their capacity to realize the full benefit of their farming and generate adequate income. Studies conducted by Mapiliyao *et al*. (2012); Kom (2016); Mthi *et al*. (2017); Fourie *et al*. (2018); Sankatane (2018) on sheep farming in South Africa have identified several production constraints related to sheep nutrition, health, infrastructure, market, access to extension services and lack of knowledge, particularly on sheep husbandry and improved production practices within the communal and smallholder production systems. Regarding animal nutrition, the fundamental findings from these studies are that the seasonal fluctuations of feed availability in quality and quantity create feed gaps within various sheep production systems.

Fodder flow planning is a key factor in any livestock system, yet this aspect of management is often neglected. Fodder shortages during winter and early spring months are the key constraints to improved sheep production in the summer rainfall areas of Limpopo province (Lamega *et al*., 2021). Small ruminants in communal systems are more vulnerable to feed gaps as they are reared by poor, unprivileged, marginal farmers under an extensive production system (Rust, 2013; Kom, 2016). Different strategies should, therefore, be pursued to rectify the feed gap and address the fodder flow constraints experienced by the communal and smallholder sheep farmers.

The use of improved forage grasses and legumes to develop farm fodder flow plans within the sheep feeding systems is one strategy that has gained traction in recent years (Mengistu *et al*., 2017). Farm fodder flow plans which integrate summer forage grasses like forage sorghum and winter annual legumes such as annual clovers and vetches applicable to specific farming conditions under a grass-crop rotation system can reap a wide range of benefits associated with climate-smart agriculture (Truter *et al*., 2015). The benefits of such a production system include increased productivity, enhanced resilience and reduced greenhouse gas emissions (GHG). Forage sorghum produces high dry matter production however, they are low in protein content, and hence often considered a medium to low-quality forage source. On the other hand, legumes such as annual clover and vetch crops provide low to average quantities of high-quality fodder (Dickinson *et al*., 2010; Zhang *et al*., 2015). Therefore integration of these forage crops can achieve increased productivity and fulfill the biomass and nutritive value requirements of sheep and undoubtedly an enhanced resilience to feed gap. Well-fed sheep will reduce GHG emissions (Rojas-Downing *et al*., 2017). Farm fodder flow plans with forage sorghum-annual clover/vetch rotations have the potential to further ensure that fodder banks are initiated through the storage of hay and/or other forages during a season of plenty for utilization during the dry seasons (Kulkarni *et al*., 2018).

Additional benefits of integration of forage sorghum and annual clovers and vetches in sheep farming have many soil conservation advantages which include improving physical, chemical, hydrological and biological properties of the soil conservation besides their primary use as high-quality forage crops. The growing need to consider these fodder strategies and other management changes within the communal and smallholder sheep farming system can accelerate efforts aimed at ensuring greater resilience, adaptability and flexibility for the communal and smallholder sheep farming sector in the Limpopo province.

1.2 Problem statement

Poor animal nutrition due to the lack of adequate quantity and quality forage is the weakest link in the management practices of sheep production in semiarid regions such as Limpopo province, contributing more than 75% of the total variable costs of production (Mudzengi *et al*., 2020). Rangelands play an important role as the cheapest feed resource for livestock in smallholder and communal sheep systems

(Mapiliyao *et al*., 2012; Herrero *et al*., 2013; Tahir *et al*., 2018). However, the natural seasonal fluctuations of feed availability in quality and quantity from this feed resource tend to negatively impact the productivity of sheep if not well understood and planned by farmers. This is so mainly because naturally, grasses in the tropical semi-arid regions are more succulent, highly nutritious and more abundant in the rainy season (October- May) as opposed to the dry season (around June - September). During the dry season, grasses become fibrous and devoid of most essential nutrients such as protein, energy, minerals and vitamins required for optimum rumen microbial fermentation in animals, which limits intake, digestibility and utilization, a situation most common in the smallholder systems where grazing land is a sole source of feed (Kidake *et al.,* 2016). Additionally, during the wet season, the crude protein of the grasses ranges from 8 - 10% and declines to 2 - 4% during the dry season (Tainton, 2000). Consequently, animals are underfed, suffer severe nutritional stress and decreased productivity (Lamidi and Ologbose, 2014) during the dry season. For sheep to express and reach their production potential, the available feed resources must match their roughage and nutrient demands throughout their different production cycle each year.

The majority of communal farmers are landless and rely on communal rangelands for grazing their sheep. However, there has been great concern about the sustainability of communal rangelands (FAO, 2020). Over the years, the utilization and pressure on rangelands have increased to the extent that both rangelands and livestock productivity have been gradually compromised. In semi-arid savanna areas, rangeland degradation has worsened and the loss of palatable, perennial and highly productive grasses is evident (Palmer and Bennett, 2013). One of the driving factors of degradation in communal rangelands as observed by Vetter (2013) is that many of these rangelands are considered overstocked and overgrazed, hence degraded and unproductive. This is being exacerbated by the seasonal and inter-annual climate variability leading to low and erratic rainfall (Meissner *et al*., 2013).

Additionally, Munyai (2012) reported that diminishing rangelands due to changes in land use from grazing to settlement and industrialization have a negative impact on the rangelands' grazing potential. Furthermore, Mndela *et al*. (2022) found that bush thickening has increased vigorously, leading to the decline in rangeland grazing potential, owing to the reduction in forage production. Consequently, the rangelands are constrained to deliver a key ecosystem service of providing sufficient and high-quality forage for the whole year (Linstädter *et al*., 2016; Lamega *et al*., 2021). According to Mapiliyao *et al*., (2012) in South Africa and Hailemariam *et al*. (2013) in Ethiopia, the marked effects of feed shortages during the long dry season are animal weight losses, mortality and largely low sheep production.

Sustainable sheep production depends on the supply of good quality and quantity fodder all year round (Havlík *et al*., 2013). Currently, Lucerne (*Medicago sativa*) is the major winter forage legume grown in the Limpopo region and contributes a large proportion to all fodder used by livestock producers (Truter and Dannhauser, 2011). In recent years, with the transformation and development of the livestock industry, the demand for forage with high yield and quality has increased year by year, which has led to Lucerne production alone being insufficient to consistently support the pressure of the expanding livestock industry. This is exacerbated by the fact that livestock farmers of this region typically lack a variety of adapted forage species to diversify their forage production. Hence, they depend on a narrow range of forage crops such as Lucerne.

Vicia dasycarpa (annual grazing vetch), *Vicia sativa* (common vetch), *Trifolium alexandrinum* (Berseem or Egyptian clover), *Trifolium incarnatum* (Crimson clover) and *Trifolium resupinatum* (Persian clover) are forage legumes with great potential to produce adequate forage of high quality during the winter season (Getnet and Ledin, 2001; Huang *et al*., 2017). A large number of these winter annual forage legumes are used in South Africa mostly as cover crops but less as forage crops. Literature on their production potential in semi-arid conditions is limited and outdated. Declining soil fertility and limited farmer access to inorganic fertilizer frequently cause sub-optimal crop yields throughout sub-Saharan Africa (Tonitto and Ricker-Gilbert, 2016). These forage legumes can improve soil fertility through the biological nitrogen fixation processes. Following the worst drought in 2015, a research letter on the reality of drought, consequences and mitigation strategies for livestock production in South Africa emphasized forage sorghum (*Sorghum bicolor* (L.) Moench) as one of the alternative, more drought resistant crop which can provide forage, fodder and grain sources for basal livestock feeding (Scholtz *et al*., 2016). Forage sorghum is one of the most popular annual summer forage crops which produces large biomass under a wide range of soil and seasonal conditions. These forage crops are multipurpose crops that can be used for grazing, hay, silage, foggage, and soil improvement, hence they are extremely important to bridge the winter feed gap (Truter and Dannhauser, 2011).

1.3 Rationale

A notable feature of climate change is global warming, which is the rise in global temperature due to the generation and accumulation of greenhouse gases (IPCC, 2014). Thornton and Herrero (2014) highlighted that climate change is expected to have several impacts on fodder crops through changes in pasture growth, productivity and forage quality. According to the IPCC report in 2018, the global average temperature over the last 5 years (2014–2018) has increased by 1.04°C compared to the preindustrial baseline and will reach 1.5°C by 2030 (IPCC, 2018). On the contrary, cool-season pasture crops require a low temperature of 10 °C for optimum growth and development (Dickinson *et al*., 2010). Widespread changes in rainfall and temperature patterns threaten agricultural production and increase the vulnerability of the people who depend on agriculture for their livelihoods.

Temperature is one of the most variable environmental factors that is linked to climate change. Temperature affects most plant physiological processes, including photosynthesis and transpiration. Heat stress due to high ambient temperatures is a serious threat to crop production worldwide amid climate change. Temperatures are expected to increase in West, East and Southern Africa, with multimodel climate projections indicating a warming of 1°C to 4°C in the decades of 2081–2100 relative to 1986–2005 depending on the representative concentration pathway (RCP) considered (IPCC, 2013). Warmer temperatures in winter season as a result of climate change thus, threatening the reliability of traditional planting dates for winter pastures (Raza *et al*., 2019).

Planting date is an agronomic tool that the farmers can use to manipulate the effects of temperature on the crops. In the study conducted in Beltsville, northeastern United States, delaying planting by two to three weeks reduced vetch biomass by 43% when harvested at vegetative stage and by 20% when harvested at flowering

(Teasdale *et al*., 2004). Virendra *et al*. (2000) and Gul *et al*. (2011) concluded that delaying the planting date of annual clovers by six weeks decreased fresh and dry forage yield but increased the seed yield in India and Pakistan respectively. These studies in pasture crops generally reported biomass production and morphological parameters such as plant height, leaf width and length and the number of branches. Information on physiological parameters or processes driving the growth and development of biomass is however limited. From the literature, there are knowledge gaps regarding how the variability in agrometeorological factors during the growing season influences pasture growth, physiology and nutritive value of annual *Vicia* and *Trifolium* cultivars for fodder production. This makes it extremely difficult to make recommendations to farmers based on international literature. Quantifying the effect of planting date on physiological processes associated with biomass accumulation such as stomatal conductance, carbon dioxide (CO_2) assimilation, photosynthetic rate, transpiration rate, water use efficiency (WUE) and biological nitrogen fixation (BNF) during different plant developmental stages is critical. Furthermore for identification of specific cultivar traits required for future plant breeding programs to develop novel pasture cultivars that will thrive and yield high-quality biomass under rising temperatures driven by climate change is important.

Similar to all legumes, winter annual *Vicia* and *Trifolium* species are agronomically beneficial because they can fix atmospheric nitrogen (N_2) through a symbiotic relationship with the rhizobium, contribute nitrogen (N) to succeeding crops in rotation systems (Zhang *et al*., 2004; Stagnari *et al*., 2017), and reduces the amount of synthetic nitrogen fertilizer needed. There is little knowledge available regarding their ecosystem services on short-term rotations with forage sorghum. Nitrogen (N) is one of the most limiting crop nutrients, and to produce the required protein sources from crops, large inputs of N are required. Based on this concept, farmers tend to manipulate the growth of forage sorghum using N fertilization, a practice that could have serious environmental and economic consequences.

Over fertilization with nitrogen fertilizers is often harmful as it can result in lower yields (Phohlo *et al*, 2022). Furthermore, excess input of N fertilizers also results in severe environmental pollution, climate change and biodiversity loss. There is no literature on the use of crop simulation models to predict crop N thresholds under various environmental and climatic conditions. Assessing the forage sorghum N thresholds by measuring crop response growth parameters such as biomass production, leaf area index and plant height under climate change is required. To achieve this through agronomic field experimentations is time consuming and requires considerable space and funding resources (Ojeda *et al*., 2018). Crop simulation models such as the Agricultural Production System Simulator Model (APSIM) are key tools in extrapolating the impact of climate change and crop N nutrition management from limited experimental evidence to broader soil types, crop management regimens and climate change scenarios (Rauff and Bello, 2015).

1.4 Aim of the study

The study aimed to increase the utilization of winter annual vetch and clover cultivars as well as forage sorghum to alleviate winter forage shortfalls for sheep production in different climatic zones of the Limpopo Province.

1.5 Objectives

The objectives of the study are to:

i. Assess the factors affecting the adoption of winter annual forage legumes by sheep farmers in addressing winter forage gaps in the Limpopo Province and investigate the question “Does production practices of communal and smallholder sheep farmers of Limpopo Province contribute to feed gaps”?
ii. Measure the leaf gaseous exchange, biomass production, biological nitrogen fixation and nutritive value of no-till winter annual vetch and clover cultivars under different planting dates for climate change adaptation.
iii. Determine the growth and nutritive value of forage sorghum, planted after the winter annual forage legumes in combination with nitrogen application in a short-term rotation and validation of forage sorghum growth with APSIM.

1.6 Hypotheses

The hypotheses of the study are:

i. Sheep farmers in the Limpopo Province have not adopted winter annual forage legumes to address winter forage gaps.

ii. Planting date does not affect the leaf gaseous exchange, biomass production, biological nitrogen fixation and nutritive value of no-till winter annual vetch and clover cultivars.
iii. The growth and nutritive value of forage sorghum are not influenced by preceding winter annual vetch and clover cultivars and nitrogen application in a short-term rotation. Experimental results on the performance of no-till forage sorghum under different planting dates and N levels will not differ from the APSIM simulation result.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews existing literature on sheep production, winter feed gap challenges in sheep production, planting date effects on annual clover, vetch and forage sorghum growth, physiology, productivity and nutritive value. In addition, the review covers nitrogen levels and residual N effects on forage sorghum productivity, forage sorghum N-nutrition simulations using APSIM.

2.2 Background on sheep production in Limpopo province

Trends in the Agricultural Sector 2019 report, indicated that the total number of sheep in South Africa was estimated to be 22, 06 million, with Limpopo province contributing about 203 thousand (DAFF, 2019). According to the 2019 Abstract of Agricultural Statistics, South Africa is an importer of sheep and sheep products, implying that domestic land and mutton consumption exceeds domestic production (DAFF, 2019). It also revealed that the lamb and mutton supply has been unable to positively respond to improving market conditions. Demand for livestock products including lamb and mutton is expected to rise in developing countries as populations and income levels rise, creating a once-in-a-lifetime opportunity for sheep farmers to expand production systems (Nyam *et al*., 2020). Increased lamb and mutton production to first meet domestic demand could stimulate economic growth and development, ultimately reducing poverty, if the sheep production sector can realize its full production growth potential.

When compared to other provinces, Limpopo province contributes about 1% to national sheep statistics (DAFF, 2019), yet it is home to breeds such as BaPedi sheep. Furthermore, the province's climatic, physiographic and vegetation type-related conditions allow for the housing of other indigenous meat breeds like Doper, Damara, Van Rooy, Black-headed Persian sheep and Meatmaster which are generally well adapted to extensive rangeland-grazing farming systems (Cloete *et al*., 2014). Despite the existence of all these adapted breeds, Limpopo province has not realized the full benefits from the sheep production sector due to low animal productivity which is attributed to many constraints.

The sheep industry in the province is fragmented into commercial, smallholder and communal sectors based on the capital investment, land tenure, level of management level of technology and production orientation used in sheep production (Aliber *et al.,* 2013; Gwiriri *et al*., 2019). The industry is dominated by commercial sheep farmers who own more than two-thirds of the sheep in the province and supply meat products locally and nationally. In contrast to the smallholder and communal farmers, commercial production is generally intensive and mainly based on the use of concentrate feeds and improved forage technologies. Commercial farms are inclusive of farms that have relatively high turnovers and use modern production techniques that are capital intensive and have links with key input and output markets (Karaan and Vink, 2014).

The smallholder sheep farmers are described by Cousins (2010) and Jayne *et al*. (2015) as emergent farmers or medium–scale holders of between 5 and 100 hectares either as cooperatives or individually, many of whom supply agricultural products for sale through informal and formal markets and for subsistence. In this system, smallholder farmers continue to be constrained by the inability to enter competitive markets due to low yields, lack of knowledge, lack of appropriate technology and inherent market risks as a result of ineffective institutional and market linkages (Aliber *et al*., 2010; Khapayi and Celliers, 2016).

Sheep farming in the communal sector is mostly subsistence in nature and sells live animals at the farm gate and is characterized by a low-input and low-output system with wide social dimensions impacting positively or negatively on productivity (Molotsi *et al*., 2019). The communal system involves the grazing of sheep owned by different households on the same piece of rangelands owned by the chief. Communal farmers are overwhelmingly dependent on agriculture which has shown little productivity improvement until the last century (Mthi *et al*., 2017).

2.3 The role and constraints of communal and smallholder sheep production

The South African government, through the livestock development policy, has acknowledged that livestock has huge potential to end poverty and food insecurity in the country by increasing the productivity of smallholder livestock farmers. Expansion of the livestock industry will result in more jobs, higher incomes, and socioeconomic development in the country, particularly in rural areas where livestock production predominates (DAFF, 2019).

Small-ruminant production is one of the largest agricultural sub-sector in South Africa, contributing approximately 25 to 30% of the total agricultural output per annum (DAFF, 2019). Sheep are one of the most valuable small ruminants in Sub-Saharan Africa (SSA) (Oluwatayo and Oluwatayo, 2012). Many studies have been conducted to examine the roles of sheep activities in the rural household economy of South Africa in terms of their contribution to poverty and vulnerability reduction towards livelihood improvement (Molotsi *et al*., 2017; Nyam *et al*., 2020). Sheep, according to these studies, contribute to household food and nutrition security as a source of animal protein in a form of meat and milk (Kosgey *et al*., 2008). Sheep production is a significant financial instrument as a source of income. They are also kept as a form of capital, providing farmers with savings, insurance and investment opportunities to build wealth (Abebe *et al*., 2020). Furthermore, according to these studies, sheep provide financial security and assist smallholder farmers in financing planned and unplanned expenditures, a buffer against non-remunerative crop prices or poor harvest and a source of employment all along the sheep value chain.

Similar economic and food security roles were observed by other researchers in SSA. For instance, according to Assefa *et al.* (2015) in Southern Ethiopia; Adams *et al*. (2021) in Ghana; Lukuyu *et al*., (2021) in Uganda sheep provide their owners with a vast range of products and services such as meat, milk, skin, wool, mohair and manure for food security and cash income. As noted by Legese *et al*. (2014) and Alary *et al*. (2015) sheep production enables farmers to meet a variety of social and cultural obligations, serving as gifts and exchanges for marriage and other cultural and religious ceremonies.

Bettencourt *et al*. (2013) and Hatab *et al*. (2019), gave evidence of the multiple roles of sheep also in terms of services and inputs supplied to the agricultural sector including manure for crop production and agricultural diversification. Furthermore, they contribute to the development of areas where others activities are not possible. According to Smith *et al*. (2013), overall sheep production is a financial instrument with great potential to reduce household food insecurity both directly and indirectly providing a credible path out of poverty.

Despite its potential importance to sustainable economic growth and poverty reduction, the development of the sheep sector has received little attention from various stakeholders and the government in recent years. As a result, it is confronted by a myriad of constraints. Constraints to small ruminant productivity included low levels of management, disease and parasite challenges, inadequate feed and poor marketing (Paul *et al*., 2020). Scarcity of quantity and quality feed has been a key constraint to productivity of smallholder crop-livestock systems in SSA (Ayele *et al*. 2012).

Rangeland degradation, loss of diversity and productivity are some of the biggest challenges that livestock farmers/pastoralists face today, which will be aggravated by climate change. Despite growing urgency to reconcile food production and environmental protection, land-use change from grazing to settlement and industrialization remains a major global problem, being one of the leading causes of shortage of herbage. Mthi and Nyangiwe (2018) highlighted that the most important challenges of sheep production perceived by the farmers were disease and parasites, shortage of feed, lack of infrastructure, organized market access, lack of water availability and high cost of drugs/vaccines and stock theft. Furthermore, as with any other livestock production in Sub-Saharan Africa, sheep face shrinking rangeland sizes and poor quality feed from natural pastures and crop residues (Mupangwa and Thierfelder, 2014).

2.4 Winter forage gap

Fodder is a critical component in giving adequate nutrition to animals. However, it seems challenging to supply high-quality fodder in adequate amounts throughout the year in tropical areas such as South Africa. Fodder deficiency during the dry season diminishes livestock productivity potential in Sub-Saharan Africa’s (SSA) arid and semi-arid regions (Mpanza *et al*., 2020). Lack of adequate winter feed is probably the most important production constraint to high animal production in arid and semiarid regions in the world. It is critical to feed the right feed at the right time in a sheep's development. The reproductive ewe has the most variable feed requirements of any sheep class, and meeting her nutritional needs will have the greatest impact on profitable production. Loss of body weight during the dry season is used as an unequivocal indicator of a feed constraint (Ben Salem, 2010).

According to Gizaw *et al*. (2010) ruminant animals in the smallholder farming sector depend on natural pastures and crop residues for the greater part of the year. During the dry season, the natural pastures and crop residues available for animals after crop harvest are usually fibrous and devoid of most essential nutrients including proteins, energy, minerals and vitamins which are required for increased rumen microbial fermentation and improved performance of the host animal (Munyai, 2012).

Feed affects sheep welfare and productivity, profitability, human food and nutrition security, and has an environmental impact due to greenhouse gas (GHG) emissions from animals (Makkar, 2016a). Hence, there is a demand to improve feed quality and nutritive value by enhancing the availability of nutrients (e.g. proteins, oils, starch, amino acids and vitamins). A lack of adequate quality fodder is caused by several constraints, including small land holdings, limited knowledge and skills, a lack of seeds and planting materials and poor forage targeting (Mwendia *et al.*, 2017).

Irrigated pastures are used with great success by dairy farmers (Truter and Dannhauser, 2011) and lately, by sheep farmers in parts of South Africa, ensuring better availability of quality fodder. Huang *et al*. (2017) highlighted that legumes such as vetches have the potential to contribute significantly to the sustainable intensification of livestock production in the tropics, along with the provision of ecosystem services. Extensive evaluation of winter annual legume crops by Lamei *et al.* (2012), resulted in the recognition of vetch as the potential crop to provide greater biomass and nutritive value to livestock from May to July, a forage deficit period in the cold region of Iran.

2.5 Diversifying the forage resources for fodder flow planning

Diversifying the feed base to include combinations of forage sources provides the capacity to increase the stocking rate significantly at the same time as reducing or maintaining the risk of feed gaps occurring on mixed farms (Bell *et al*., 2018). This demonstrates that there is significant potential to build forage-based feed systems that overcome critical feed gap periods and their-by mitigate the risks of increasing farm stocking rates required to improve the total productivity of livestock systems. Maponya and Mpandeli (2012) highlighted that crop diversification forms part of the risk aversion strategy to deal with extreme climatic events, high climate variability and change.

2.6 Characteristics of annual vetch, clover and forage sorghum

Winter annual clover and vetch species are Mediterranean annual forage legumes that are more commonly utilized in agronomy as cover crops than forage crops for animal feeding in South Africa. They have a wide range of significance, which includes nutritional benefits to livestock feeding systems owing to their high protein content (Leitão *et al*., 2021). Additionally, rapid growth and minimal fertilizer requirements are two of their unique agronomic qualities, enabling them to play an important role in sustainable fodder production systems (Stagnari *et al*., 2017).

Vicia dasycarpa (Grazing vetch) and *Vicia sativa* (Common vetch) are hard-seeded trailing/ climbing herbaceous legumes originating from the Mediterranean areas of southern Europe (Huang *et al*., 2017). The leaves are compound, made of several (10 to 16) pairs of leaflets and have blue to purple flowers. They are commonly used as cover crops and green manure or for fodder (Getnet and Ledin, 2001).

Trifolium alexandrinum (Berseem or Egyptian clover), *Trifolium incarnatum* (Crimson clover) and *Trifolium resupinatum* (Persian clover) belong to the family "Papillionaceae (Leguminoseae)" and genus "Trifolium". These clovers are annual, soft seeded, cool-season, erect forage crops. (Mahar *et al*., 2017). The leaves are trifoliate with broad and cordate leaflets. It is generally believed among scientists that they originated in the Mediterranean region. They are commonly used as cover crops and fodder crops. They can be fed either as green forage or in hay form during winter months. When seasonal conditions permit, they have the advantage of multiple (4 to 5) harvests during a growing season of 4 to 5 months (depending on day temperature) (Gul *et al*., 2011).

Forage sorghum (*Sorghum bicolor* (L.) Moench) is an annual, warm-season forage crop following a C_4 photosynthetic pathway (Jirim *et al*., 2013). Desirable traits of forage sorghum include its adaptation to harsh environments with limited rainfall, high temperatures and low soil fertility (Afzal *et al*., 2012), high water and nutrient use efficiency and high biomass production potential (Bollam *et al*., 2021), which makes it an important livestock feed in several arid and semi-arid climatic regions (Deep *et al*., 2019). Farmers in semi-arid areas with extremely high summer temperatures, low and highly irregular rainfall conditions can consider forage sorghum as drought, heat and flooding tolerant crops with sustained crop yields. It is adapted to marginal systems (low soil fertility, low use of fertilizers) are advised to shift to sorghum as yield declines are moderated under low fertility.

2.7 Adoption of on-farm fodder production

Improved forages provide several benefits which include social benefits by improving the welfare of individuals, households, communities, and entire countries. They can generate a variety of economic benefits, including improved soil quality, increased water infiltration, and lower fertilizer requirements. (Ayarza *et al*., 2007). Improved livestock feeding and forages have previously been highlighted as a triple-win strategy toward achieving climate-smart agriculture (CSA), increasing food security and resilience, and decreasing GHG emission intensities (Thorntorn *et al*., 2018). The adoption of introduced forages in tropical developing countries has been limited due to a lack of evidence of economic profitability or inadequate technical support, such as seed availability (Reddy *et al*., 2003).

Poor rates of adoption of improved forage technologies have been reported in most parts of Sub-Saharan Africa (SSA) where they were introduced in Malawi (Ngwira, 2003); Ethiopia (Gebremedhin *et al*., 2003); Central Kenya (Mwangi and Wambugu, 2007); Zimbabwe (Mapiye *et al*., 2006) and in Tanzania (Ndah *et al*., 2017). If agricultural technologies developed by research for improving the livelihoods of farmers are not appropriately adopted, the efforts by researchers/developers would have been in vain. The question is why forage technologies, which have the potential to greatly improve livestock productivity and even the livelihoods of farmers, do not seem to be meeting the targeted responses?

Forages can allow higher land and animal productivity, resulting in a shift from subsistence orientation to market orientation. Traditional livestock products may give way to new value chains for special market niches, such as the sale of fresh forage in Thailand (Nakamanee *et al*., 2008) and pasture seed (Pizarro and Sauma, 2007). In general, the characteristics of the proposed technology, farmers' perceptions of its benefits and need, as well as the availability and distribution of production factors (e.g. land, labor/time, capital, knowledge, skills, etc.) all influence adoption of resource conservation technologies. Farmers' attitudes toward experiments and risk, institutional support/knowledge sharing and the policy environment are also important factors (Senyolo *et al*., 2021).

2.8 Climate change impacts on fodder production

Climate change is a worldwide phenomenon characterized by changes in average atmospheric carbon dioxide (CO_2) concentration, ambient temperature, rainfall intensity and patterns, winds, and solar radiation (IPCC, 2018). It poses a significant threat to agricultural production and is expected to have a regionally environmental-specific impact on the rangelands and forage crops consumed by ruminants. In the tropical and subtropical regions both elevated temperatures and decreased rainfall appear to be more likely to result in lower forage quantity in the future (Henry, 2018), restraining their potential to support sustainable livestock production. The potential impacts of climate change on livestock include changes in production and quality of feed crops and forages (Chapman *et al*., 2012; Polley *et al*., 2013).

Forage quantity and quality are affected by a combination, of elevated atmospheric carbon dioxide (CO_2), precipitation variability and increases in temperature (Thornton and Herrero, 2014). According to the report by Renta *et al*. (2022), since 2000, the global atmospheric carbon dioxide amount has risen by 43.5 parts per million (ppm), an increase of 12 percent and setting a record of 412.5 ppm in 2020. Effects of increased CO_2 on crop yield, biomass and photosynthesis have been demonstrated in many studies using growth chambers, and a review by Long *et al.* (2006) indicates that yield increases for several C_3 crops may be in the order of 20 to 30% at elevated CO_2 concentrations of 550 ppm. The increased atmospheric CO_2 concentration is known to partially lead to the closure of stomata, which reduces water loss by transpiration and thus improves water-use efficiency. All other things being equal, this leads to improved crop yield, even in conditions of mild water stress. The effect is much larger in C_3 plants than in C_4, but there is also a small effect on C_4 plants. Legume pasture growth may be enhanced by increasing CO_2 concentrations but limited by factors such as increases in temperature and precipitation changes. However, this positive impact can be offset by the effects of rainfall variability and increasing temperatures.

Rainfall variability in intensity and season is another aspect that is highly influenced by climate change. Changing seasonality of precipitation may result in excess water during off-seasons and limited water during critical crop growth periods. The most significant rainfall reductions, more than 40 mm/ annum are predicted for the eastern parts of Limpopo and Mpumalanga, the south-western Cape and the Cape south coast. (Meissner *et al*., 2013). Adapting to climate change is of paramount importance to an agricultural food production system.

Furthermore, Southern Africa is predicted to become drier and the average temperature may rise by 1.5ºC to 2ºC (IPCC, 2014). The effects on seasons of a changing climate are already being seen across the country and vary from region to region: temperatures have risen across seasons, growing seasons for summer crops have become longer and as temperatures rise, evapotranspiration and the need for irrigation increase. At the same time, rising temperatures can shorten the growing season and increase the number of irrigation days (Yoon and Choi, 2020). Hence the proper application of agronomic management practices is essential in managing the effects of climate change on forage crops.

2.9 Importance of crop rotation and no-tillage practices

Conservation agriculture (CA) systems are based on minimal soil disturbance, crop residue retention and crop rotation (Janh *et al*., 2020). Crop rotation can be considered the best strategy for yield improvement, but it requires increased expertise and different management practices (Jiang et al., 2011.) Under crop rotation systems, various agronomic management practices can be employed for improving the yield and quality of different forage crops. These include crop husbandry factors (e.g. seeding rate, spacing/plant density, time of planting, fertilizer application). These management practices have the potential to mitigate stress factors (abiotic: drought, salinity, temperature, day length; and biotic: diseases and pests).

It is critical to improve and maintain soil quality in terms of ecosystem functions supported by microbial activity in order to restore soil productivity and achieve sustainable production systems. No-tillage cultivation has been one of the most successful and widely used practices for restoring degraded agricultural soils (Frasier et al., 2016). Furthermore, no-tillage has proven to have a significant ecological, economic, environmental, and social benefits when compared to the conventional system, especially when used in conjunction with crop rotation, which is considered an important form of management of soil fertility (Pissinati *et al*., 2016).

2.10 Planting date effects on physiological response and biomass production of winter annual vetch, clover and forage sorghum *(Climate change adaptation strategy)*

Planting date is an important management practice used to adjust the timing and occurrence of crop phenological phases according to environmental conditions for crop development (Dickinson *et al.*, 2010). Managing the planting date influences crop growth and development as well as the interaction between growth and development and stressful periods (Reddy *et al.,* 2003). Furthermore, it can be manipulated for high crop growth and maximum productivity and for ensuring the seasonal distribution of forage availability.

In the study conducted at Beltsville, North-eastern United States, delaying planting by two to three weeks reduced vetch biomass by 43% when harvested at vegetative stage and by 20% when harvested at flowering (Teasdale *et al*., 2004). In Pakistan Peshwar Valley, maximum fresh forage yield on Berseem clover (18400 kg ha^{-1}) was recorded from planting in late autumn, followed by early winter (16083 kg ha^{-1}), while minimum fresh forage yield (7417 kg ha^{-1}) was recorded from mid-winter planting (Subhan *et al.,* 2015). Virendra *et al*. (2000) and Gul *et al*. (2011) concluded that delaying the planting date of annual clovers by six weeks decreased fresh and dry forage yield but increased the seed yield. Early planting may produce high yields and more harvests than late planting. Quantifying the effects of planting date on forage production is critical for farmers to make planting decisions that maximize crop growth and quality.

2.11 Nitrogen nutrition in forage sorghum

Nitrogen assumes greater importance in improving the yield and quality of fodder. In sorghum, nitrogen (N) application increased CP, ash, content but decreased CF and non-structural carbohydrate content (Mohamed and Hamd, 1988). Previous research has shown that the application of N up to 120 kg ha^{-1} increased the green forage, dry matter and CP contents and decreased NDF contents (Chakravarthi *et al*., 2017). While application of N at the rate of 100–120 kg ha^{-1} was suggested as optimum in sorghum (Reddy *et al*., 2003). Mahama *et al*. 2014 found that soil N deficits result in lower sorghum biomass due to reductions in leaf area, chlorophyll index, and photosynthetic rate.

2.12 Use of annual winter vetch and clover in short-term rotation

Nitrogen fertilizer is an expensive but essential input for optimum production of non-leguminous crops. Legume cover crops provide important ecosystem services as they can fix atmospheric nitrogen (N_2) and build soil N, increasing the productivity and yield of subsequent crops while reducing the need for inorganic N fertilizer (Dabney *et al*., 2010; McCartney and Fraser, 2010). Strauss and Hardy, (2014) stated that nitrogen production from annual legumes ranges from 45 to 220 kg N ha^{-1}. According to Seo *et al*. (2000), hairy vetch (*Vicia villosa* Roth.) supplied 50-155 kg of N ha^{-1} to a subsequent maize crop. Findlay and Manson (2011) also concluded that annual clovers can contribute to the soil organic matter and provide 40 to 100 kg N ha^{-1} to the soil profile, up to 40% of which is available to the subsequent crop. Frame (1992) reported that unfertilized grass following clover pastures was able to produce 6 to 9 t DM ha^{-1} while grass monoculture swards could only produce 2 to 5 t DM ha^{-1} under the same conditions. The portion of N available to a subsequent crop is usually about 40 to 60% of the total amount contained in the legume. Nitrogen fixed by a legume crop is dependent upon legume type and variety, rhizobium strain (introduced and indigenous populations), soil fertility and rainfall. In turn, the N contribution of legumes to a subsequent crop will depend upon the legume's growth habit, yield, N partitioning patterns and the efficiency of N_2 fixation (effective nodulation) and residue management (Lupwayi *et al.*, 2011).

2.13 Nutritive value of annual winter vetch, clover and forage sorghum

Getnet and Ledin (2001) indicated that the fresh Vetch forage at early flowering is quite high in protein, 18 to 29% on a dry matter basis with a moderate to high fiber content and Acid Detergent Fibre (ADF) of 25 to 32%. Organic matter digestibility in sheep can reach 74%. The nutritive value of Vetch shows a progressive decrease in digestibility and degradability as its vegetative structures mature but digestibility remains relatively high (69%) and a crude protein content close to 20% on a dry matter basis at the mature seed stage (hay) (Tisserand *et al*., 1989).

Annual winter clovers are nutritious forage, high in protein, minerals and vitamin A. Pereira-Crespo *et al*. (2012) reported that annual winter clovers are high-quality forage, characterized by a high protein concentration of 16 to 24% at the leafy growth stage. Quality declines rapidly with maturity to 9 to 13% protein at late flowering. Clover hay has a good nutritive value, with a dry matter protein content of 17% and 39% neutral detergent fiber (Mahar *et al*., 2017).

2.14 APSIM

The Agricultural Production Systems Research Unit in Australia created the Agricultural Production Systems sIMulator (APSIM) model. Agricultural Production System Simulator Model (APSIM) is a modular framework composed of a set of biophysical modules that simulate physical and biological processes in farming systems, as well as a set of management modules that allow for the configuration of specific management rules by the user who characterizes a scenario being simulated and controls the response of the simulation (Holzworth *et al.*, 2014). It was developed in response to the need for crop production modeling tools that provided accurate predictions based on climate, genotype, soil and management factors, while also addressing long-term resource management issues in farming systems (Keating *et al*., 2003).

APSIM has been used in numerous studies to guide day-to-day decisions, such as investigating the effects of management options such as sowing time, plant population density, irrigation regime (timing, frequency), and fertilizer applications in different conditions on long-term mean yield and yield probability (Aramburu *et al*., 2015). Climate change variability, particularly weather extremes, is currently a great concern for both scientists and the general public, APSIM can be used to study the potential impact of climate change across continents (Pembleton *et al.* 2013). According to Chimonyo *et al*. (2016), multi-location studies are frequently required to develop appropriate recommendations across diverse agro-ecologies, but they are less desirable to implement due to the time, cost, and technical skills required to study spatial and temporal production using field experiments. As a result, crop models such as Agricultural Production Systems Simulator APSIM have been used as tools for generating useful data for assessing current and future productivity.

The APSIM model was evaluated and found to have a credible performance in predicting the development, growth, and yield of various crops such as sorghum, maize, and wheat (Wolday and Hruy, 2015). According to Pembleton *et al*. (2016), the APSIM model has been demonstrated to accurately represent the factors influencing forage crop growth and development in south-eastern Australian regions. The results of this indicated that the modeled response to elevated CO_2 of irrigated sorghum biomass was similar to that observed in experiments whereas the response of dryland forage sorghum was lower than the observations for this crop species but was within the range of observations for annual C_4 grasses. As a result, it can be used to make better decisions about genotype selection and management options for agricultural sustainability.

CHAPTER 3: FARMERS' PERCEPTION AND PRODUCTION PRACTICES IN MANAGING FEED GAPS IN LIMPOPO PROVINCE.

3.1 Production practices of communal and smallholder sheep farmers of Limpopo Province: Does it contribute to feed gaps?

3.1.1 ABSTRACT

Sheep (*Ovis aries*) rearing is a key enterprise of great benefit to society. The study sought to describe the demographic and socio-economic characteristics of communal and smallholder sheep farmers, identify sheep feeding practices, and describe the constraints that hinder the sustainable productive growth of communal and smallholder sheep systems. Data were collected from one hundred and twenty (120) sheep farmers using a structured questionnaire across three agro-ecological zones of Limpopo Province. The results revealed that overall, the majority of sheep farmers were males (78%) and farmers were above 60 years old (48%). Mean sheep flock size differed significantly between communal (24.74) and smallholder (62.36) farmers. Indigenous crossbreeds were the dominant breed kept by communal (86%) and smallholder (77%) farmers. The majority of the communal and smallholder farmers (90% and 96%, respectively) reared their sheep under an extensive system with rangelands as the main source of feed. As a result, they experience a critical feed gap between June and September, the late winter-early spring in Limpopo until the first rain. Feed shortages and diseases were ranked as the first and second production constraints by sheep farmers in both the production systems. This means that any measures designed to improve sheep productivity in the province should enhance the nutrition and health aspects of the production practices.

Keywords: Constraints, communal, feed gap, health, sheep farmers, smallholder.

3.1.2 INTRODUCTION

Livestock has evolved to form the foundation and backbone of human wellbeing, a significant feature of the South African agricultural landscape (Stroebel *et al*., 2011). Small ruminants such as sheep (*Ovis aries*) are a key resource of great benefit to society. Sheep raised by communal and smallholder farmers play a unique role in their lives since they provide a significant portion of household income and also contribute to food and nutrition security (Kosgey *et al.,* 2008; Herrero *et al.,* 2013), consequently poverty alleviation and improved socio-economic status (Alary *et al.,* 2015). Additionally, farmers use the sheep droppings as manure for their backyard gardens to increase crop yield. Furthermore, sheep are an essential component of heritage, tradition and cultural festivities as well as religious celebrations (Mahlobo, 2016).

Another important consideration cited by Hulelai (2020) is that sheep a small framed type of livestock, are docile and easier to handle as compared to goats and cattle, making it possible for the vulnerable groups of the society such as women and youth to actively participate in multifaceted activities of rearing and management. The involvement of women and youth is critical for inclusive rural economic growth and bridging gender-based economic disparities in communal areas. The livestock industry in South Africa contributes 34.1% to the total domestic agricultural production and provides 36% of the population’s protein needs (DAFF, 2019). Indeed sheep can generally be considered a key asset associated with the livelihoods of the society and local economic developments (Mapiliyao *et al*., 2012: Fourie *et al*., 2018).

An added positive aspect of sheep rearing is based on their genetic and adaptive traits. According to Rust and Rust (2013) and Berihulay *et al*. (2019), they have shorter production cycles, they are hardy, resilient and able to strive in diverse and often adverse climatic and environmental conditions. Sheep require a small space and fewer feed quantities, therefore they are efficient meat producers for the communal and smallholders in areas where farmers do not have adequate grazing lands (Taye *et al*., 2016). Most of the ecology in Limpopo Province of South Africa is semi-arid to arid (Cloete *et al*., 2014). The vegetation is classified as savanna rangelands, with diverse veld types producing vast herbaceous and woody species diversity (Mucina and Rutherford, 2006), making the province more suitable for game and livestock farming. Sheep like other ruminants can convert biomass from herbaceous and woody plants into high-quality nutrient-dense foods (Smith *et al*., 2013a).

Despite all the well-acknowledged socio-economic roles played by sheep and their adaptive capabilities, sheep productivity in Limpopo province is still low, making their economic contribution less significant than anticipated. As reported by DAFF (2019), the contribution of Limpopo province to the national sheep industry remains minor, at 1%. The point of departure is that, despite the existence of indigenous breeds like BaPedi, Doper, Damara, Van Rooy, Black-headed Persian sheep and Meatmaster, possess adequate fitness traits to make them well adapted to prevailing climatic and environmental conditions in this province (Molotsi *et al*., 2017), productivity is still low compared to the potentials expected from the industry.

Production factors and processes of sheep flocks reared under communal and smallholder production systems of Limpopo province have been given less attention and hence undocumented. This highlights the importance of generating data to define and describe the current state of sheep production in these systems, as well as to stimulate discussion about the feasibility of sustainable growth for the sheep industry, with a particular emphasis on reducing vulnerability in communal and smallholder production systems in Limpopo Province. According to Amejo *et al*. (2018), difficulties in agricultural development are related not only to the complexity of livestock production systems but also to the inability of role-players to understand how these systems function, which is primarily a problem of quantification and comprehension.

The sheep industry in the province is fragmented into commercial, smallholder and communal sectors based on the capital investment, land tenure, level of management and level of technology used in sheep production. Numerous studies which were conducted on sheep production in Sub-Saharan Africa (SSA) have characterized communal and smallholder sheep farming systems by low productivity, high level of mortality, low reproduction rate, low fertility rates, low weaning percentage, high incidence of diseases, low-quality output products and low turnover (Gizaw *et al*., 2013; Taye *et al*., 2016; Mthi *et al*., 2017; Nkonki-Mandleni, 2019). Molotsi *et al*. (2017) reported that low production performance levels of most smallholder sheep production systems are mainly attributed to various non-genetic reasons, suggesting that apart from the genetic effects, other fundamental factors impede the ability of communal and smallholder farmers to exploit the full potential of their sheep for sustainable and profitable production systems.

The literature revealed that in South Africa sheep farmers are confronted by constraints such as poor management practices, limited access to information and services due to poor access to extension services, climate change effects on feeding resources and disease occurrences (Meissner *et al*., 2013), the incidence of predation (Turpie and Akinyemi, 2018), stock theft (Clack, 2013), lack of infrastructure and working capital, unstable feed availability due to overexploitation of resources and limitations to grazing rights (Mapiliyao *et al*., 2012; Molotsi *et al*., 2019). Similarly, Duguma and Janssens (2021) indicated that sheep feeding systems are subjected to overstocking of rangelands by livestock farmers, decrease in biomass productivity and quality of rangelands particularly in the dry seasons as a result of climate variability, inadequate knowledge of rangeland and improved planted pastures management are the core factors that need to be addressed to create sustainable extensive sheep feeding systems. Among the aforementioned restraints, nutrition is the primary constraint on sheep production, accounting for more than 75% of total variable costs (Mudzengi *et al*., 2020).

Admittedly, the lack of contextual and environmental information from farmers' perspectives on their socioeconomic status, sheep farming practices and constraints limits the scope of developmental interventions aimed at increasing resource efficiency, ensuring social equity, and strengthening the resilience of the two production systems. The current study was initiated to provide a better understanding of communal and smallholder sheep farming systems in the Limpopo Province and complements past studies done in the semi-arid regions of Sub-Saharan Africa. The specific objectives of this study were to describe the demographic and socio-economic characteristics of communal and smallholder sheep farmers, identify sheep production and feeding practices as well as describe the constraints that hinder the sustainable productive growth of these systems.

3.1.3 MATERIALS AND METHODS

3.1.3.1 Description of the study area

The study was conducted in the Limpopo Province, the northernmost South African province. The province covers an area of 125,755 km^2 of which approximately 81% is used for livestock grazing. Three agro-ecological zones namely warm arid, warm semi-arid and cool semi-arid zones which represent the climatic conditions of the province were purposively selected (Figure 3.1). The climatic conditions of the study areas are shown in Table 3.1.

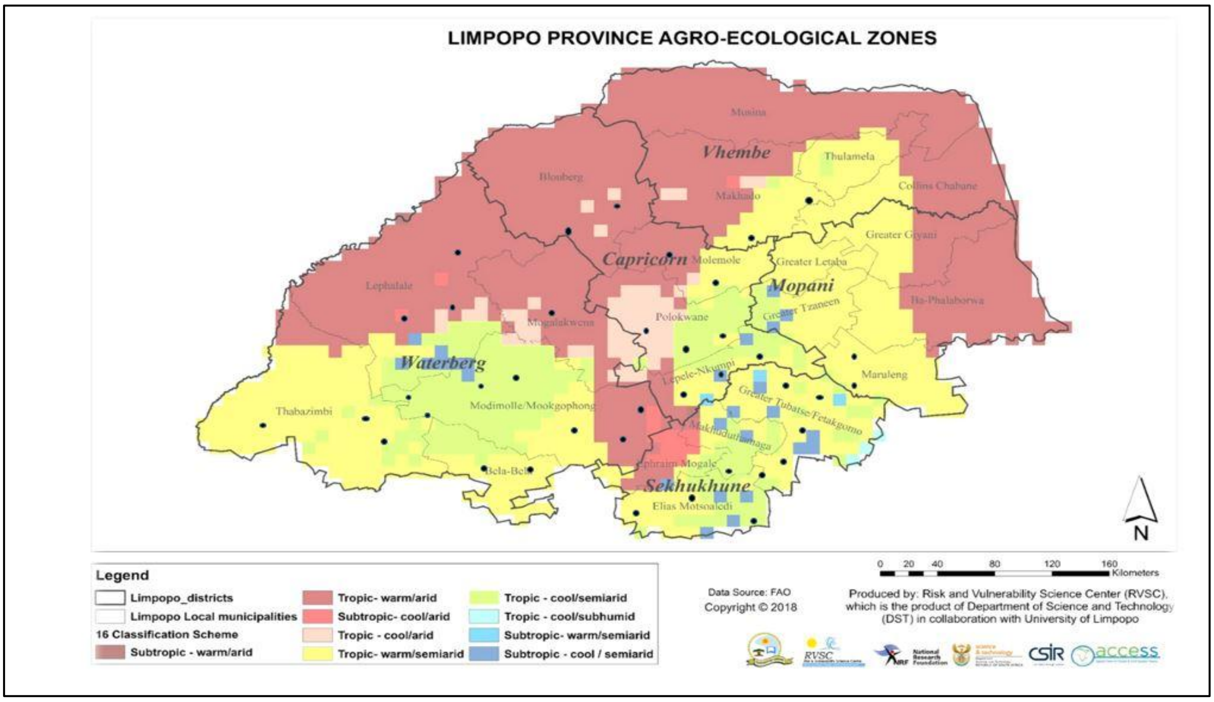

Figure 3.1 Map of Limpopo Province (Source: Produced by University of Limpopo, Risk and Vulnerability Science Center)

Table 3.1 The climatic characteristics of the selected study sites.

Agro-ecological zones	Mean altitude (m)	Range of annual precipitation (mm)
Warm arid	369	200 – 300
Warm semi-arid	681	400 – 500
Cool semi-arid	1097	500 – 600

3.1.3.2 Data collection

Sheep farmers from three ecological zones of Limpopo Province, warm arid, warm semi-arid and cool semi-arid where sheep farming was reported to be predominant were purposively selected. A partial list of sheep farmers was obtained from the Limpopo Department of Agriculture and Rural Development (LDARD) which led to the study not having a predetermined sample size. Sheep farmers from the study area were selected using the snowball sampling technique (Sotelo *et al.*, 2018). Two categories of farmers, targeted for the study were communal and smallholder farmers. The characteristics of smallholder sheep farmers in the Limpopo Province in terms of farm size, financial assets and market access tend to vary enormously. As a result, the smallholder, in the context of the study was concerned with the land tenure and economic scale of a farming operation, not just the size of the farm. Administration of a questionnaire was done on 120 sheep farmers; 92 communal and 28 smallholder farmers. The farmers are known to be crop-livestock farmers, raising sheep together with other livestock species such as goats, cattle and chickens and growing agronomic and horticultural crops.

Farmers having a sheep flock of more than five (5) heads and were willing to participate, were considered. A single-visit multiple subject formal survey technique was used for data collection using a pre-tested, semi-structured questionnaire. Interviews were conducted individually at the farmer’s house/farm by the researcher, extension officer and a community member. The extension officer and the community member helped with directions, the introduction of the researcher and the interviews. Ethical clearance was obtained for the study from the University of Limpopo Ethical Clearance Committee (TREC/350/2019:PG). Before the interview, respondents were informed of the study's content and aim and assured that participation was voluntary and their identities would be kept confidential. Each respondent signed a consent form before the interview could be conducted. The questionnaire was originally formulated in English, the questions were asked in Sepedi by a community member and the researcher. The questionnaire was subdivided into sections based on the objectives of the study that aimed at understanding farmers’ demographic and socio-economic characteristics, farm characteristics, management and feeding practices, flock dynamics and production constraints.

3.1.3.3 Data analysis

The software Statistical Package for Social Sciences (IBM SPSS, 2019) version 26. and Microsoft Excel was used to analyze the data. Farm stratification occurred according to the agricultural system (communal vs smallholder) based on similarities or differences in production scale and resource availability. Demographic and socio-economic data, farm-based characteristics, feeding practices and flock dynamics were summarized using descriptive statistics such as frequency, percentage, median, mean, variance and standard deviation. Mean, percentage and Pearson's chi-squared test (χ2) values of various parameters were compared across the two production systems.

To identify and explain the production constraints faced by farmers, each farmer was asked to rate the severity of the problem confronting each limitation on a four-point scale of high, medium, low, and not at all according to the methodology used by Kabir *et al.* (2019). Weights of 3, 2, 1, and 0 were then assigned to these responses. An overall score of the problems confronting the communal and smallholder farmers was computed for each farmer by adding their scores of the problems in all the 10 selected problems.

Problem Confronting Index (PCI) was computed using the following formula:

$$PCI = Ph \times 3 + Pm \times 2 + Pl \times 1 + Pn \times 0 \ldots\ldots\ldots \text{(Kabir et al., 2019).}$$

Where,

PCI = Problem Confrontation Index

Ph = Number of sheep farmers having high problem

Pm = Number of sheep farmers having medium problem

Pl = Number of sheep farmers having low problem

Pn = Number of sheep farmers having no problem

Results of the study were presented through graphs, figures and tables.

3.1.4 RESULTS AND DISCUSSION

3.1.4.1 Socio-economic characteristics and farming activities

The summary statistics of the farmers' demographic, socio-economic and farm-based characteristics are presented in Table 3.2. According to Table 3.2, the majority of the 120 sheep farmers interviewed are males in both the communal (77%) and smallholder (79%) systems. These findings corroborate previous research indicating that sheep farming is dominated by men (Zenda and Malan, 2021). In terms of farmer age, it was discovered that the majority (48%) of farmers within the communal system are senior citizens over the age of 60, followed by those between the ages of 50 and 60 (21%). A similar finding was made in the smallholder system, where approximately 75% of farmers were 50 years of age or older. The smallholder system does not have individuals under the age of 30. A similar case was reported in which young adults were reported to be uninterested in community-based small-scale sheep farming (Zenda and Malan, 2021). Van den Berg (2013) indicated that even though increased age may not directly impair the managerial capability of an aged farmer, a significant proportion of them may not be physically able to perform some tasks related to animal husbandry.

Table 3.2 Farmers' demographic and socio-economic of sheep farmers.

Variables	**Communal system**		**Smallholder system**		**Overall Total**	
Frequency	**N = 92**	**%**	**N = 28**	**%**	**N = 120**	%
AGRO-ECO ZONES						
Warm arid	25	27	12	43	37	31
Warm semi-arid	35	38	14	50	49	41
Cool semi-arid	32	35	2	7	34	28
Gender						
Male	71	77	22	79	93	78
Female	21	23	6	21	27	22
Age						
<30	10	11	0	0	10	8
30-40	11	12	3	11	14	12
40-50	10	11	4	14	14	12
50-60	16	17	9	32	25	21
>60	45	49	12	43	57	48
Education						
Primary	24	26	1	4	25	21
Secondary	33	36	11	39	44	37
Tertiary	35	38	16	57	51	43
Occupation						
Full-time farmer	70	76	19	68	89	74
Part-time farmer (wage employed)	19	21	9	32	28	23
Unemployed	3	3	0	0	3	3
Rands/month						
<2000	61	66	4	14	65	54

2000-4999	18	20	9	32	27	23
5000-9 999	11	12	8	29	19	16
10000-20000	1	1	6	21	7	6
>20000	1	1	1	4	2	2

According to the educational characteristics of the farmers in Table 3.2, the majority of them (48 %) hold a tertiary level qualification. Only 4% and 26% of communal and smallholder farmers have stopped their formal education at primary school, respectively. The result of this study shows that the majority of the respondents are literate which has significant importance and an indication of great potential in them to acquire knowledge and apply sustainable sheep management practices if granted the opportunity (Zenda and Malan, 2021). Farming was found to be the primary occupation of 76% of communal farmers and 68% of smallholder producers. Only 23% of farmers were found to be professionals and 3% regarded themselves as unemployed. According to the study's findings, the majority (66%) of communal farmers and only 14% of smallholder farmers rely on state social grants and old-age pensions wage of R2000 per month as their primary source of income. This is in agreement with the finding of Omotayo (2018) who reported that about 55% of the respondents in the Sekhukhune district of Limpopo province mainly depended on pensions as their primary source of income.

Table 3.3 Communal and smallholder sheep farm-based characteristics

Variables	**Communal system**		**Smallholder system**		**Overall Total**	
Frequency	**N = 92**	**%**	**N = 28**	**%**	**N = 120**	%
Farmer-group Membership						
Member	52	57	11	39	63	53
Non-Member	40	43	17	61	57	47
Land ownership						
Own	0	0	11	39	11	9
Lease	2	2	13	46	15	13
Tribal/Communal	90	98	4	14	94	78
Number of years in farming						
<5	34	37	6	21	40	33
6 - 10	19	21	10	36	29	24
11--15	9	10	4	14	13	11
16--20	8	9	4	14	12	10
>21	22	24	4	14	26	22
Farming activities						
Livestock	24	26	4	14	28	23

Livestock-Crop	39	42	12	43	51	43
Livestock-Crop-Poultry	26	28	10	36	36	30
Livestock-Crop-Piggery	2	2	0	0	2	2
Livestock-Poultry-Piggery	0	0	1	4	1	1
Livestock-Crop-Poultry-Piggery	1	1	1	4	2	2

Being a member of a commodity farmer group has a positive and significant influence on-farm productivity because it creates a convenient platform where farmers can learn and exchange ideas on different production practices. According to Table 3.3, 57% and 39% of communal and smallholder farmers respectively are members of either a livestock or sheep farmer group. All sheep farmers under the communal production system do not own land because lands are governed by the chiefs (traditional authority). However, 98% of farmers access the land to graze their sheep with only 2% of farmers having land leases from privately owned farms (Thamaga–Chitja and Morojele, 2014). From the study, 39% of smallholder land is privately held, 46% have lease contracts with the Department of Agriculture and Rural Development under the Land Redistribution for Agricultural Development (LRAD) program, and 14% are dependent on communal property. It was observed that 37% and 31% of the communal and smallholder farmers, respectively, have less farming experience in sheep farming, generally less than 5 years. Overall, 24% of the farmers have 5 - 10 years of experience and 21% were reasonably experienced in farming having 11 - 20 years’ experience. Twenty-two communal farmers (24%) and only four smallholder farmers (14%) were well experienced in sheep farming, with more than 20 years in the enterprise. This indicates that they have enough farming experience to enhance sheep production. Experience impacts the farmers’ managerial ability to make decisions, enabling them to set realistic goals and achieve them. It can be established that the farming activities in the study area were dominated by mixed crop-livestock (42% and 43% for communal and smallholder systems respectively) where both crops and livestock production were practiced within the same management. In addition to sheep production, other livestock kept by farmers included cattle and goats. Other farmers also keep poultry and piggery as additional animal-related activities. The food crops grown by these farmers include maize, sorghum, groundnuts, cowpea and vegetables which are also grown in considerable amounts. Farmers indicated that all these farming activities are meant to diversify sources of income and ensure food security. The same trend of farming activities conducted by sheep farmers was recorded by (Duguma and Janssens, 2021).

3.1.4.2 Management practices and flock composition

- **Management practices**

Smallholder and communal farmers in the Limpopo Province practice different management and feeding systems to rear their sheep as illustrated in Figure 3.2. The vast majority of communal and smallholder farmers (90% and 96%, respectively) utilized an extensive system for sheep management. Animals graze continuously, with rangeland grazing serving as their primary source of nutrition. Some communal farmers (8%) use a semi-intensive system with partial grazing to raise their sheep. Sheep graze during the day, and feeding stalls are also provided within the kraals for additional feeding. Only 2% of communal farmers engage in zero-grazing. In this feeding system, concentrates and hay were fed to sheep in feeding stalls and troughs, this finding is in agreement with the work reported by Belay *et al.* (2012).

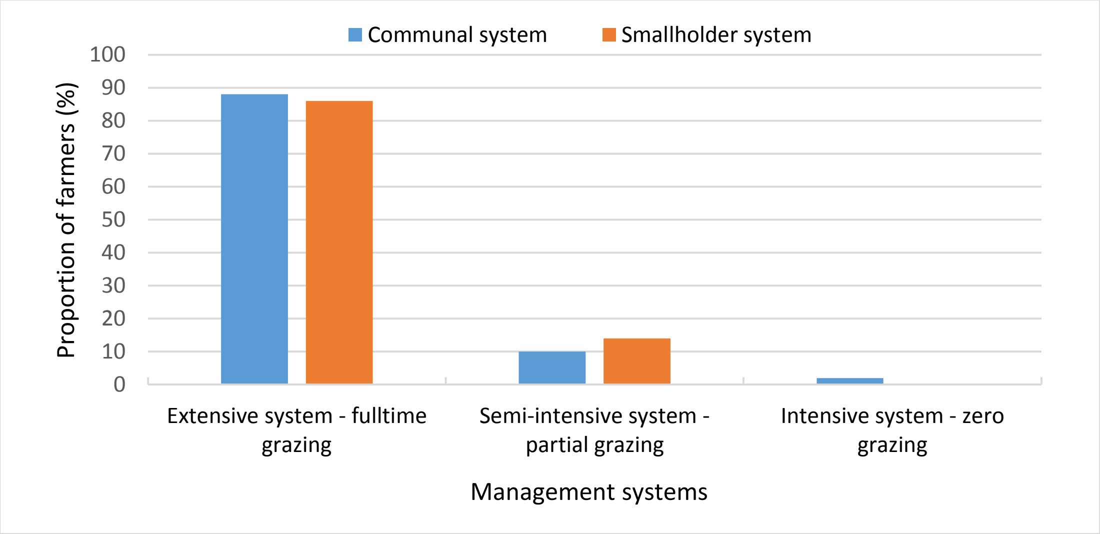

Figure 3.2 Sheep management system practiced by farmers in the study area.

- **Breeds**

Breeds of sheep observed in the study areas are indicated in Figure 3.3. Indigenous crossbreeds were the most reared breed by communal (86%) and smallholder (77%), followed by Dorper, BaPedi or Meatmaster.

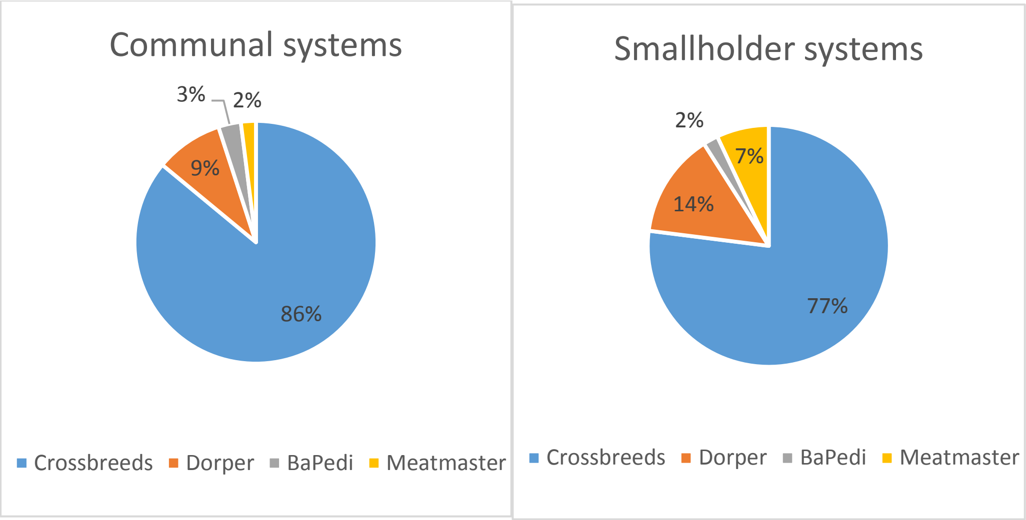

Figure 3.3 Sheep breeds kept by communal and smallholder farmers in the Limpopo province.

- **Flock dynamics**

The sheep flock composition and size per production system are presented in Table 3.4. The sizes of flocks differed significantly (P ≤ 0.01) within the production systems with the average size of 24.74 and 62.36 under communal and smallholder systems respectively. The average number of ewes were 17 and 43 communal and smallholder, respectively, and differs significantly (P<0.05). Of the total sheep, ewes constitute an average of 17 and 43 in communal and smallholder systems respectively, a larger proportion of the flock. This finding of the proportion of ewes (43%) under the smallholder system is comparable with previous works done in different parts of Sub-Saharan Africa including Ethiopia such as Abebe *et al*. (2000) (42.4%) and Gebrekiristos and Duguma (2012) (49.7%). The average number of rams kept per flock was significantly different among the production systems (1.64 ± 1.20 for communal and 3.75 ± 4.60 for smallholder). The relatively fewer mature rams compared to breeding females observed in this study agree with the findings of Gebrekiristos and Duguma (2012), that this may reflect those male animals are sold or consumed early in life while females are retained for breeding. Growing animals such as lambs differed significantly across the systems with an average of 4.37 and 14.29 in the two systems. However, there were no significant differences for the weaners.

There is a positive relationship between flock size owned by farmers and land at their disposal. Smallholder farmers who owned and leased land from the government through the LRAD program owned higher flock sizes ranging between 8 and 224 heads, with communal farmers who utilize rangelands owned by the chief having fewer flock sizes, 4 to 99 heads. However, some communal farmers rear their sheep under a semi-intensive system with partial grazing. Under this system, the farmers provide additional feeds in feeding stalls, hence they were able to keep bigger flock sizes.

Table 3.4 Flock composition and size of communal and smallholder sheep farmers.

	Communal system N=92			Smallholder system N=28			
Flock composition	Min	Max	Mean (±SD)	Min	Max	Mean(±SD)	Sig.
Rams	0	6	1.64 ± 1.20	1	20	3.75 ± 4.60	.000***
Ewes	2	55	17.07 ± 12.02	5	120	43.04 ± 27.43	.000***
Lambs	0	19	4.37 ± 4.27	0	90	14.29 ± 19.09	.000***
Weaners	0	28	1.77 ± 3.87	0	10	0.96 ± 2.56	.302ns
Flock size	4	99	24.74 ± 16.75	8	224	62.36 ± 47.03	.000***

Mean rank: Sig = Significance level, ***Significant at p< 0.01, ns=non-significant

- **Feed resources**

Smallholder and communal farmers utilized a wide range of feed resources for their sheep nutrition management depending on the management system. Figure 3.4 illustrates the feed resources of sheep in the Limpopo Province. Overall, the dominant feed resource within the two systems was natural grasses that grow in the rangelands, roadsides, fallow lands around homesteads and browse plants during all seasons, consistent with a study conducted by Belay and Negesse (2018). Farmers indicated that although quantity and quality from the rangelands are adequate during the rainy season, grass biomass declines during the dry season, resulting in the sheep losing weight and occasionally prolonged drought mortality had been observed by Ayele *et al.* (2021). This is largely influenced by poor rangeland management principles which result in rangeland deterioration and poor livestock conditions. Under a communal system, the chief control the grazing lands and rights, not the livestock keepers.

All the farmers indicated that they supplemented their sheep flock using different feed resources, particularly during the dry season. Communal (76%) and smallholder farmers (68%) stated crop residue as a supplementary feed during the dry season. The commonly used crop residues were maize stover and grain sorghum, oats straw, cowpea and groundnut haulms and vegetables residues. This result corroborated the findings of Lukuyu *et al*. (2011) and Lemma *et al*. (2016) who reported the use of different crop residues for supplementation. Between 86-89% of sheep farmers fed purchased lucerne and grass hay to sheep in the dry seasons. However, there is limited use of on-farm planted pastures to supplement feed gaps in the study areas, only 12% of communal and 36% of smallholder farmers have incorporated on-farm planted pastures in their feeding systems. Other feed resources included in the feeding systems were commercial feeds (pellets) which were used by 95% of communal and 61% of smallholder farmers, as Belay and Negesse (2018) reported. This can be associated with the availability and ownership of grazing lands. Smallholder farmers who have control over the grazing lands can apply better grazing management practices to curb feed shortages. Furthermore, industrial by-products such as maize bran, molasses, and orange pulps as well as non-conventional feeds such as dried bread were also used to bridge the feed gaps (Lamidi and Ologbose, 2014). The majority of both communal and smallholder farmers (90%) embraced mineral licks throughout the year to increase feed intake. Overall, one of the main shortcomings in communal extensive feeding systems was high feed costs. This finding is in agreement with earlier research by Belay *et al.* (2012).

It was observed that for sheep drinking water, 35% of the communal farmers used flowing rivers as the major source of water, 28% used dams while 37% provide drinking water from boreholes into the drinking troughs in their households whereas all the smallholder sheep farmers provide water from the boreholes on their farm. The major concerns raised by farmers with drinking water from the rivers were the quality of water and the distance traveled to reach the rivers. Furthermore, farmers are concerned about the siltation of rivers and dams which result in the loss of water storage capacity and reduce their value as sources of water. The concerns with drinking water from the rivers were also reported by Tonamo *et al*. (2015) in southern Ethiopia.

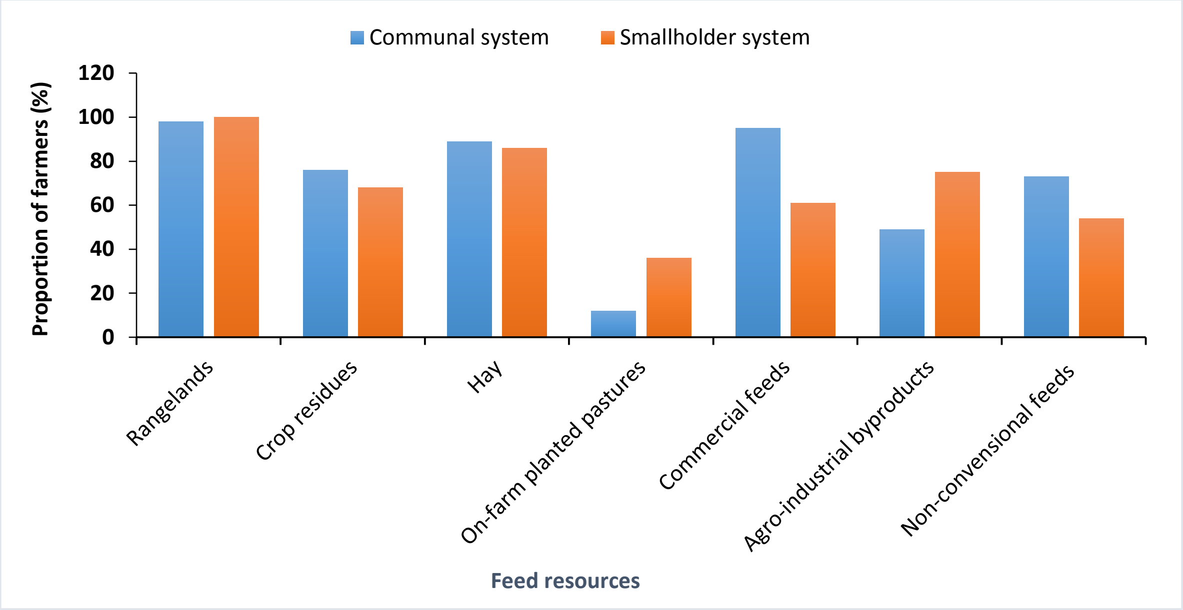

Figure 3.4 Frequency distribution of feed resources utilized by communal and smallholder sheep farmers.

- **Feed gaps**

The feed gap aspects of sheep reared under communal and smallholder production systems in the Limpopo Province are presented in Table 3.5 and Figure 3.5. According to Table 3.5, feed-gap challenges experienced by sheep farmers did not differ significantly across the two production systems with 93 - 99% of sheep farmers experiencing feed shortages. The findings of this study conform to the results indicated by Kom (2016) who reported that about 81% and 97% of sheep farmers in Mbewuleni and Sheshegu villages of the Eastern Cape Province experienced feed shortages, especially in the winter months when there was less vegetation in most areas during that period. About 38% of farmers under the communal system perceived the extent of the feed gap to be between high to very high whereas between 32 and 36% of farmers under the smallholder system perceived it to be medium to high to very high.

Table 3.5 *Perceptions of feeding gap aspects of communal and smallholder sheep farmers.*

Variables	Communal N=92	%	Smallholder N=28	%	X^2
Feed shortage					0.0596 ns
Yes	91	99	26	93	
No	1	1	2	7	

The extent of feed shortage					0.0278 ns
Very high	34	37	7	25	
High	35	38	10	36	
Average	23	25	9	32	
Low	0	0	2	7	
Consultation regarding feed gaps					0.00155 ns
Yes	47	51	23	82	
No	45	49	5	18	

The season of feed gap indicated by farmers ranges from mid-May to September before the first rain (Figure 3.5). The majority of the farmers perceived that the season of feed gap begins at the end of the autumn season in May. For the communal farmers, this perception of the onset of the feed gap is driven by the distance the sheep travel from the homelands in source feed from grazing land and the time taken to return to the kraals. The feed gap gradually increases during the month of June across the two farming systems, 13% and 1% for communal and smallholder, respectively. Communal farmers indicated that in July, the crop residue fields are opened for grazing and a slight decrease in feed gap is noticed. The study further revealed that 99% of communal farmers and 93% of smallholder farmers perceived the critical feed gap to be in August and September and this is marked by the loss in animal body weight whereas. Still, on the feed gap, 7% of smallholder farmers reported that no feed shortage is experienced during this critical time but indicated that the quality of grazing is critically low. During this time a wide range of supplementary feed resources indicated in Figure 3.4 will be incorporated into their feeding systems. The same feed gap trends were reported by Lamega *et al.* (2021).

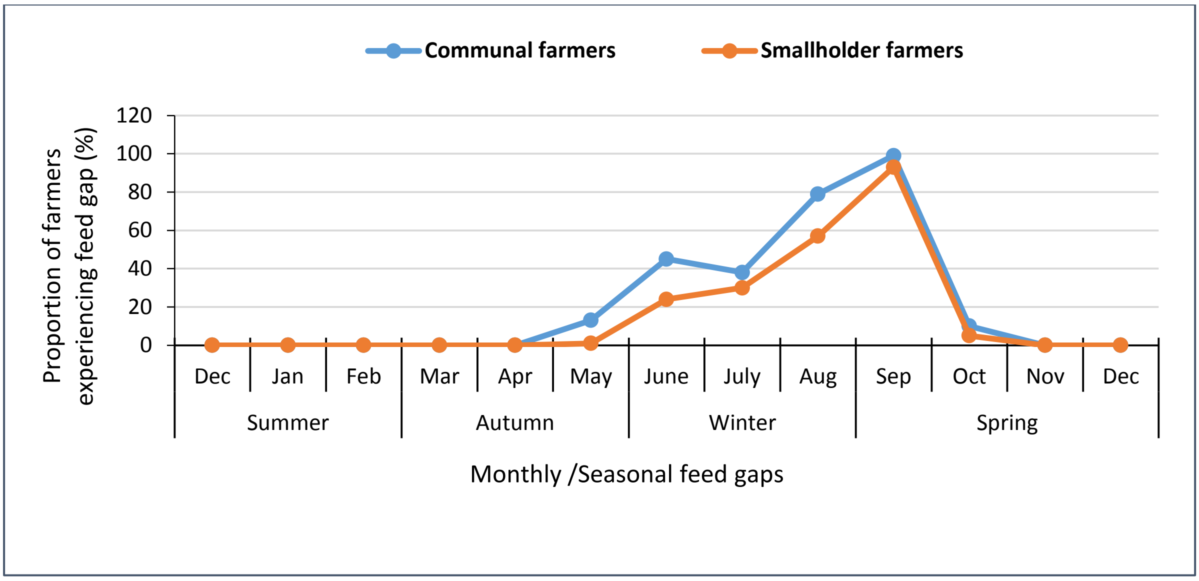

Figure 3.5 *Seasonal trends of feed gap experience of farmers.*

3.1.4.3 Farmers' production constraints confronted by sheep production

The results on problems confronted by sheep farmers are presented in Tables 3.6 and 3.7 for communal and smallholder systems, respectively. Feeding was ranked first, indicating that it was the primary constraint in both systems with a PCI value of 275 (communal) and 82 (smallholder) systems. The results reveal that most of the farmers confronted feeding as a problem of high significance in their production.

Diseases and parasites were ranked a second constraint by both communal and smallholder farmers with the PCI of 273 and 81 respectively. The most common diseases mentioned by farmers were tick-borne diseases (anaplasmosis and heartwater) and internal parasites which cause the mortality of infected animals. The results of the current study agree with Nkonki-Mandleni *et al*. (2019), which showed that feed shortages in combination with the prevalence of diseases are the highest constraints affecting sheep production of smallholder farmers in South Africa and Namibia. Above all, Underwood *et al.* (2015), explained that diet has a greater impact on the overall health of both the individual animal and the flock than any other factor identified in veterinary management of sheep. The third most important problem confronted by farmers was predation which was deemed of high or medium-level by communal farmers and smallholder farmers. The most common predators identified were jackals and wild dogs which normally target young animals. Van Niekerk *et al*. (2019) reported that the impact of predators on the livestock industry is underestimated and indicated that farmers lose up to 8% of their small livestock to predators.

Lack of technical knowledge was ranked fourth by communal farmers with the PCI of 226 while smallholders ranked it fifth with the PCI of 55. The aspect of knowledge mentioned by farmers includes animal husbandry, disease management and feeding knowledge. Good knowledge of rangeland management, feeding, and health in sheep production is of cardinal importance. Stock theft was ranked fifth by communal farmers and fourth by smallholder farmers. Farmers indicated that the factors contributing to stock theft were stock negligence, unmarked animals and a high rate of unemployment. This constraint has a huge negative economic and emotional impact on their farming. The impact of stock theft is supported by studies done by Clack and Minnaar (2018) and Maluleke *et al.* (2019) who also reported that stock theft contributes approximately 12% of all losses suffered on farms with sheep being the most livestock susceptible to this obstacle.

Lack of infrastructure was ranked sixth by farmers in both systems. Infrastructure challenges raised by farmers included the non-existence and/or aging of facilities such as dipping tanks, crush pens, loading zones and housing. Sheep farmers ranked lack of institutional support as the seventh and tenth constraint among communal and smallholder farmers respectively. The concerns mentioned included inadequate extension support and veterinary services which hinders the flow of farming information and knowledge. Capacity building of farmers is the backbone of any self-sustainable farming enterprise (Marandure *et al*., 2020b).

The lack of an organized market was ranked as the eighth and seventh constraint by communal and smallholder farmers respectively. This is mainly due to assess to market facilities, low sheep numbers and farmers' inability to meet formal market standards which results in low selling prices. Maintaining and improving a good breeding stock is a critical aspect of a productive flock. The breeding-related constraint was ranked the ninth and eighth constraint by communal and smallholder farmers respectively. According to the findings of this study, the majority of communal farmers lack good quality rams and planned breeding programs, hence they practice uncontrolled breeding. This jeopardizes planning for mating season and selection criteria and as a result, sheep tend to lamb throughout the year. Water shortage was ranked as the ninth and tenth constraint. The results of the current study agree with Kom (2016) and Molotsi *et al*. (2017). The concerns about water were discussed above under feed resources.

Table 3.6 Constraints confronted by communal sheep farmers.

Problems confronted by communal farmers	**High**	**Medium**	**Low**	**No Problem**	$^{\varphi}$**PCI**	**RANK**
Feed shortage	91	1	0	0	275	1
Lack of organized market	8	32	49	3	137	8
Diseases and parasites	89	3	0	0	273	2
Stock theft	51	29	11	1	222	5
Predation	58	27	3	4	231	3
Lack of technical knowledge	50	34	8	0	226	4
Infrastructure	13	40	39	0	158	6
Shortage of drinking water	4	30	47	11	119	10
Poor quality of animal genetics	9	29	46	8	131	9
Lack of institutional support services	20	26	45	1	157	7

$^{\psi}$ Problem Confrontation Index (PCI); n = 92

Table 3.7 Constraints confronted by smallholder sheep farmers.

Smallholder production constraint	High	Medium	Low	No Problem	$^{\psi}$PCI	RANK
Feed shortage	26	2	0	0	82	1
Lack of organized market	4	15	6	3	48	7
Diseases and parasites	25	3	0	0	81	2
Stock theft	20	6	2	0	74	4
Predation	21	5	2	0	75	3
Lack of technical knowledge	7	14	6	1	55	5
Infrastructure	3	17	8	0	51	6
Shortage of drinking water	1	13	13	1	42	9
Poor quality of animal genetics	3	11	12	2	43	8
Lack of institutional support services	1	2	22	3	29	10

$^{\psi}$ Problem Conforention Index (PCI).

3.1.5 CONCLUSION

This study was initiated to describe the demographic and socio-economic characteristics of communal and smallholder sheep farmers, identify sheep production and feeding practices as well as describe the constraints that hinder the sustainable productive growth of these systems. It can be concluded that the majority of the sheep farmers interviewed are males, about half of the farmers are senior citizens over the age of 60 years and there are no farmers under 30 years of age in the smallholder sector. Furthermore, half of the sampled farmers hold a tertiary qualifications and farming was found to be the primary occupation of 76% of communal farmers and 68% of smallholder producers. The critical feedback on the socioeconomic characteristics of farmers is the low proportion of females and youth within the communal and smallholder sheep sector as well as the fact that some sheep farmers still regard their occupation as unemployed in the process of rearing sheep.

Regarding their production and feeding practices the study identified that overall, the dominant feed resource within the two systems was natural grasses that grow in the rangelands, roadsides, fallow lands around homesteads and browse plants during all seasons. As a result, farmers experienced feed shortages from mid-May to September before the first rain and about 38% of farmers perceived the extent of the feed gap to be between medium to very high.

The sustainable growth of these sheep systems is constrained predominantly by feed scarcity and disease prevalence, the two main pillars of a productive flock. These were followed by predation, stock theft and lack of institutional support. The impact of these constraints is exacerbated by the socioeconomic characteristics of farmers and agro-ecological conditions. Undoubtedly, communal and smallholder sheep production systems denote the grey area of the industry with tremendous untapped potential and opportunity to change the low productivity level of the province.

3.1.6 RECOMMENDATIONS

The development of programs and the institutional support toward climate change resilience of communal and smallholder farmers should consider farmers' socioeconomic factors and agro-ecological conditions where the animals are reared. Such programs should consider youth and women to improve their participation in the sheep value chain and general livelihood. Furthermore, strategies to be developed should focus on enhancing the nutrition and health aspects of the production practices. Development of these sheep systems can be a sustainable way to respond to the United Nations Sustainable Development Goal 2030 Agenda which seeks to end poverty and hunger, realize the human rights of all, achieve gender equality and the empowerment of all women and youth and ensure the lasting protection of the natural resources.

3.2 Drivers and barriers to adoption of on-farm forage legume production by communal and smallholder sheep farmers to address feed gaps in Limpopo Province

3.2.1 ABSTRACT

Communal and smallholder sheep farmers face several production constraints, including inadequate and poor quality feeds. They use a variety of farmer-specific strategies to cope with and adapt to the increasing trend of feed gaps. Improved forages have been widely advocated as a critical step toward resolving this challenge. However, the adoption and utilization of improved technologies such as on-farm forage legume production by these farmers have been very low, contributing to the province's low sheep productivity. Primary data was collected from a sample of 120 sheep farmers selected through a snowball sampling technique. The objectives were to determine the factors that influence the adoption of on-farm forage legume production and the perceived barriers to adoption by communal and smallholder sheep farmers in the Limpopo province. A Probit regression model and Principal Component Analysis (PCA) were used to analyze the data. The study revealed that about 25% of the sheep farmers practice on-farm forage production on an average of 0.5 to 1 ha. The commonly grown forages are Lucerne and perennial white clover under irrigation. The probability of the adoption of on-farm forage production by communal and smallholder sheep farmers is influenced by several factors, including gender, farming experience, knowledge of forage legume production, source of income, membership in farmer associations, access to extension services, and farm size. Farmer perceived barriers to adoption of on-farm forage legume production identified by this study were low institutional support, lack of resources, lack of knowledge, shortage of water and objectives of the farmer. There is an urgent need for related stakeholders to improve forage technology training and extension services, make forage production resources available to farmers and promote on-farm forage production to transform communal and smallholder sheep feeding practices.

Keywords: Adoption; barriers; on-farm forage legume production; communal and smallholder sheep farmers

3.2.2 INTRODUCTION

In the era of climate change and an increasing human population, producing sustainably is becoming increasingly important in agriculture and food systems. Sheep (*Ovis aries)* play an important socio-economic role such as household food and nutrition security, as a source of income and form of capital to alleviate poverty

(Mapiliyao *et al*., 2012; Molotsi *et al*., 2019). Literature has revealed that feed shortage is one of the fundamental constraints contributing significantly to the low productivity of animals (Mapiliyao *et al*., 2012; Abebe *et al*., 2013; Ogunkoya, 2014; Taye *et al*., 2016; Lamega *et al*., 2021). These authors indicated that seasonal fluctuations in feed availability in quality and quantity create feed gaps within various animal feeding systems. According to Ayele *et al.* (2021), the majority of semi-arid regions of SSA experience a feed balance that is 40% deficient. Particularly because feed costs account for roughly two-thirds of total production costs (Makkar and Ankers, 2014).

Rangeland grazing contributes the most significant share of all feed sources in ruminant diets. However, communal rangelands can no longer provide sufficient and high-quality feed for the whole year (Mapiliyao *et al*., 2012; Muyekho *et al*., 2014) because their grazing potential has declined due to overstocking, bush encroachment, unplanned veld fires, hence unproductive (Vetter, 2013; Mndela *et al*., 2022). Crop residues are an important strategic feed resource (Blümmel *et al.*, 2012), however, the reliance on them can be limited by their availability and low nutritive value to provide all the nutritional requirements for growth and production (Mahesh and Mohini, 2013; Mutimura *et al*., 2015; Paul *et al*., 2020).

Communal and smallholder sheep farmers are known to purchase the formulated conventional/concentrate feeds for supplementation during feed gaps (Lamidi and Ologbose, 2014). With the present trend of rising feed raw material and fuel prices, price fluctuation due to demands, the cost of concentrates tends to be high and limits the farmers to rely on them (Makkar, 2018). Agro-industrial by-products such as maize bran and molasses and non-conventional feeds are used to fill the feed gaps, however, their use is defied by the inconsistency of supply from industries (Ajila *et al*., 2012; Lamidi and Ologbose, 2014). Feeding sheep with purchased hay is also the most widely adopted strategy concerning planted pastures (Duguma and Janssens, 2016) however the cost of purchase is influenced by the price of hay bales, distance to fodder markets, supply and demand, as well as their forage quality, can impede their use. As mentioned by Mupangwa and Thierfelder (2014) feed challenges are exacerbated by the lack of intentional production of fodder crops on smallholder farms, even though various legume and non-legume species have been tested and shown great potential for providing dry season feed. Duguma and Janssens (2016) indicated that the contribution of most feed resources depends on the agroecology, socio-economic status of farmers, the type of crops, planted pastures and by-products produced, availability, accessibility and market prices.

The growing gap between demand and supply of fodder in Limpopo province necessitates the use of appropriate technologies that can maximize fodder production to overcome current feed gaps. Over the years, researchers have tested and introduced nutritious and low-cost forage-based feeding systems to improve protein availability, intake and increase livestock productivity in Sub-Saharan Africa (SSA). According to Thornton *et al.* (2018), improved forage-based systems are known to produce a wide range of socioeconomic and ecological benefits, including increased productivity, reduced impacts on climate risks and shocks, and climate change mitigation through reduced GHG emissions. Furthermore, improved forage technologies such as forage legumes, are rich in protein and can enhance sheep productivity resulting in a shift from subsistence orientation to market orientation (Rao *et al.,* 2016). However, their adoption and utilization by communal and smallholder farmers have proven to be very low and unsatisfactory, contributing to the province's low sheep productivity.

Adoption refers to the decision to use new technology, method, practice, etc. by a farmer. At the farm level, an individual adoption reflects a farmer’s decision to incorporate new technology into the production process (Beshir, 2014). Franzel and Wambugu (2007) found that despite heavy sensitization on more nutritive forage technologies in East Africa, only 10% of smallholder farmers had adopted them. Technology adoption and specifically the transition to incorporate on-farm forage legume production is affected by several factors. As indicated by Mwangi and Kariuki (2015), the dynamic interaction of the technology's characteristics and the external environment influence farmers' decisions on whether and how to adopt agricultural technologies. Furthermore, Beshir (2014) showed that farmers' decisions to use improved forage technologies are influenced by a combination of factors such as household characteristics and socioeconomic and physical environments in which farmers operate. According to Meijer *et al.* (2015), it is also critical to pay attention to the internal decision-making process, looking beyond the mere characteristics of the innovation and the household to include psychological and motivational factors such as knowledge, perception, attitude and practice in technology adoption.

Consequently, in addition to the highlighted socioeconomic factors, investigating the role of socio-psychological factors such as farmer perceptions of specific attributes of improved technologies could contribute to our understanding and ongoing discussion of improved forage adoption (Senyolo *et al*., 2021). Perception is defined as the process by which a person receives information or stimuli from their surroundings and converts them into psychological awareness (Paing, 2020). Farmers' decisions to adopt new agricultural technology are influenced by their knowledge, attitudes and perceptions of the characteristics of the improved technology (Emmanuel, 2014; Meijer *et al*., 2015). Literature highlights the perceived barriers to include the availability of inputs, cost and benefits of the technology, related to capital and high costs of labor, uncertainty, gender, socio-cultural practices, access to market, access to credits and lack of knowledge among others (Meijer *et al*., 2015; Senyolo *et al*., 2021; Serote *et al*., 2021). Understanding the context of the socio-ecological state and objectives of farmers, as they are the rational decision-makers and primary users of technology is very critical. Therefore, there is a need for location-specific empirical information on the adoption of improved fodder production such as on-farm forage legume production technologies and the various factors affecting them in the study area, to understand the adoption scenario and design appropriate policy action to improve the on-farm legume fodder production. The objectives of the study were to 1) analyze factors that influence the adoption of on-farm forage legume production to bridge the winter feed gap 2) identify farmers' perceptions of barriers to the adoption of on-farm forage legume production.

3.2.3 MATERIALS AND METHODS

3.2.3.1 Description of the study area

The study was conducted in the Limpopo Province, the northernmost South African province, bounded by Zimbabwe to the north; Mozambique to the east; the provinces of Mpumalanga, Gauteng, and North West to the south; and Botswana to the west and northwest. The province covers an area of 125,755 km^2 of which approximately 81% is used for livestock grazing. Three agro-ecological zones namely warm arid, warm semi-arid and cool semi-arid zones which represent the dominant climatic conditions of the province were purposively selected (Figure 3.1).

3.2.3.2 Sampling and data collection

Communal and smallholder sheep farmers from three ecological zones of Limpopo Province, warm arid, warm semi-arid and cool semi-arid where sheep farming was reported to be predominant were purposively selected. A partial list of sheep farmers was obtained from the Limpopo Department of Agriculture and Rural Development (LDARD) which led to the study not having a predetermined sample size. Sheep farmers from the study area were selected using the snowball sampling technique (Sotelo *et al*., 2018). Administration of a questionnaire was done on 120 sheep farmers; 92 communal and 28 smallholder farmers. The farmers are known to be crop-livestock farmers, raising sheep together with other livestock species such as goats, cattle and chickens and growing agronomic and horticultural crops.

Farmers having a sheep flock of more than five (5) heads and were willing to participate, were considered. A single-visit multiple subject formal survey technique was used for data collection using a pre-tested, semi-structured questionnaire. Interviews were conducted individually at the farmer’s house/farm by the researcher, extension officer and a community member. The extension officer and the community member helped with directions, the introduction of the researcher and the interviews. Ethical clearance was obtained for the study from the University of Limpopo Ethical Clearance Committee (TREC/350/2019:PG). Before the interview, respondents were informed of the study's content and aim and assured that participation was voluntary and their identities would be kept confidential. Each respondent signed a consent form before the interview could be conducted. The questionnaire was originally formulated in English, the questions were asked in Sepedi by a community member and the researcher. The questionnaire was subdivided into sections based on the objectives of the study that aimed at understanding farmers’ demographic and socio-economic characteristics, farm characteristics, management and feeding practices, flock dynamics and production constraints.

The questionnaire was subdivided into sections based on the objectives of the study that aimed at understanding farmers' demographic and socio-economic characteristics, farm characteristics, flock size, knowledge of forage legume production, and stakeholder support as possible factors affecting adoption of on-farm forage legume production.

To measure knowledge, firstly farmers were asked to give the name of the forage legumes they know (Number of forage legumes given). Secondly, to measure the level of knowledge of the technical/ production practices, five questions were asked to each farmer to determine knowledge of forage legume production practices. The questions cover different aspects of production practices including establishment, fertilization, irrigation, utilization and conservation methods. Each production practice was assigned by '2' marks. So the mark range varied from 0 to 10. If any farmer failed to describe all of the above-mentioned production aspects correctly, '0'marks was obtained, which meant no knowledge, described 2 production practices – '4' marks which meant poor knowledge, 3 described practices – '6' marks which meant fair knowledge, 4 described practices – '8' marks which meant good knowledge and 5 correctly described practices – '10' marks which meant excellent knowledge. To use in the probit model, points 0 and 4 meant no knowledge (0) and 6-10 meant to know (1).

3.2.3.3 Data analysis

The software Statistical Package for Social Sciences (IBM SPSS Statistics 27) and Microsoft Excel were used to analyze the data. The Probit regression model was used to determine possible factors influencing the adoption of on-farm forage legume production by communal and smallholder sheep farmers to bridge the winter feed gap. The Principal Component Analysis (PCA) method was used to analyze the perceived barriers to the adoption of on-farm forage legume production by communal and smallholder sheep farmers. These different analytical techniques are explained in detail in the following subsections.

Probit regression model

This study adopts the Probit model to determine factors that influence the adoption of on-farm forage legume production to bridge the winter feed gap. This adoption

study attempt to explain only the probability of adoption versus non-adoption rather than the extent and intensity of adoption therefore, it is based on a binary regression model. The Probit regression model was selected because the dependent variable (adoption of on-farm forage legume production) is binary and takes a value of 0 or 1, meaning that it takes 1 if the farmer adopted on-farm forage legume production and 0 if the farmer did not adopt on-farm forage legume production. Adopters are farmers who have planted forage legumes on their farms, plots, or backyard intended to feed livestock and non-adopters are farmers who have not planted forage legumes during the survey year (2020/2021 production year). The conceptual analysis of the model used in this study is similar to the model adopted by Tarekegn and Ayele (2020).
Thus the Probit model used is described as follows:

$$D_i^* = \alpha Z_i + V_i \qquad D_i = \begin{cases} 1 \; if \; D_i^* > 0; \\ 0 \; otherwise \end{cases}$$

Where D_i^* represents the dummy variable which is whether a farmer has adopted the on-farm forage legume production or not. Thus, $D_i^* = 1$ means the sheep farmer has adopted and produced the forage legumes on their farm to supplement sheep in the dry season, while otherwise implies no adoption by the farmer. Z_i Is a set of independent or explanatory variables which influence the decision to adopt. α Represents the Probit index for a one-unit change in the predictor while the error term which assumes normal distribution is represented by V_i.

The existing adoption literature contains several potential factors that are known to influence agricultural technology adoption. Farmers' decisions to adopt improved agricultural technologies are thought to be influenced by the dynamic interaction between factors that can be categorized under the farmer's demographic and socioeconomic realities, characteristics of physical environments in which the farmer operates as well as the attributes of the technology itself (Nkamleu and Manyong, 2005; Turinawe *et al*., 2011; Beshir, 2014; Ng'ang'a *et al.,* 2020; Tarekegn and Ayele, 2020; Senyolo *et al*., 2021; Serote *et al*., 2021). In this study, the choice of the variables that were hypothesized to influence the adoption of on-farm forage legume production was based on the regularity with which a variable was cited in this literature. Using this criterion, the following variables described in Table 3.7 were included in the Probit regression model.

Table 3.8 Description of variables in the Probit logistic regression model.

Variable	Description
Dependent variable	
Famer adoption of on-farm forage legume production	1 if the farmer adopted the on-farm forage legume production and 0 otherwise
Independent/ explanatory variables	
Gender	1 = male, 0 otherwise
Formal education	1 = literate, 0 otherwise
Farming experience	Years of farming experience
Knowledge of forage legume production	1 = have the knowledge, 0 otherwise
Household income	Monthly Rands
Sources of income	Earning salary (yes = 1), Recieving grants (yes = 1), Have farm income (yes = 1), Have off farm business (yes = 1), 0 otherwise
Farm size	Number of sheep owned (head counts)
Land ownership	1 = yes, 0 otherwise
Farmer group association	1 = yes, 0 otherwise
Access to extension services	1 = yes, 0 otherwise

The Principal Component Analysis (PCA) Method

The PCA method was applied in this study to generate factors with strong patterns explaining farmers' perceptions of on-farm winter forage legume production.

PCA is a popular linear dimension reduction technique that reduces an excessive number of correlated variables by building a linear combination of uncorrelated variables that maximize the total variance explained. In doing so, the relevant information is extracted from large data and the dimensionality of the data set is reduced by providing new and meaningful variables (Jolliffe and Cadima, 2016). The use of PCA is validated through Barlett's test of sphericity chi-square of 344.995, which was significant. Components with eigen values of at least one are retained based on the Kaiser criterion (Montgomery, 2012). The retention of statements with factor loadings above 0.5 for use in composing perception indices was a threshold adopted in this study (Domingues *et al.,* 2020; Senyolo *et al*., 2021).

3.2.4 RESULTS

3.2.4.1 Factors that influence the adoption of on-farm forage legume production to bridge the winter feed gap

The study revealed that about 25% of the sheep farmers practice on-farm forage production on an average of 0.5 to 1 ha. The commonly grown forages are Lucerne and perennial white clover under irrigation. Furthermore, it was also observed that 16% of sheep farmers grew perennial grasses such as *Anthephora pubescens* and *Cenchrus ciliaris* under dryland conditions.

The factors that potentially influence the adoption of on-farm forage legume production by communal and smallholder sheep farmers are presented in Table 3.8. In this current study, the model fit from the Pearson Chi-Square is statistically significant at 1% which implies that the included explanatory variables in the model fit the model (Table 3.8). The results revealed that gender was found to be negatively and statistically influencing the adoption of on-farm forage legume production at a 10% significance level. This infers that being male reduces the probability of adopting this technology among sheep farmers. The results indicated that farmers' years of experience in sheep production positively influenced farmer adoption of on-farm forage legume production. The variable farming experience indicated a statistical significance of 5% thus suggesting that having an additional year of experience in sheep production positively increases the probability of adoption of on-farm forage legume production. Knowledge of forage legume production was found to be positive and significantly to influence the adoption of on-farm forage legume production highly.

Knowledge of forage legume production showed a statistical significance of 1%, suggesting that knowing forage legume production positively increases the probability of adoption of on-farm forage legume production.

A salary and farm income as sources of income to farmers were both found to have a statistically positive relationship with the adoption of on-farm forage legume production among farmers at 1% and 10% significance levels, respectively. This implies that having a salary and also relying on farm income increases the probability of adoption of on-farm forage legume production among sheep farmers. Furthermore, the results of the study revealed a positive significant relationship between the variable farm size and adoption of on-farm forage legume production by farmers with a 1% level of significance. The 1% significance provides sufficient evidence to imply that having more sheep increases the probability of adoption of on-farm forage legume production. Farmer group association was found to positively and significantly influence the adoption of on-farm forage legume production highly. The increased likelihood to adopt on-farm forage legume production for sheep nutrition when farmers belonged to a farmer group association, could suggest that the groups were sources of information about the technologies. Access to extension services was observed to have a statistically positive relationship with the adoption of on-farm forage legume production among farmers at a 5% significance level. The likelihood to adopt on-farm forage legume production for sheep nutrition increases when farmers have access to extension services.

Table 3.9 Factors that influence the adoption of on-farm fodder legume production.

Parameter	**Coefficient**	**Std. Error**	**Z**	**Sig.**
Farmer characteristics				
Gender (Male = 1)	-0.157*	0.089	-1.773	0.076
Formal education (yes = 1)	0.149	0.186	0.802	0.423
Farming experience (years)	0.074**	0.027	2.742	0.006
Knowledge of forage legume production (yes = 1)	0.454***	0.159	2.851	0.004
Household income (Monthly Rands)	-0.046	0.045	-1.022	0.307
Sources of income				
Salary (yes = 1)	0.349***	0.115	3.022	0.003
Grants (yes = 1)	0.081	0.096	0.844	0.399
Farm income (yes = 1)	0.247**	0.120	2.063	0.039

Off farm business (yes = 1)	-0.130	0.192	-0.676	0.499
Farm characteristics				
Farm size (number of sheep owned)	0.006***	0.002	3.459	<0,001
Land ownership (yes = 1)	0.189	0.139	1.359	0.174
Institutional factors				
Farmer group association (yes = 1)	0.256***	.086	2.973	0.003
Access to extension services (yes = 1)	0.203**	.103	1.983	0.047
Pearson Goodness-of-Fit Test		Chi-Square	df^a	Sig.
		330.471***	105	<,001

P*i* = probability that communal and smallholder farmers are willing to adopt on-farm forage legume production given X

3.2.4.2 Perception on barriers to adoption of on-farm forage legume production.

The decision of farmers to adopt a technology may be influenced by the perception of the characteristics of the proposed technology. Communal and smallholder sheep farmers were asked to scale the significance of the barriers to adopting the on-farm forage legume production using the Likert scale (1-5 points) from least important to highly important. Table 3.9 present the farmers‟ perceptions of the barriers to adopting on-farm forage legume production. The Kaizer criterion was used for selecting the number of essential principal components explaining the data. All components with Eigen values of less than one were left out, following the rule of thumb when conducting Principal Component Analysis (PCA) using a correlation matrix (Senyolo *et al*., 2021). Subsequently, the factor loadings for the reduced components as suggested by the criterion of Eigen values were retained for further analysis. The five components extracted explained 70% of the variance compared against the original 11 perceived barrier components. Due to the cross factor loading of lack of equipment in principal components 1 and 2, we decided to assign it to component 2 for its positive correlation. These components are as follows:

Principle component 1*: Low institutional support*, accounts for 17.74% of the variance. A total of three barriers loaded heavily into this component and they are lack of financial resources, shortage of land and low government support. These barrier factors are related to institutional support.

Principle component 2: *Lack of resources* accounts for 16.59% of the variance. A total of three barriers loaded heavily into this component and they are lack of equipment, labor-intensive, and lack of production inputs. Lack of equipment and labor-intensive had positive signs, implying that these barriers are positively correlated. They are likely to influence the adoption of on-farm forage legume production by communal and smallholder sheep farmers.

Principle component 3: *Lack of knowledge* accounts for 14.45% of the variance. Lack of awareness and knowledge and cost of production loaded heavily in this factor and reflected a positive correlation. These variables indicate that lack of knowledge is a barrier because the farmers don't know what forage legumes are and their production practices.

Principle component 4: *Shortage of water* accounts for 10.82% of the variance. *Shortage of irrigation water* loaded heavily in this factor. Water access to their homes and plots is a barrier to the adoption of on-farm forage production.

Principle component 5: *Objectives of the farmer* account for 9.91% of the variance. Given less priority loaded heavily in this factor. These variables indicate that a barrier to adoption might be that the farmer's objectives have not been well defined because farmers do not give forage production a priority in their production plans.

Table 3.10 Perception of barriers to adoption of winter fodder legumes.

Barriers of WFL adoption	Average* (n = 120)	Principal Components				
		1	2	3	4	5
Lack of awareness and knowledge	4.74	- 0.310	-0.260	**0.799**	-0.137	0.142
Cost of production	3.76	0.081	0.291	**0.722**	-0.280	-0.291
Lack of financial resources	5.69	**-0.602**	-0.172	0.318	0.098	0.018
Lack of equipment	4.13	-0.571	**0.601**	-0.009	0.241	-0.057
Labour intensive	4.04	-0.151	**0.577**	-0.335	-0.175	0.087

Shortage of land	5.11	**0.664**	0.352	-0.296	0.067	-0.190
Low government support	7.11	**0.778**	-0.181	-0.058	0.092	-0.081
Shortage of irrigation water	8.03	-0.007	-0.436	0.103	**-0.788**	0.299
Lack of production inputs	7.52	-0.072	**-0.573**	-0.006	0.497	0.361
Lack of seeds in the nearby market	5.68	0.045	-0.382	0.270	0.288	-0.440
Given less priority	10.44	0.289	0.357	0.206	0.179	**0.720**
Eigenvalues		**1.951**	**1.825**	**1.590**	**1.191**	**1.090**
Total Variance explained (%)		**17.74**	**16.59**	**14.45**	**10.82**	**9.91**
Barlett's test of sphericity chi-square		344.995***				
Kaiser-Meyer-Olkin Measure of sampling adequacy (KMO)		0.137				

Note: Component loadings greater than 0.50 appear in bold in Table 3.9. Kaiser-Meyer-Olkin's measure of sampling adequacy (KMO) and Barlett's test of sphericity chi-square of 0.137 and 344.995 respectively.

3.2.5 DISCUSSION

3.2.5.1 Socio-economic factors that influence the adoption of on-farm winter fodder legume production

Concerning gender, the results revealed that being a male reduces the probability of adopting on-farm forage legume production. These results contradict the findings of Beshir (2014), who discovered that males use improved forage seed more than females. However, these results are consistent with the findings of Musafiri *et al.* (2022), who reported that females were more likely than males to engage in agroforestry. The findings revealed that experienced farmers are more likely to adopt on-farm forage legume production and the study's findings agree with those of Nkamleu and Manyong (2005), who discovered that farmers may be able to make a more accurate assessment of the various benefits of agroforestry as their experience grows. Furthermore, knowledge of forage legume production, membership in a farmer group association and access to extension services were found to be highly significant and positively influence the likelihood of on-farm forage legume production adoption. This finding agrees with those of Beshir (2014), Tarekegn and Ayele (2020) and Serote *et al.* (2021). Membership in a farmer group was found to have a positive and significant impact on technology adoption because it serves as a convenient platform for networking, interaction, knowledge and information sharing on the benefits and application of new technology (Mwangi and Kariuki, 2015).

Having a salary or relying on farm income was observed to increase the probability of adoption of on-farm forage legume production among sheep farmers. Present findings resonate with the findings of Ng'ang'a *et al. (*2020) and Serote *et al.* (2021) who reported that farm income could positively drive the level of climate-smart agriculture adoption because increased income from farming activities allows the farmer to acquire resources needed for adoption. Concerning farm size and adoption of on-farm forage legume production by farmers, having more sheep increases the probability of adoption of on-farm forage legume production. Similar findings were reported by Turinawe *et al.* (2011) and Jera and Ajayi (2008) who found that as the herd size grows, the need to supplement grazing with improved forages arises due to a lack of adequate grazing.

3.2.5.2 Perception on barriers to adoption of winter fodder legumes.

Principle component 1: Low institutional support, accounts for 17.74% of the variance. Low government support is a barrier to the adoption of on-farm forage legume production by communal and smallholder sheep farmers. This finding conforms to earlier work of Mwangi and Kariuki (2015) and Kephe *et al.* (2020b) who found that a lack of institutional support in a form of extension services to the provision of advice, training and farm visits together with a lack of investments in production resource creates a barrier to adoption of improved agricultural technologies.

Principle component 2: Lack of resources accounts for 16.59% of the variance. The result implies that lack of resources is a barrier to adopting on-farm forage legume production. This agrees with the findings of Assefa *et al.* (2015) and Kephe *et al.* (2020b) who reported that lack of resources such as land, infrastructure and capital is a key barrier to the adoption of improved forage types.

Principle component 3: Lack of knowledge accounts for 14.45% of the variance. Lack of knowledge is a barrier because the farmers who don't know what forage legumes are and their production practices are unlikely to adopt the on-farm forage legume production. Present findings resonate with the findings of Ng’ang’a *et al*. (2020) that showed that knowledge plays an essential role in technology adoption because the adoption of a particular technology can only be improved if the farmers are aware of such technology. Therefore much time should be invested in farmer awareness, learning, and experimentation to acquire technical skills. Key players such as the government provide training to farmers through various agricultural development programs.

Principle component 4: Shortage of water accounts for 10.82% of the variance. Water access to their homes and plots is a barrier to the adoption of on-farm forage production. The results of the study agree with the findings of Serote *et al.* (2021) who indicated that rainfall, dams/rivers, communal taps, wells, and boreholes are the primary water sources in most rural areas; however, due to varying rainfall amounts, some water sources are seasonal, making it difficult for rural farmers to have reliable water for irrigation of forage legumes.

Principle component 5: Objectives of the farmer account for 9.91% of the variance. These variables indicate that a barrier to adoption might be that the farmer’s objectives have not been well defined because farmers do not give forage production a priority in their production plans. A similar finding was reported by Paul *et al.* (2020) that production intensification may not be the top priority for farmers who keep livestock primarily to provide drought power, as an asset and risk management strategy, or for cultural reasons hence the adoption of improved forage technologies is not their priority.

3.2.6 CONCLUSION

The sustainable adoption of on-farm forage legume production has a critical potential role in alleviating feed gaps for proper fodder flow and fodder bank development. The results determined that factors such as gender, farming experience, knowledge of forage legume production, source of income, membership in farmer associations, access to extension services and farm size all exert a significant positive influence on the decision to adopt on-farm forage legume production. Additionally, the perceived barriers identified by this study were low institutional support, lack of resources, lack of knowledge, shortage of water and objectives of the farmer. This indicates that to overcome these barriers, the adoption of on-farm forage production depends on the priorities and associated activities of a wide variety of stakeholders, including multiple levels of government (provincial–district–local). Dialogue between stakeholders should consider the determining factors and identified barriers to the adoption of on-farm forage production in planning and developing enabling environments, vital policies, strategic programs and much-needed investments. The required activities to reduce the identified barriers should include increased institutional support such as accessibility of extension services, initiation of sheep farmer associations, increased awareness and training sessions, including forage production resources in government farmer support programs and designing economic feeding systems for various sheep rearing systems.

3.2.7 RECOMMENDATIONS

Policies that strongly focus on farmer support programs targeting on-farm forage production to alleviate feed gaps and improve the productivity of communal and smallholder sheep production systems in the Limpopo province are recommended. In addition, there are many forage legume species with improved cultivars such as clovers, vetches, forage cowpea, lupin and forage pea which can be incorporated into on-farm forage production. The potential of these forage legumes depends on agronomic management practices and prevailing environmental conditions. Studies should therefore be carried out both on-farm and on-station to evaluate their performance for informed recommendations in forage legume production and capacity building of farmers. Furthermore, with most farmers having the crop-livestock enterprises, it is therefore recommended that farmers be capacitated on crop residue conservation methods to improve their nutritional quality for dry season feeding.

CHAPTER 4: PHYSIOLOGICAL TRAITS AND PRODUCTIVITY OF ANNUAL CLOVER AND VETCH CULTIVARS AS INFLUENCED BY PLANTING DATE AND HARVESTING STAGE IN A SEMI-ARID ENVIRONMENT

4.1 ABSTRACT

Climate change has increased the intensity of heat stress, with adverse effects on crops. Planting date, harvesting stage and cultivar selections are key management and breeding approaches that have a high potential to mitigate and adapt to the effects of climate variability on crops. There is a knowledge gap on how these climate change mitigation approaches will influence the productivity of winter annual forage legumes in the Pietersburg Plateau of Limpopo province. A three-year field experiment laid in a split-plot design with four replications was conducted to measure the effects of planting date and cultivar and harvesting stage on the physiological traits associated with biomass production, forage quality and nodulation activity of annual clover and vetch species. The results showed that the planting date and cultivar significantly influenced leaf gaseous exchange and biomass production. When sampling or harvesting stage was factored in the data analysis, the above parameters were significantly influenced by the sampling stage as well. A non-significant effect of planting date on nutritive value was observed. Intercellular CO_2 concentration, transpiration rate, stomatal conductance, instantaneous water use efficiency and intrinsic water use efficiency in cultivars increased with delayed planting, while a decrease in photosynthetic rate, shoot DM, root DM and nodule DM was observed. Overall, among the cultivars, Resal, Alex, Elite, Laser and Dr Baumans showed more consistency in terms of leaf gaseous exchange, biomass production and quality traits under varying planting dates and harvest days. It can be concluded that these cultivars have great potential to mitigate feed gaps under the current climate change scenarios.

Keywords: Annual clover and vetch, biomass, harvest stage, nutritive value, physiological traits, planting date.

4.2 INTRODUCTION

Quality fodder production and supply have a substantial role in livestock health and productivity (Makkar, 2018). There is a growing demand for high-protein forages to supplement rangelands and crop residue-feeding resources during the winter season in the semi-arid savannah regions (Castro-Montoya and Dickhoefer, 2020). The IPCC report in 2018 indicated that the global average temperature over the last 5 years (2014–2018) has increased by 1.04°C compared to the preindustrial baseline and will reach 1.5°C as soon as 2030 (IPCC, 2018). Climate change-related biotic and abiotic stresses, such as rising temperatures, to which winter annual forage legumes will be increasingly exposed, will pose significant challenges in ruminant feeding systems (Ziervogel, 2014). As a result, agronomical and breeding approaches to improve the adaptation of winter forage legumes to high temperatures for better livestock productivity are essential (Chand *et al*., 2021).

Vicia and *Trifolium* species, originating from and adapted to cool climatic zones, are Mediterranean forage legumes that are more commonly utilized in agronomy as cover crops than forage crops for animal feeding in South Africa, particularly in Limpopo province. The study by Boswell *et al*. (2003) in New Zealand has proven that these legumes are competitive and productive in semi-arid environments which experience warm summers and cold winters like Limpopo province. Physiologically, these winter season forage legumes are categorized as C_3 species since they utilize the C_3 photosynthetic pathways. Cardinal temperatures and thermal time requirements for germination, emergence and growth reported for winter legume species are a base temperature (Tb) ranging from 0 to 4 °C, optimal temperature (Topt) between 12 and 25 °C and maximum temperature (Tmax) between 25 and 30 °C (Lonati *et al*., 2009; Nori *et al*., 2014). Increases beyond the optimum temperature threshold that result in damage to plant physiology, metabolism and productivity are defined as heat stress (Porter, 2005).

In the era of climate change, the temperature is one of the major factors affecting crop growth when moisture is not a constraint (Hatfield and Prueger, 2015). High temperatures have several negative effects on plant growth, development and survival, but the impact of heat stress on the photosynthetic system is thought to be especially important because photosynthesis is frequently inhibited before other cell functions are impaired (Haldimann and Feller, 2004; Moore *et al*., 2021). A moderate increase in air temperature is likely to affect the yield of most winter crops (Fahad *et al*., 2017). However, the responses to temperature differences among crop species and cultivars throughout their life cycle. For each species and cultivar, a defined range of maximum and minimum temperatures forms the boundaries of observable growth (Korres *et al*., 2016).

Biomass production of high quantity and quality is an important trait for fodder production systems (Delaby *et al.,* 2020). The photosynthetic carbon assimilation on green leaves drives biomass production and the transportation of photoassimilates from source sites of production (leaves) to sink sites (stems and roots) for storage and use promotes forage plant growth (Gotoh *et al*., 2018). According to Capstaff and Mille (2018), for crops to achieve their genetic potential, they respond to environmental changes by changing their morphological and physiological traits. The capacity of annual forage legumes to respond to environmental variation and agronomic practices can therefore be reflected in the plasticity of the key morphological and physiological traits responsible for adequate quality biomass production (Fahad *et al*., 2017).

According to Trytsman *et al*. (2019), breeding forage species and selecting cultivars with improved adaptability and stress tolerance traits under specific marginal agro-ecological conditions is required to ensure fodder availability during the critical feed shortage season. Chand *et al.* (2021), indicated that breeding for forage quality traits is considered an important secondary activity compared with higher forage yield, disease and pest tolerance. Delays in systematic breeding and poor cultivation of winter annual forages like clover and vetch have contributed to the misconception that they are low-yielding forage crops. With the development and release of new cultivars, information on their growth, biomass production and nutritive value is lacking and requires enlightenment, particularly for climate change adaptation.

In fodder production systems, the planting date is one of the most important agronomic practices for manipulating crops for maximum growth and productivity to ensure the seasonal distribution of forage availability (Anderson *et al*., 2020). Furthermore, for adequate forage quantity and quality, the planting date and harvesting stage must be optimized under any climatic conditions. This can be accomplished by planting at a time when there is enough radiation at an appropriate crop growth stage to provide enough growing degree days for optimal stomatal conductance, low transpiration, and high photosynthetic rate for assimilate accumulation into vegetative parts before the end of the growing season (Sajid and Hu, 2022). According to Hatfield and Prueger (2015), the best time to plant a cultivar is determined by relevant environmental factors for germination, establishment, seedling survival and other growth stages. Early planting, according to Wang *et al*. (2019), may result in poor germination, poor plant stands, low growth and poor biomass accumulation.

Nori *et al*. (2014) and Baxter *et al*. (2019) found that planting too late can result in low biomass due to unfavorable climatic conditions such as increased photoperiod, which accelerates flowering in winter annual forage legumes. Furthermore, late planting can expose forage crops to high temperatures, which can impair physiological processes like photosynthesis (Fahad *et al*., 2017). Forage legume species' nutritive value and dry matter (DM) composition are primarily determined by their developmental morphology, which is greatly influenced by the planting date and harvesting stage. Well-organized harvesting plans are required to ensure that the crops are fully utilized in their most productive and nutritious phases of growth. Furthermore, information on forage nutritive values at each harvesting stage is important to help farmers in choosing the best crop utilization time and methods to improve animal performance (Saffariha *et al*., 2021).

Studies focusing on the impacts of planting date, cultivar choice and harvesting stage on winter forage legume biomass accumulation relative to climate change are lacking in semi-arid regions. Such studies are required for screening and testing existing cultivars for breeding programs to create novel cultivars for changing growing conditions. Furthermore, they contribute to knowledge on how to optimize agronomic management practices for climate change mitigation to achieve high biomass of adequate quality from winter annual forage legumes. Such knowledge is needed to substantiate the decisions of farmers to adopt the annual clover and vetch as improved forage technologies to alleviate feed gaps. Hence, investigating the effect of planting date, cultivar and harvesting stage on the leaf gaseous traits, biomass production, nodulation activity and nutritive value of annual clover and vetch species is a key objective of this study.

4.3 MATERIALS AND METHODS

4.3.1 Experimental site

A field experiment was carried out at the University of Limpopo Experimental Farm, Syferkuil (23° 50' 10'' S, 29° 44' 15'' E), for three winter growing seasons 2018-2020, from June to November each year. The experimental site is located in a semi-arid region receiving between 350 and 500 mm of rainfall per year, with 85% of that falling in the summer between November and March. Average minimum and maximum temperatures are 4 to 20 ^{o}C in winter and 17 to 30 ^{o}C in summer. The soil was classified as a Chromic Luvisol (Hypereutric) with sandy clay loams overlaying sandy clay (Munjonji *et al*., 2017). The experimental site was previously used to plant triticale, followed by 3 years of fallow under no-till irrigated conditions. The experimental site is shown on the map below (Figure 4.1).

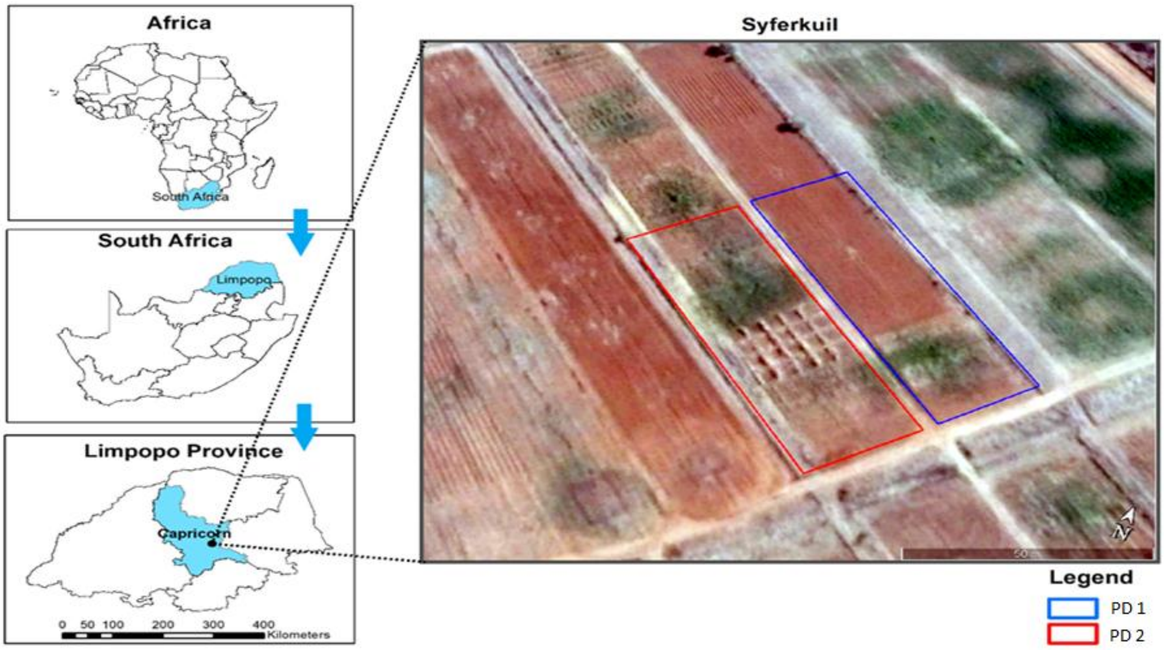

Figure 4.1 Locality map of the study location-Syferkuil Experimental Farm.

4.3.2 Experimental design and treatments

The experimental design was a split-plot in a randomized complete block design (RCBD) replicated four times. Treatments were two planting dates (June and July), ten cultivars (which were two species of annual vetch and three species of annual clover, each with two cultivars as indicated in Table 4.1) and four harvesting stages (mid and late vegetative stage, flower initiation and 50% flowering which were recorded as days after planting (DAP)). The planting date was the main plot, the cultivar was the sub-plots and the harvesting stage was the sub-sub plots.

Table 4.1 Cultivars of five winter annual forage legume species, source and planting densities.

	Common name	Scientific name	Cultivar	Source	Planting density
1	Common vetch	*Vicia sativa*	Timok	South Africa	30 kg ha^{-1}
2			Candy	Germany	30 kg ha^{-1}
3	Hairy vetch	*Vicia villosa*	Capello	South Africa	30 kg ha^{-1}
4			Dr Baumans	Germany	30 kg ha^{-1}
5	Berseem clover	*Trifolium alexandrinum*	Ellite	South Africa	20 kg ha^{-1}
6			Alex	Germany	20 kg ha^{-1}
7	Crimson clover	*Trifolium incarnatum*	Opolska	South Africa	20 kg ha^{-1}
8			Linkarus	Germany	20 kg ha^{-1}
9	Persian clover	*Trifolium resupinatum*	Lazer	South Africa	20 kg ha^{-1}
10			Resal	Germany	20 kg ha^{-1}

4.3.3 Soil sampling and analysis

Soil samples at the experiment site were collected before planting at the depths of 0–15 cm and 15–30 cm using a random sampling technique. The soil composite from two sampling depths was formed to represent each plot and was analyzed for physical and chemical properties. The soil samples were sieved to pass through a 2 mm sieve for chemical analysis. Soil pH was determined by potassium chloride (KCl) (Reeuwijk, 2002). Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), manganese (Mn) and copper (Cu) were extracted following the procedure of the Mehlich-III multi-nutrient extraction method. Soil bulk density using a metal ring at each soil depth following the procedure of Prikner *et al*. (2004). Available mineral nitrogen (N) was determined using the colorimetric method for ammonium and nitrate. The Bray-1 method was used to determine available phosphorus (P) and cation exchange capacity (CEC) following the procedure of Rayment and Higginson (1992). The Walkley and Black method were used to determine organic carbon (C). Soil particle size was determined using the hydrometer method (Anderson and Igram, 1993). The physical and chemical properties of the soils before planting are indicated in Table 4.2. The soil of the experimental plots was silt clay having a pH of

7.54 and 7.45. Plots had higher pH, N, K, Ca, Mn and organic carbon compared. Winter annual clover and vetch species prefer well-drained soils, sandy to loam with a neutral to slightly alkaline pH (7-8) for optimum growth.

Table 4.2 Soil chemical and physical properties before pasture establishment in 2018.

Soil properties	
pH(KCl)	7.50
N (%)	0.10
P (mg/L)	27.50
K (mg/L)	391
Ca (mg/L)	921
Mg (mg/L)	594
Zn (mg/L)	2.46
Mn (mg/L)	15.5
Cu (mg/L)	3.1
Org. C (%)	0.89
Clay (%)	33
Silt (%)	16
Sand (%)	51

4.3.4 Crop husbandry

Before planting, the land was prepared by first controlling the weeds using a motorized slasher, followed by the application of Roundup, a non-selective, systematic, broad-spectrum glyphosate-based post-emergence herbicide one month after slashing. A 250 mL volume of Roundup was used in 10 liters of water. Annual clover and vetch cultivars were planted 15 days after herbicide application by hand in rows of 5 m with an inter-row spacing of 15 cm under a no-tillage condition. Each subplot was 5 m x 3 m, giving an area of 15 m^2. Planting density was as presented in Table 1. All seeds were inoculated with the appropriate *Brady rhizobium* species. Seeds were planted on the 26th June 2018 and 25th July 2018, 23rd June 2019 and 25th July 2019, 24th June 2020 and 25th July 2020 for planting dates 1 and 2, respectively. According to Dickinson *et al.* (2004), optimum P-levels (Bray 1) of > 30 mg/kg and K-levels of > 140 mg/kg are required. Therefore, 20 kg P ha^{-1} of superphosphate was applied before planting to improve the phosphorus level. Irrigation (15 mm) was carried out twice a week by Rain Bird sprinklers. Estimates of water applied were measured regularly using rain gauges and readings were taken after each irrigation period. Weeding was carried out manually during the 3rd and 4th weeks after planting and as the need arose, using hoes and handpicks.

4.3.5 Weather conditions during the experimentation

Daily/seasonal weather data for the duration of the experiment was acquired from South African Weather Services (SAWS) through a weather station located at the farm, which was used to access daily weather data.

4.3.6 Agronomic data collection

Leaf gas exchange [photosynthetic rate (A), stomatal conductance (Gs), transpiration (E) and intercellular CO_2 concentration (Ci)] were measured biweekly on five of the youngest fully expanded, solar radiation-exposed leaves per treatment using a portable photosynthesis system (ADC Bio Scientific, UK). All the measurements were carried out under steady-state conditions in full sun between 10:00 am and 1:00 pm (Clifford *et al*., 1997).

Using the measured leaf gaseous exchange parameters, the eco-physiological approach method according to Katerji *et al*. (2008) was used to compute two water-use efficiency parameters at leaf level for each cultivar: Instantaneous water use efficiency (WUEinst), which is defined as the ratio of photosynthetic rate (A) to transpiration rate (E) per leaf unit area (A/E). Intrinsic water use efficiency (WUEintr) was computed as the ratio of photosynthetic rate (A) to stomatal conductance Gs (A/Gs).

The most important trait of any forage crop is rapid biomass production during early vegetation stage (Capstaff and Miller, 2018). Biomass production was quantified on biweekly sampling, which was initiated at the 49 DAP when pastures are deemed ready to be grazed until 50% flowering for each cultivar. At 49 DAP pastures deemed ready for grazing because they have accumulated adequate leave biomass to tolerate grazing and enough photosynthates for fast regrowth post grazing (Rotz and Muck, 1994) and (Bumb *et al.,* 2016). Final harvesting at 50% flowering is critical because pastures have reached the development and growth stages associated with biomass production, and as they enter the seed setting stage, all the photosynthates from leaves to seed development (source-sink) deviate and eventually lose all the good quality characteristics required for livestock feeding (Herrmann *et al*., 2010). At each harvesting stage, plots were irrigated a day before harvesting and whole plants from 1 x 1 m^2 quadrat were uprooted from each plot to determine biomass production. Plants from all harvested plots were separated into shoots (leaves and stems), roots and nodule fractions. Nodule production from five plants randomly selected in a quadrat was determined by placing plants in a plastic bucket filled with water to loosen the bound soil with a sieve to cater for the detached nodules. The nodules were hand-picked from the roots, and the fresh nodule weight was ultimately measured using an electronic micro-scale. Samples were dried at 80°C for 48 h and weighed for determination of dry mass.

The dried samples collected for shoot DM determination at 105DAP (50% flowering) were milled through a 1 mm screen using a hammer mill to determine the nutritive value of forages. The standard macro-Kjeldahl method (Association Of Analytical Chemists, 2005, method no. 978.04) was used to determine the total nitrogen content and was converted into crude protein (CP) by multiplying percentage of N content by a factor 6.25. The ash, NDF, and ADF were measured using standard processes of the Van Soest *et al*. (1991).

4.3.7 Data analysis

Data were analysed with the Statistical Analysis System 9.4 (SAS 9.4) software using the standard procedure of analysis of variance (ANOVA) to determine the effects of planting date, cultivar and harvesting stage on the parameters studied. Data were analysed for 2018, 2019 and 2020 growing seasons separately. Post Hoc comparisons for observed means were compared at probability levels of $p \leq 0.05$ using least significant difference (LSD). Relationships between parameters were assessed through correlation analysis.

4.4 RESULTS

4.4.1 Weather parameters during the growing season

Figures 4.2 and 4.3 illustrate the 7-year long-term monthly temperatures and the growing season temperatures respectively. The long-term minimum temperature ranged from 6.36 °C - 14.98 °C, maximum temperature from 24.10 °C - 27.45 °C, and the average, from 15.23 °C - 21.22 °C. In the 2018 growing season, the minimum and maximum temperatures were recorded at 3.34 °C and 22.7 °C, 3.53 °C and 20. 29 °C for June and July respectively (Figure 4.3) with June's average temperature being 1 °C higher while July was 1 °C lower than the 7-year long-term monthly average of the same months (Figure 4.3). The 2019 temperatures ranged between 12.95 °C and 22.86 °C, 12.60 °C and 23.96 °C for June and July respectively with the June and July average temperatures similar to their long-term averages. In 2020, the minimum and maximum temperatures were between 18.84 °C and 25.42 °C, 18.82 °C and 25. 52 °C for June and July respectively. Both the June and July average temperatures were 5°C higher than their long-term monthly averages. According to Lonati *et al*. (2009) and Nori *et al*. (2014), temperature requirements for clover and vetch are the base temperature ranging from 0 °C to 4 °C, optimal temperature between 12 °C and 25 °C and maximum temperature between 25 °C and 30 °C. Therefore, June and July months were suitable for planting the annual clover and vetch pastures.

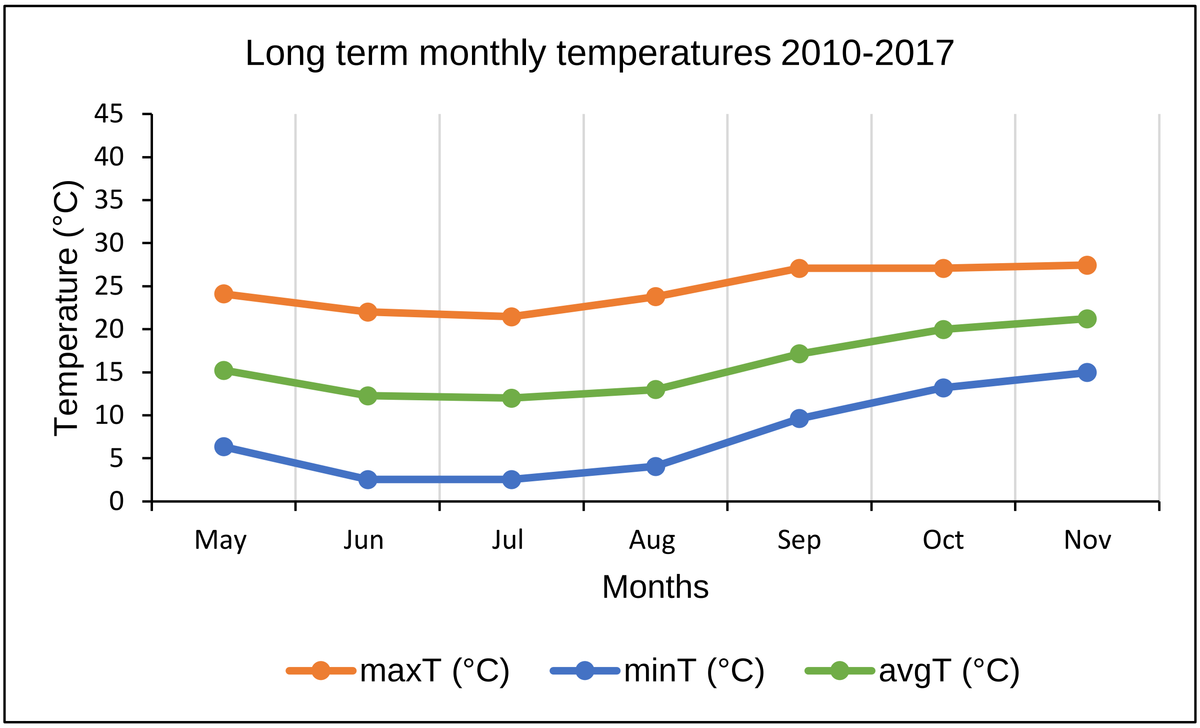

Figure 4.2 Long-term monthly average temperatures 2010-2017. maxT-Mean monthly maximum, minT-mean monthly minimum and avgT-Average monthly temperatures temperatures at the project site.

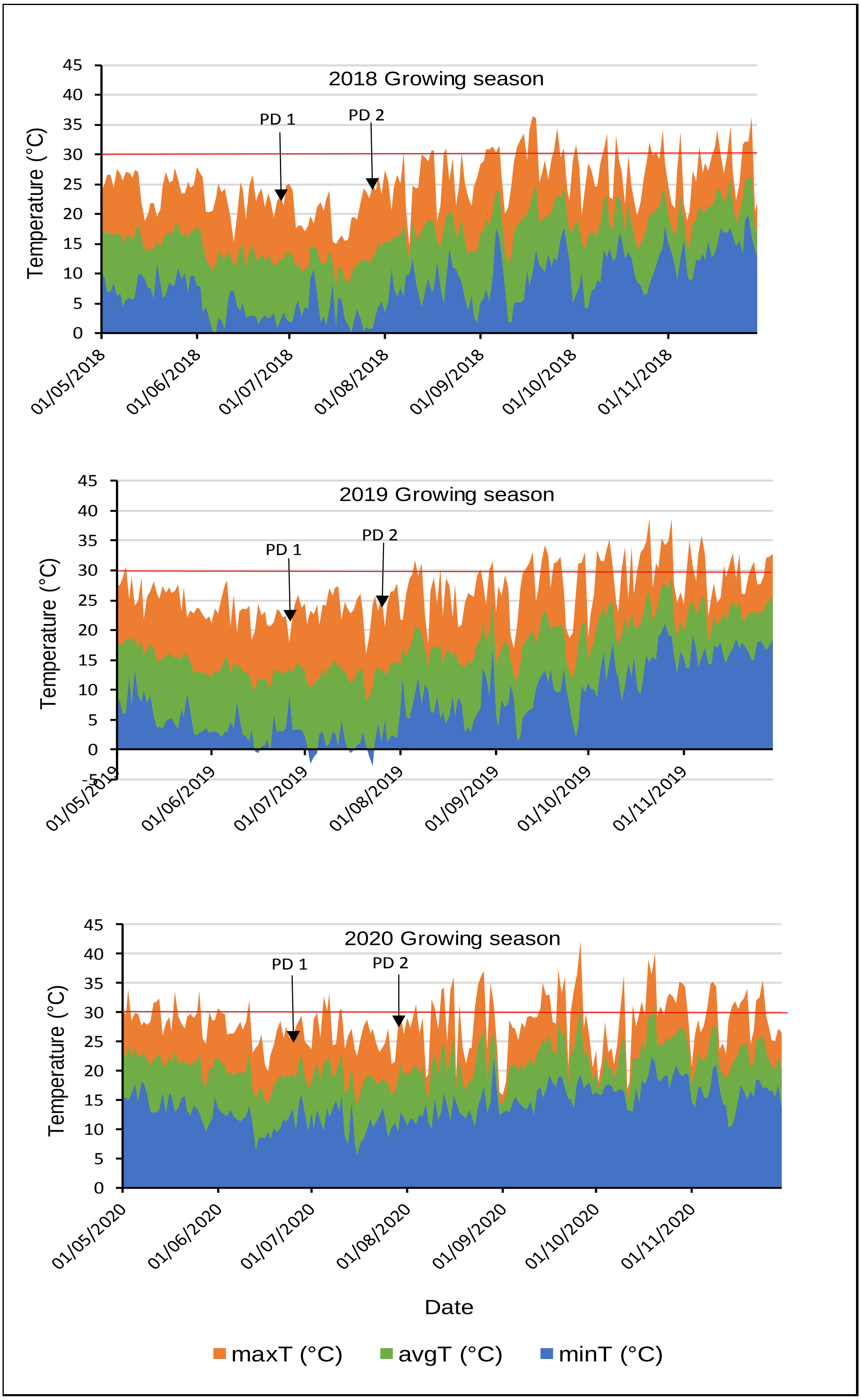

Figure 4.3 Daily maximum, average and minimum temperatures during 2018, 2019 and 2020 growing seasons. Black Arrows indicate June and July as planting dates respectively. The red horizontal line indicates temperatures above the maximum requirements of legumes.

4.4.2 Leaf gaseous exchange

Planting date, cultivar and harvesting stage had a significant effect on the leaf gaseous exchange parameters including Ci- intercellular CO_2 concentration, E-transpiration rate, Gs-stomatal conductance, A-photosynthetic rate, WUEinst-instantaneous water use efficiency and WUEintr-intrinsic water use efficiency of annual clover and vetch cultivars across the three growing seasons. The results are presented in Tables 4.3, 4.4 and 4.5 for 2018, 2019 and 2020 growing seasons, respectively. As shown in Table 4.3, in 2018, the interaction of planting date x cultivar had no significant effect on Ci, E and Gs. Except for the Gs and A, other leaf gaseous exchange traits such as Ci, E, WUEinst and WUEintr were not significantly affected by planting date x harvesting stage interaction. The cultivar x harvesting stage interaction had significant effects on all the leaf gaseous exchange traits. The three-factor interaction had a significant effect on all the leaf gaseous exchange traits except for E and the results are illustrated in Figure 4.4.

Table 4.4 present the leaf gaseous exchange response in the 2019 growing season. The interaction of planting date x cultivar had a significant effect on all the leaf gaseous exchange traits except on E, Gs and WUEinst. Planting date x harvesting stage interaction had significantly affected E, A, WUEinst and WUEintr. The cultivar x harvesting stage interaction had significant effects on all the leaf gaseous exchange traits. The three-factor interaction had a significant effect on all the leaf gaseous exchange traits except for E and the results are shown in Figure 4.5.

Table 4.5 present the leaf gaseous exchange response in the 2020 growing season. The interaction of planting date x cultivar had a significant effect on all the leaf gaseous exchange traits except on WUEinst. Planting date x harvesting stage interaction had a significant effect on all leaf gaseous exchange traits except on E. The effect of cultivar x harvesting stage interaction on all the leaf gaseous exchange traits was also significant. The planting date x cultivar x harvesting stage interaction was significant on all the leaf gaseous exchange traits and the results are shown in Figure 4.6.

Table 4.3 Leaf gaseous exchange response of annual clover and vetch cultivars to planting date and harvesting stage, 2018 growing season.

			2018 Growing season			
Treatments	Ci (mol m^{-2} s^{-1})	E (mmol m^{-2} s^{-1})	Gs (mol m^{-2} s^{-1})	A (µmolm^{-2} s^{-1})	WUEinst (µmol mmol^{-1})	WUEintr (µmol mol^{-1})
Planting date (PD): Across cultivars and harvesting stages						
PD1- June	255b	8.52b	0.37a	19.74a	2.53a	55.95a
PD2 - July	281a	9.68a	0.35b	14.75b	1.69b	46.92b
LSD	**8.077**	**0.2292**	**0.0179**	**0.4564**	**0.0893**	**3.3109**
Cultivar (CV): Across planting dates and harvesting stages						
Alex	240e	5.73f	0.36ab	18.35c	3.26a	52.94ab
Baumans	265cd	10.31ab	0.37ab	20.46ab	2.16d	59.02a
Capello	274abcd	10.38a	0.33b	14.61e	1.53g	47.09bc
Ellite	263cd	6.95e	0.35b	19.83b	2.88b	59.56a
Hanka	262cd	10.35ab	0.36ab	14.84e	1.54g	43.79c
Laser	256de	9.77c	0.35b	16.91d	1.82ef	54.95ab
Linkarus	291a	9.27ab	0.35b	14.52e	1.73fg	44.55c
Opolska	285a	9.65b	0.35b	16.59d	1.97de	51.36abc
Resal	266bc	8.74a	0.40a	20.91a	2.53c	54.27ab
Timok	279ab	9.81ab	0.36ab	15.41e	1.70fg	46.81bc
LSD	**18.061**	**0.5126**	**0.04**	**1.02**	**0.1997**	**7.40**
Harvesting stage (HS): Across planting dates and cultivars						
63DAP	330a	5.21d	0.27c	9.86d	2.00b	40.25c
77DAP	257c	8.16c	0.40b	21.70a	2.87a	57.89b
91DAP	213d	13.31a	0.47a	19.90b	1.65c	44.06c
105DAP	273b	9.72b	0.29c	17.52c	1.93b	63.54a
LSD	**11.48**	**0.33**	**0.025**	**0.619**	**0.124**	**4.695**
PD*CV	0.2543ns	0.3008ns	0.5061ns	0.0002 **	0.0001***	0.0001***
PD*HS	0.1885ns	0.0579ns	0.0001 ***	0.0001***	0.3754ns	0.1847ns
CV*HS	0.0001***	0.0001***	0.0034**	0.0001***	0.0001***	0.0001***
PD*CV*HS	0.0028**	0.7192ns	0.024*	0.0001***	0.0001***	0.0001***

Numbers represent the means. Letters designate significant differences. Means with the same letters within the columns are not significant from each other at a 5% probability level. Ci- Intercellular CO2 concentration, E-Transpiration rate, Gs-Stomatal conductance, A-Photosynthetic rate, WUEinst-Instantaneous water use efficiency, WUEintr-Intrinsic water use efficiency, *** indicate highly significant difference P < 0.001, ** indicate significant differences P < 0.01, * indicate significant differences P < 0.05, ns-non significant.

Table 4.4 Leaf gaseous exchange response of annual clover and vetch to planting date and harvest day, 2019 growing season.

			2019 Growing season			
Treatments	Ci (mol m^{-2} s^{-1})	E (mmol m^{-2} s^{-1})	Gs (mol m^{-2} s^{-1})	A (μmolm^{-2} s^{-1})	WUEinst (μmol $mmol^{-1}$)	WUEintr (μmol mol^{-1})
Planting date (PD): Across cultivars and harvesting stages						
PD1- June	251b	9.69b	0.39b	18.97a	2.08a	51.56 a
PD2 - July	274a	10.91a	0.48a	15.04b	1.48b	32.61 b
LSD	**7.713**	**0.277**	**0.020**	**0.633**	**0.083**	**3.344**
Cultivar (CV): Across planting dates and harvesting stages						
Alex	252de	7.58f	0.49ab	18.79ab	2.52a	40.26bcd
Baumans	283ab	10.77c	0.43cde	19.85a	2.01c	51.57a
Capello	264cd	11.62ab	0.39e	14.55ef	1.30e	45.36abc
Ellite	265cd	8.28e	0.45bcd	19.51a	2.35ab	43.75bc
Hanka	291a	12.05a	0.41de	14.82ef	1.33e	39.78bc
Laser	242ef	9.73d	0.42cde	17.66bc	1.84c	47.19ab
Linkarus	268bcd	11.08bc	0.46bc	13.78f	1.30e	31.97d
Opolska	271bc	11.24bc	0.44cd	16.51cd	1.53d	39.55c
Resal	229f	8.69e	0.52a	19.23a	2.29b	38.24cd
Timok	264cd	12.00a	0.39e	15.40de	1.35de	43.19bc
LSD	**17.248**	**0.6196**	**0.045**	**1.41**	**0.186**	**7.47**
Harvesting stage (HS): Across planting dates and cultivars						
63DAP	353a	6.06d	0.32c	9.77c	1.67b	36.01c
77DAP	266b	10.08c	0.45b	20.50a	2.22a	50.14a
91DAP	188d	14.51a	0.54a	21.22a	1.57b	41.16b
105DAP	245c	10.56b	0.45b	16.55b	1.68b	41.04b
LSD	**10.90**	**0.384**	**0.028**	**2.46**	**0.911**	**4.62**
PD*CV	0.0073 **	0.0903 ns	0.1542ns	0.0034**	0.2472ns	0.0214*
PD*HS	0.2646 ns	0.0001***	0.5217ns	0.0001***	0.0002**	0.0281*
CV*HS	0.0001 ***	0.0001***	0.0001***	0.0001***	0.0001***	0.0003**
PD*CV*HS	0.0002 **	0.0736ns	0.0293*	0.0121*	0.0036**	0.0225*

Numbers represent the means. Letters designate significant differences. Means with the same letters within the columns are not significant from each other at a 5% probability level. Ci- Intercellular CO2 concentration, E-Transpiration rate, Gs-Stomatal conductance, A-Photosynthetic rate, WUEinst-Instantaneous water use efficiency, WUEintr-Intrinsic water use efficiency, *** indicate highly significant difference P<0.001, ** indicate significant differences P < 0.01, * indicate significant differences P < 0.05, ns-non significant.

Table 4.5 Leaf gaseous exchange response of annual clover and vetch to planting date and harvest day, 2020 growing season.

	2020 Growing season					
Treatments	Ci (mol m^{-2} s^{-1})	E (mmol m^{-2} s^{-1})	Gs (mol m^{-2} s^{-1})	A (μmolm^{-2} s^{-1})	WUEinst (μmol $mmol^{-1}$)	WUEintr (μmol mol^{-1})
Planting date (PD): Across cultivars and harvesting stages						
PD1- June	223a	8.39b	0.33b	18.19a	6.33a	62.04a
PD2 - July	216b	9.72a	0.37a	15.94b	5.03b	43.66b
LSD	**5.37**	**0.29**	**0.015**	**0.61**	**0.32**	**4.30**
Cultivar (CV): Across planting dates and harvesting stages						
Alex	197d	6.85d	0.37bc	20.71a	8.95a	58.19bc
Baumans	230ab	8.41c	0.32ef	19.66a	7.29b	66.40ab
Capello	213c	9.56b	0.32f	16.77bc	4.92de	56.10cd
Ellite	216c	8.41c	0.34cdef	18.10b	7.15bc	60.11abc
Hanka	216c	11.00a	0.35bcde	16.12c	3.82g	50.15de
Laser	242a	8.60c	0.33def	16.79bc	5.41d	55.45cd
Linkarus	214c	9.99b	0.41a	13.72d	4.64ef	33.96f
Opolska	217c	9.34b	0.37bc	14.48d	4.09fg	42.88ef
Resal	224bc	8.58c	0.36bcd	20.97a	6.48c	67.88a
Timok	234ab	9.83b	0.38ab	13.37d	4.08fg	37.42f
LSD	**12.03**	**0.66**	**0.033**	**1.35**	**0.72**	**9.62**
Harvesting stage (HS): Across planting dates and cultivars						
63DAP	305a	4.91d	0.24c	10.24d	2.27b	53.56a
77DAP	184c	9.82b	0.44a	23.12a	16.58a	54.85a
91DAP	170d	13.57a	0.43a	18.11b	1.48c	44.81b
105DAP	222b	7.93c	0.31b	16.80c	2.41b	58.19a
LSD	**7.60**	**0.41**	**0.02**	**0.86**	**0.46**	**6.08**
PD*CV	0.0001***	0.0081**	0.0162*	0.0033**	0.2999ns	0.0035**
PD*HS	0.0001***	0.3395ns	0.0001***	0.0262*	0.0001***	0.0001***
CV*HS	0.0001***	0.0001***	0.0001***	0.0001***	0.0001***	0.0002**
PD*CV*HS	0.0001 **	0.0008**	0.0006**	0.0022**	0.0201*	0.0011**

Numbers represent the means. Letters designate significant differences. Means with the same letters within the columns are not significant from each other at a 5% probability level. Ci-Intercellular CO2 concentration, E-Transpiration rate, Gs-Stomatal conductance, A-Photosynthetic rate, WUEinst-Instantaneous water use efficiency, WUEintr-Intrinsic water use efficiency, *** indicate highly significant difference P < 0.001, ** indicate significant differences P < 0.01, * indicate significant differences P < 0.05, ns-non significant.

Intercellular CO_2 concentration (Ci) was significantly higher ($P < .0001$) at planting date 2 (July) than that of planting date 1, 281 vs 255 molm^{-2} s^{-1} in 2018. A similar effect was observed for the 2019 and 2020 growing seasons, which recorded 274 vs. 251 molm^{-2} s^{-1} and 223 vs. 216 molm^{-2} s^{-1}, respectively. Cultivars responded differently across the planting dates and harvest days (P <.0001). Linkarus, Opolska, Timok Capello, Hanka and Dr Baumans were the cultivars that consistently had higher Ci values across the different planting dates and harvesting stages. Resal, Alex and Lazer had constantly the lowest Ci recorded across the three growing seasons. Ci of all cultivars was high at 63DAP and gradually declined with time as the crops grew, reaching the minimum values at 91DAP (flower initiation), followed by an increase until 105DAP at 50% flowering (Figures 4.4, 4.5 and 4.6). Contrary to this trend, cultivars like Opolska and Hanka responded slightly differently, recording the lowest Ci at 77DAP followed by a gradual increase until 105DAP.

Transpiration rate (E) was significantly affected (P < .0001) by planting date, with higher rates observed in planting date 2 compared to planting date 1 across the three growing seasons. The E recorded for planting date 2 was 9.68, 10.91 and 9.7 mmolm^{-2} s^{-1} in 2018, 2019 and 2020, respectively, while that of planting date 1 was 8.52, 9.69, and 8.39 mmolm^{-2} s^{-1} for the three growing seasons. In 2018 and 2019, the transpiration rate was non-significantly responsive to the interaction of plant date, cultivar and harvest day. However, the E of cultivars increased with harvest days as crops developed, plateaued at 91DAP (flower initiation) and then declined. Capello, Hanka, Timok and Linkarus were observed to have high E at 91DAP, while Alex, Elite, Laser and Resal consistently had low E across planting dates and growing seasons (Figures 4.4, 4.5 and 4.6).

Stomatal conductance (Gs) was significantly higher (P ≤ 0.0279) for planting date, with planting date 1 recording The planting date x cultivar x harvesting stage interaction was significant on all the leaf gaseous exchange traits higher value (0.37 molm^{-2}s^{-1}) compared to planting date 2 (0.35 molm^{-2}s^{-1}) in 2018. Contrary results were observed in the 2019 and 2020 growing seasons where high Gs were recorded on the planting date 2 crops. Cultivars also responded differently (P < .0001) across the harvesting stages. Three response curves were observed based on the marked varied fluctuation patterns of cultivars (Fig. 4.4, 4.5 and 4.6). Gs of cultivars like Resal, Elite, Dr Baumans, Hanka, Timok and Linkarus increased gradually until reaching a peak at 91DAP, then followed by a decline. However, Alex and Capello showed a Gs spike increase in 77DAP followed by a decline until 105DAP. Lastly, the Gs of Laser and Opolska tend to start at a higher rate and continue to fluctuate across the harvest days and peak at 105DAP.

Across the three growing seasons, the photosynthetic rate (A) was significantly higher ($P < .0001$) under planting date 1 than planting date 2. Photosynthetic rate values recorded for planting date 1 were 19.74, 18.97 and 18.19 molm^{-2} s^{-1} in 2018, 2019 and 2020, respectively, relative to 14.75, 15.04 and 15.94 molm^{-2} s^{-1} of planting date 2. Cultivars responded differently across the planting dates and harvest days ($P < .0001$). Generally, A of most cultivars started at a lower rate but increased with harvest days and reached a peak at either 77DAP or 91DAP. Overall, post 91DAP, flower initiation, a decline in A was observed for all the cultivars. Higher rates were recorded by Resal, Alex, Lazer, Elite and Dr Baumans and lower rates by Capello, Hanka and Linkarus on both planting dates across the three growing seasons (Figures 4.4, 4.5 and 4.6).

Instantaneous water use efficiency (WUEinst) of cultivars decreased with planting date, planting date 1 yielding a significantly higher ($P < .0001$) WUEinst in all three growing seasons. In 2018, 2019 and 2020, the WUEinst observed for planting date 1 was 2.53, 1.69, and 1.48 µmol mmol^{-1} compared to 2.08, 5.03, and 6.33 µmol mmol^{-1} for planting date 2. Across the two planting dates, WUEinst of most cultivars started at a lower rate (63DAP) but increased and reached a peak at 77DAP, during the advanced vegetative phase. WUEinst was the lowest at 91DAP and remained either stable or declined further towards 105DAP. Cultivars responded significantly differently ($P < .0001$) across the harvest days and as per their response trends, three groups were observed. Alex, Elite and Dr Baumans have frequently been observed to have a higher WUEinst, followed by Resal, Laser and Hanka and lastly Timok, Opolska, Capello and Hanka as cultivars with the lowest WUEinst. (Figures 4.4, 4.5 and 4.6).

Planting date had a significant ($P < .0001$) influence on intrinsic water use efficiency (WUEintr), which decreased with delayed planting over the course of the experiment. A decrease from 62.04 to 43.66 µmolmol^{-1}, 51.56 to 32.61 µmolmol^{-1} and 62.04 to 43.66 µmolmol^{-1} in 2018, 2019 and 2020, respectively, was observed with delayed planting. The WUEintr of cultivars differed significantly ($P < .0001$) across harvest days, as evidenced by varying fluctuation responses. At 63DAP and 105DAP, lower efficiency was observed. However, cultivars reached peak WUEinst either at 77DAP or 91DAP. Across the three growing seasons, Alex, Resal, Elite, Laser, and Dr Baumans have frequently been observed to have a higher WUEintr and Linkarus, Opolska, and Timok had the lowest efficiency (Figures 4.4, 4.5 and 4.6).

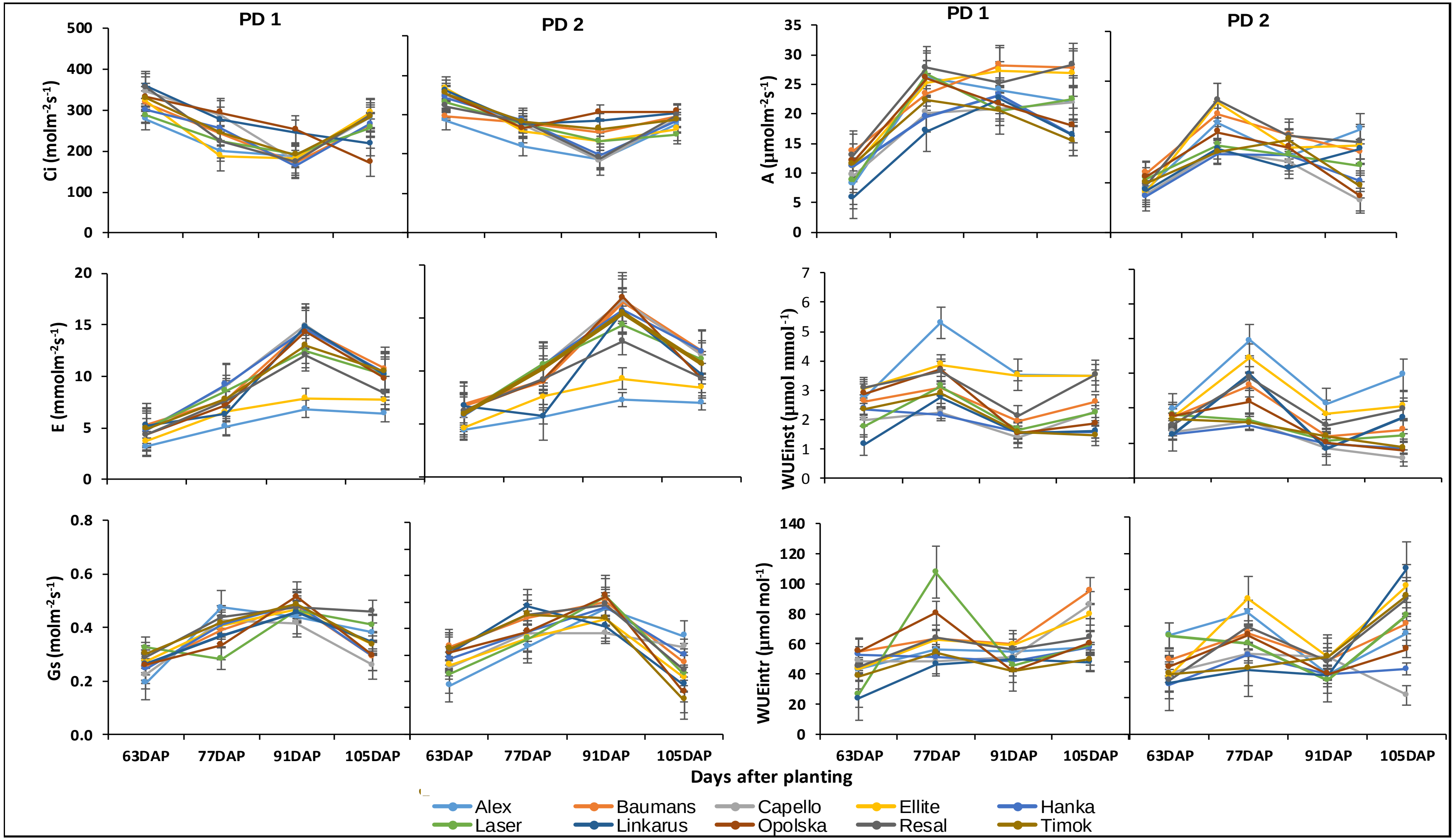

Figure 4.4 Seasonal variations in leaf gaseous exchange response of annual vetch and clover cultivars to planting date and harvest day in 2018. Intercellular CO_2 concentration - Ci, Transpiration rate - E, Stomatal conductance - Gs, Photosynthetic rate – A. Error bars represent ± standard error.

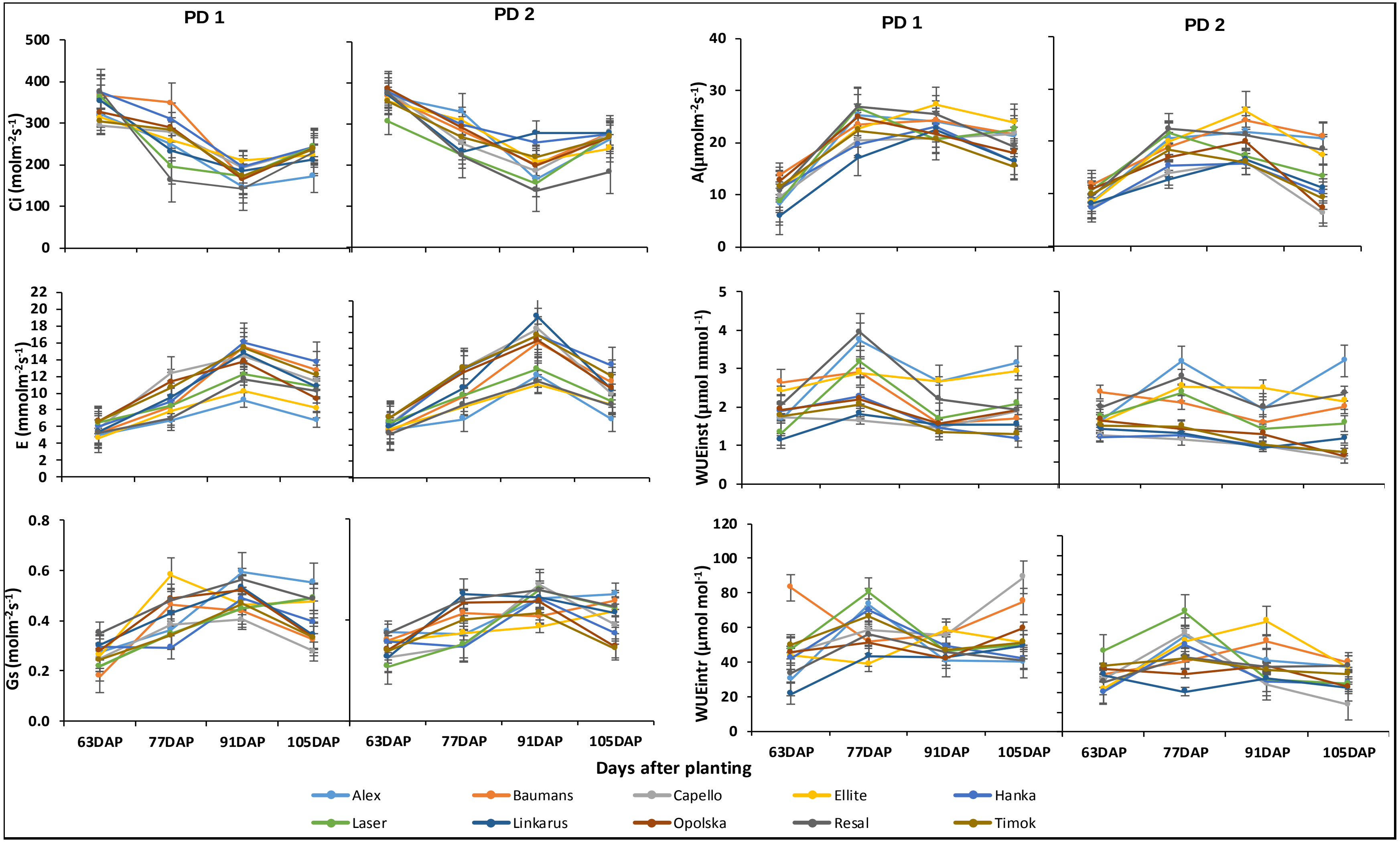

Figure 4.5 Seasonal variations in leaf gaseous exchange response of annual vetch and clover cultivars to planting date and harvest day in 2019. Intercellular CO_2 concentration - Ci, Transpiration rate - E, Stomatal conductance - Gs, Photosynthetic rate – A. Error bars represent ± standard error.

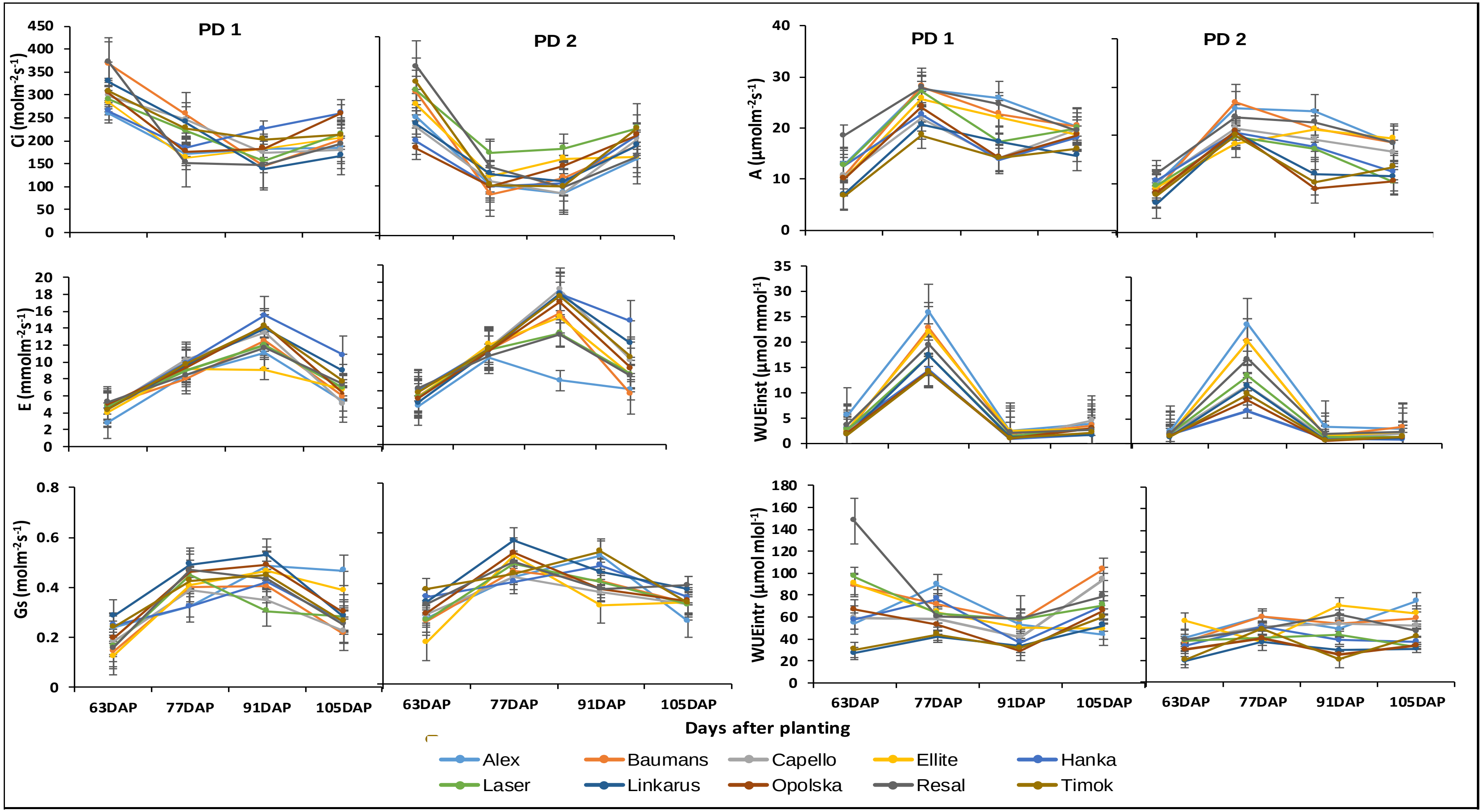

Figure 4.6 Seasonal variations in leaf gaseous exchange response of annual vetch and clover cultivars to planting date and harvest day in 2020. Intercellular CO_2 concentration - Ci, Transpiration rate - E, Stomatal conductance - Gs, Photosynthetic rate – A. Error bars represent ± standard error.

4.4.3 Biomass production

The influence of planting date, cultivar, harvest day and their interactions on biomass attributes (shoot DM and root DM) is presented in Table 4.6. The results indicate that planting date, cultivar and harvest day had a highly significant influence ($P < .0001$) on biomass attributes across the three growing seasons (2018 - 2020) of the study period. Planting date 2 (July) consistently produced significantly lower ($P < .0001$) shoot DM and root DM as compared to planting date 1 (June) in all three growing seasons. Shoot DM decreased by 20% both in 2018 and 2019 and 22% in 2020 for planting date 2 compared to planting date 1. Similarly, delayed planting in July consistently produced significantly lower ($P < .001$) root DM, as compared with early planting in June across the three growing seasons. Root DM decreased by 27%, 22%, and 12%, in 2018, 2019 and 2020 respectively for planting date 2 compared to planting date 1.

Cultivars differed significantly ($P < .001$) in terms of shoot DM and root DM produced. Shoot DM of cultivars ranged between 996 kg ha^{-1} and 3821 kg ha^{-1}, 958 kg ha^{-1} and 3713 kg ha^{-1}, 1085 kg ha^{-1} and 4539 kg ha^{-1} in 2018, 2019 and 2020 respectively. Root DM of cultivars ranged between 159 kg ha^{-1} and 669 kg ha^{-1}, 123 kg ha^{-1} and 492 kg ha^{-1}, 253 kg ha^{-1} and 742 kg ha^{-1} in 2018, 2019 and 2020 respectively. Across the three growing seasons, Resal had consistently and significantly outperformed all the cultivars and Opolska attained significantly the lowest shoot and root DM. Across the two planting dates in the three growing seasons, cultivars can be classified into distinct yield groups with Resal, Alex, Laser, Elite and Dr Baumans as high producers recording significantly higher shoot DM and root DM while Capello, Hanka, Timok, Linkarus and Opolska are low producers.

Overall, the harvest stage had a highly significant ($P < .0001$) effect on biomass accumulation. Lower shoot and root DM was observed on the initial harvest day, 49DAP while 105DAP recorded the highest DM. Harvest day had a similar effect across all three growing seasons indicating that the DM attributes increased with harvest days as the cultivars advanced with maturity.

Table 4.6 Effect of planting date, cultivar and harvest day on biomass attributes of winter annual clover and vetch.

	2018		2019		2020	
Treatments	**Shoot DM**	**Root DM**	**Shoot DM**	**Root DM**	**Shoot DM**	**Root DM**
			Planting date (PD)			
PD1- June	2897 ± 2153^{a}	503± 340^{a}	2790 ± 2049^{a}	366 ± 258^{a}	3385 ± 2469^{a}	541 ±307^{a}
PD2 - July	2312 ± 1712^{b}	367 ± 264^{b}	2224 ± 1640^{b}	287 ± 204^{b}	2650 ± 1978^{b}	477± 307^{b}
LSD	**39.61**	**9.13**	**33.58**			
			Cultivar (CV)			
Alex	3674 ± 2164^{b}	620 ± 325^{bc}	3539 ± 2056^{b}	462 ± 253^{b}	4233 ± 2449^{bc}	713 ± 355^{b}
Dr Baumans	2862± 1687^{d}	462 ± 237^{d}	2730 ± 1600^{d}	356 ± 186^{c}	3328 ± 1895^{d}	488 ± 221^{d}
Capello	2579 ± 1442^{e}	429 ± 206^{e}	2470 ± 1361^{e}	328 ± 159^{d}	3021 ± 1608^{e}	445 ± 197^{e}
Ellite	3687 ± 2273^{b}	638 ± 350^{b}	3528 ± 2153^{b}	460 ± 269^{b}	4319 ± 2535^{b}	674 ± 315^{c}
Hanka	2096 ± 1542^{f}	308 ± 192^{f}	2000 ± 1449^{f}	238 ± 158^{e}	2380 ± 1741^{f}	375 ± 210^{f}
Laser	3504 ± 2030^{c}	612 ± 328^{c}	3409 ± 1922^{c}	460 ± 248^{b}	4170 ± 2256^{c}	711 ± 333^{b}
Linkarus	1090 ± 702^{h}	183 ± 101^{h}	1961 ± 655^{h}	139 ± 80^{g}	1152 ± 788^{h}	331 ± 162^{g}
Opolska	996 ± 996^{i}	159 ± 84^{i}	958 ± 569^{i}	123 ± 65^{h}	1085 ± 692^{h}	253 ± 119^{h}
Resal	3821 ± 2249^{a}	669 ± 356^{a}	3713 ± 2175^{a}	492 ± 272^{a}	4539 ± 2604^{a}	742 ± 322^{a}
Timok	1735 ± 1208^{g}	266 ± 156^{g}	1661 ± 1136^{g}	204 ± 127^{f}	1949 ± 1338^{g}	359 ± 220^{f}
LSD	**88.59**	**20.41**	**75.08**			
			Harvest day (HD)			
49DAP	613 ± 217^{e}	119 ± 50^{d}	572 ± 204^{e}	99 ± 36^{d}	653 ± 258^{e}	181± 75^{d}
63DAP	1381 ± 713^{d}	369 ± 247^{c}	1265 ± 655^{d}	230 ± 123^{c}	1659 ± 949^{d}	405 ± 190^{c}
77DAP	2408 ± 1084^{c}	640 ± 288^{a}	2551 ± 1151^{c}	450 ± 203^{b}	3100 ± 1495^{c}	668 ± 215^{b}
91DAP	4087 ± 1714^{b}	611 ± 256^{b}	3861 ± 1619^{b}	526 ± 221^{a}	4492 ± 1969^{b}	781 ± 273^{a}
105DAP	4533 ± 1807^{b}	-	4285 ± 1712^{a}	-	5184 ± 2081^{a}	-
LSD	**62.64**	**12.91**	**53.09**			
PD*CV	0.0001***	0.0001***	0.0001***	0.0001***	0.0001***	0.0001***
PD*HD	0.0001***	0.0001***	0.0001***	0.0001***	0.0001***	0.0001***
CV*HD	0.0001***	0.0001***	0.0001***	0.0001***	0.0001***	0.0001***
PD*CV*HD	0.0001***	0.0001***	0.0001***	0.0001***	0.0001***	0.0001***

DM-Dry matter, Numbers represent the means and standard deviation for each cultivar biomass attribute in 2018-2020. Letters designate significant differences between cultivars. Means with the same superscript within the columns are not significant from each other at a 5% probability level. *** indicate significant differences $P \leq 0.0001$.

The interaction of planting date, cultivar and harvest day was found to significantly ($P < .001$) influence shoot and root DM accumulation during the 2018, 2019 and 2020 growing seasons (Figure 4.7 and 4.8). The shoot DM results (Figure 4.7) showed that the DM accumulation of all clover and vetch cultivars followed a sigmoidal growth, low DM at initial harvest day (49DAP) flowed by a gradual increase to peak production at 91DAP (flower initiation stage) and 105DAP (50% flowering). Therefore the narrative of the results of the interaction in Figure 4.7 and 4.8 focused on the aforementioned harvest days. At 49DAP of planting date 1, Resal, Alex, Laser, Elite and Dr Baumans produced a minimum shoot DM ranging between 791 kg ha^{-1} and 921kg ha^{-1}, between 617 kg ha^{-1} and 730 kg ha^{-1} in planting date 2. These cultivars are quick starters with the potential to provide fodder early in the growing season. Their maximum shoot DM at 105DAP ranged from 6901 kg ha^{-1} to 8343 kg ha^{-1} and from 5451 kg ha^{-1} to 6658 kg ha^{-1} for planting dates 1 and 2, respectively. Capello and Hanka gave second higher shoot DM which were not significantly ($P>0.05$) different from one another, but significantly ($P<0.001$) different from the highest yielding group of cultivars. Across the three growing seasons, their minimum shoot DM at 49DAP ranged from 485 kg ha^{-1} to 728 kg ha^{-1} for planting date 1 and between 323 kg ha^{-1} and 677 kg ha^{-1} for planting date 2. Their maximum shoot DM 105DAP ranged from 5026 kg ha^{-1} to 6076 kg ha^{-1}, from 4440 kg ha^{-1} to 5568 kg ha^{-1} for planting dates 1 and 2 respectively. The lowest yielding group included Timok, Linkarus and Opolska. Within this group, Timok was significantly ($P<0.05$) higher at 105DAP only. Their minimum shoot DM at 49DAP ranged from 311 kg ha^{-1} to 356 kg ha^{-1} for planting date 1 and between 270 kg ha^{-1} and 329 kg ha^{-1} for planting date 2. Their maximum shoot DM 105DAP ranged from 3598 kg ha^{-1} to 4349 kg ha^{-1}, from 2640 kg ha^{-1} to 3191 kg ha^{-1} for planting dates 1 and 2, respectively, across the three growing seasons.

The interaction of planting date, cultivar and harvest day on root DM is presented in Fig. 4.8. Elite produced significantly ($P<0.01$) the highest root DM of 198 kg ha^{-1} from planting date 1 at 49DAP, however, its root DM accumulation was exceeded by that of Resal which achieved the highest root DM of 1054 kg ha^{-1} compared with 1038 kg ha^{-1} at 91DAP. Resal produced significantly ($P<0.05$) the highest root DM for planting date 2 across all the harvest days with a minimum of 145 kg ha^{-1} and a maximum of 750 kg ha^{-1} at 49DAP and 91DAP, respectively. Compared with other cultivars, root DM of Opolska was significantly ($P<0.01$) the lowest from planting date 2, ranging between 48 kg ha^{-1} and 190 kg ha^{-1} at 49DAP and 91DAP respectively. In terms of Root DM, cultivars can be classified into similar yield groups as those identified in shoot DM.

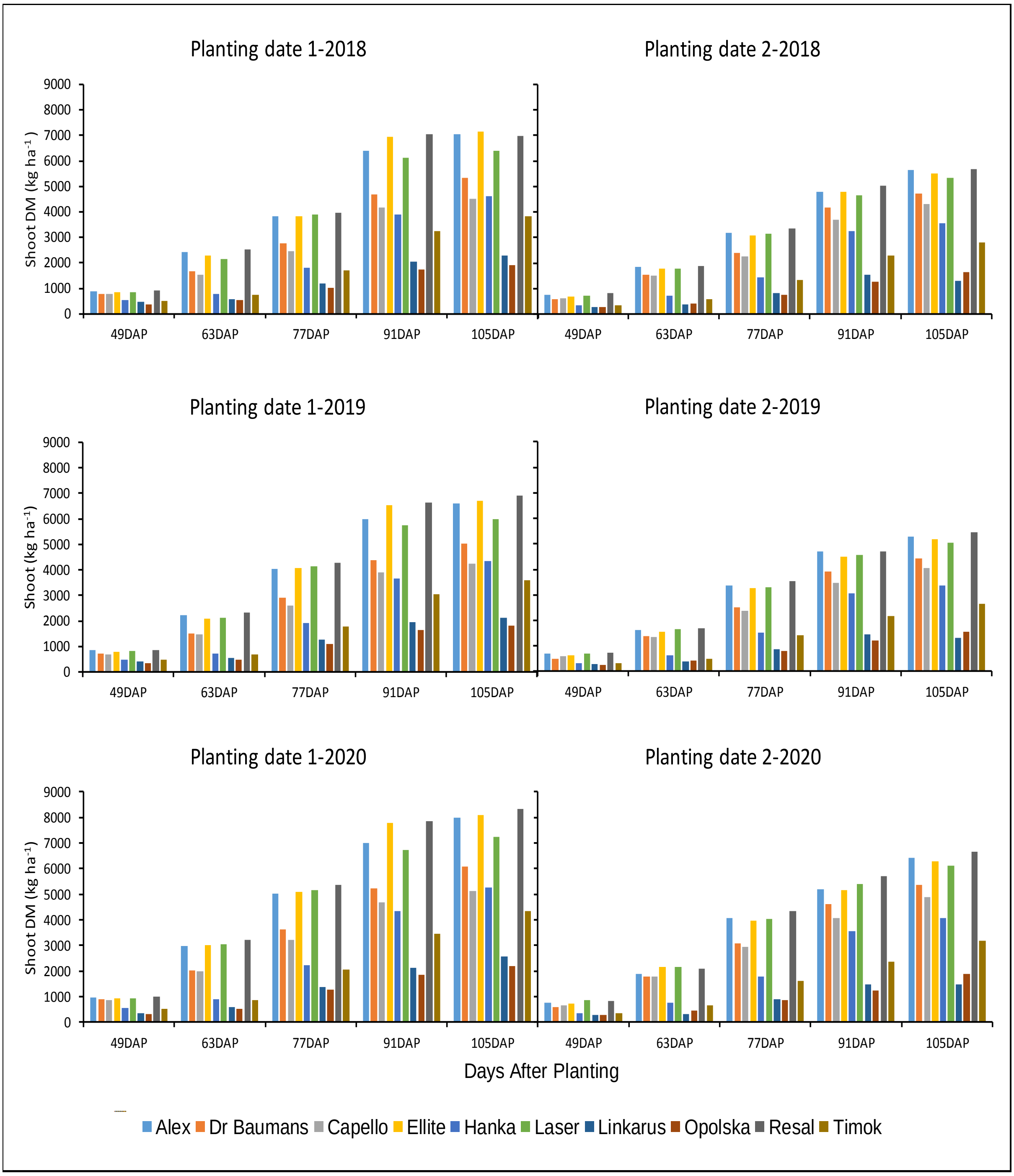

Figure 4.7 The interaction of planting date, cultivar and harvest day on shoot DM (kg ha^{-1}) observed during 2018 - 2020.

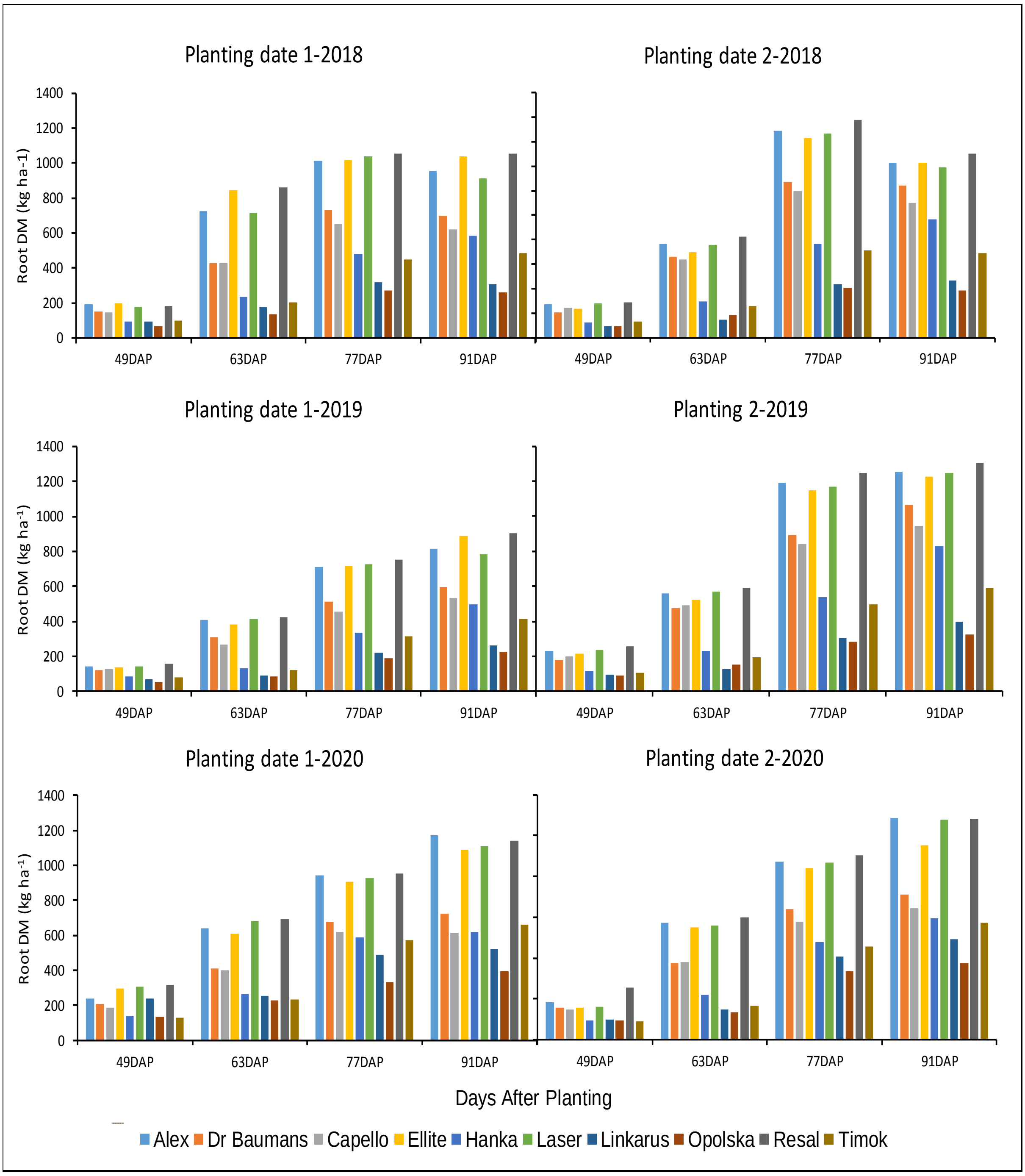

Figure 4.8 The interaction of planting date, cultivar and harvest day on root DM (kg ha-1) observed during 2018 - 2020.

4.4.4 Nodulation response

The results indicated that planting date, cultivar and harvest day had a highly significant influence ($P < .001$) on nodule DM across the three growing seasons (2018-2020). Nodule DM was not significantly affected by the interaction of planting date and harvest day in 2018 and 2020, and the interaction of planting date, cultivar and harvest day in 2019. Planting date 2 (July) consistently produced significantly lower ($P < .001$) nodule DM as compared with planting date 1 (June) in all three growing seasons. The effect of the interaction of planting date, cultivar and harvest day is shown in Figure 4.9. Hanka produced the highest nodule DM throughout the growing season with Opolska and Linkarus as the cultivars with poor nodulation ability. Nodule accumulation increased with time, significantly low at 63DAP followed by an increase until peak production at 77DAP and ultimately a decline at 91DAP, flower initiation.

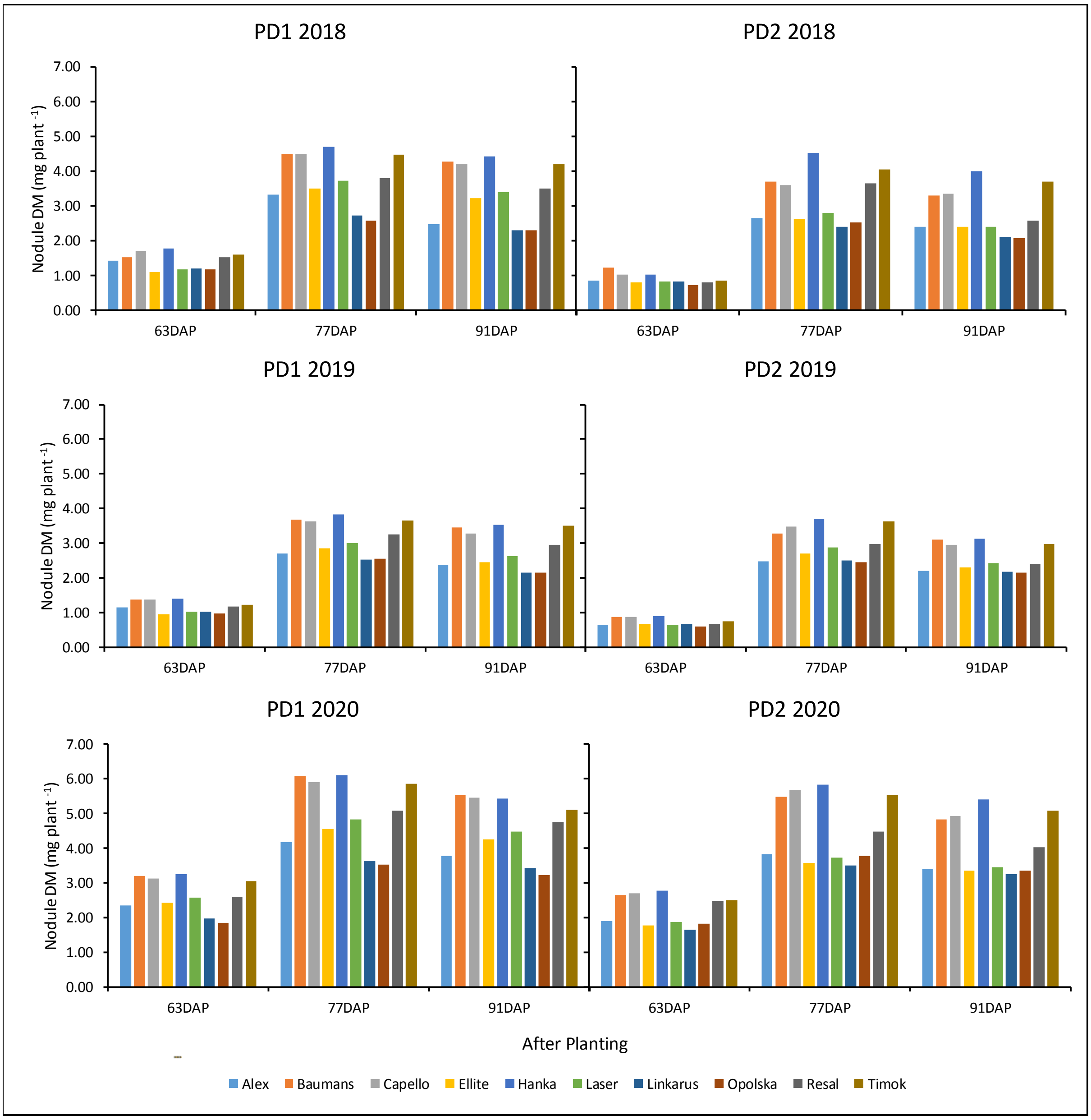

Figure 4.9 The interaction of planting date, cultivar and harvest day on nodule DM (mg plant^{-1}) as observed during 2018 - 2020.

4.4.5 Nutritive value of shoot DM

The nutritive value analysis of annual clover and vetch shoot DM harvested at 105DAP (50% flowering) revealed that neither planting date nor interaction effects were observed ($P > 0.05$) on the nutritive value traits including, ash, CP, ADF and NDF. However, a significant effect ($P < .0001$) on those traits was observed for cultivar (Table 4.7). Resal and Laser had similar but significantly ($P<0.05$) the highest ash content with Linkarus and Opolska significantly the lowest ash content, though non-significantly (P>0.05) different from each other. The ash content ranged from 9.8 to 16.5%.

Among the cultivars studied, Laser and Resal were significantly the highest with the maximum CP content of 22%, Timok and Hanka were significantly the lowest with a minimum of 14.7%. Regarding ADF, Opolska and Linkarus had significantly the highest ADF content with a maximum of 35.17% and Resal was a cultivar with significantly the lowest ADF of 27.33%. Among the ten cultivars, the highest NDF content was observed from Elite at 45.84% while the lowest content of 38.0% was found in Resal.

Table 4.7 Nutritive value of annual clover and vetch cultivars at 105DAP, 50% flowering*.*

Cultivars	Ash (%)	CP (%)	NDF (%)	ADF (%)
Alex	14.3 b	20.8 b	44.33 b	32.17 b
Dr Baumans	12.8 bc	19.5 c	41.17 e	30.00 c
Capello	11.8 de	18.2 d	42.67 cd	31.83 b
Ellite	13.8 bc	20.7 b	45.83 a	33.17 b
Hanka	9.8 g	17.7 d	44.00 bc	32.50 b
Laser	16.5 a	22.0 a	40.33 e	30.00 c
Linkarus	11.0 ef	15.3 e	41.00 e	34.83 a
Opolska	11.3 e	14.7 e	41.50 de	35.17 a
Resal	16.3 a	22.5 a	38.50 f	27.33 d
Timok	10.16 fg	18.7 d	43.33 cb	33.00 b
p value	***	***	***	***

Letters represent significant differences. Means with the same superscript within the columns are not significant from each other
at a 5% probability level. Significance levels: $*P < 0.05$, $***P < 0.001$, ns = not significant. CP-Crude protein, NDF-Neutral detergent fibre, ADF-Acid detergent fibre.

4.4.6 Correlation of shoot DM and leaf gaseous exchange parameters

The correlation analysis indicates that there were correlations between shoot DM and all the leaf gaseous parameters (Table 4.8). A strong negative correlation with Ci and E (-0.60 and -0.63, respectively) was observed. A positive correlation occurred between Gs (0.40) and A (0.40) and WUEintr (0.30) as well as a strong correlation with WUEinst (0.64), indicating the contribution of these parameters for better shoot DM accumulation. Ci was observed to have a weak negative relation with another gaseous parameter such as A, WUEinst and WUEintr however a weak positive relationship with E. A displayed a strong positive correlation with WUEinst and WUEintr. This suggests that cultivars with higher A have higher WUE.

Table 4.8 Correlation of shoot DM and leaf gaseous exchange parameters.

	Shoot DM	*Ci*	*E*	*GS*	*A*	*WUEinst*	*WUEintr*
Shoot DM	1						
Ci	**-0.60**	1.00					
E	**-0.63**	**0.32**	1.00				
GS	**0.40**	0.05	0.10	1.00			
A	**0.40**	**-0.37**	**-0.26**	**0.10**	1.00		
WUEinst	**0.64**	**-0.38**	**-0.83**	-0.02	**0.68**	1.00	
WUEintr	**0.30**	**-0.34**	**-0.26**	**-0.62**	**0.69**	**0.52**	1

4.5 DISCUSSION

Agronomical and breeding approaches are climate change adaptation strategies for sustained and increased biomass production, especially in semi-arid climatic conditions. The study hypothesized that planting date and harvest day do not affect the leaf gaseous exchange, biomass production, nodulation ability and nutritive value of no-till winter annual vetch and clover cultivars

4.5.1 Weather parameters during the growing season

According to Lonati *et al*. (2009) and Nori *et al*. (2014), temperature requirements for clover and vetch are the base temperature ranging from 0 °C to 4 °C, optimal temperature between 12 °C and 25 °C and maximum temperature between 25 °C and 30 °C. Therefore, June and July months were suitable for planting the annual clover and vetch pastures.

The daily maximum temperatures at the experimental site during vegetative growth until 50% flowering showed significant variation throughout the growing season, with planting dates ranging from June to October for planting date 1 and July to November for planting date 2. According to Figure 4.3, although maximum temperatures proximity to the optimal requirements in the early season may have beneficial effects on clover and vetch early biomass production, increased maximum temperatures above 30°C (maximum requirements), decreased the growth capabilities of legumes during the late vegetative phase towards flowering. Pastures under the late planting date treatment were exposed to elevated temperatures across the three years which was likely to cause thermal stress. According to Nadeem *et al.* (2018), temperatures that are considered above specific crop thresholds during various developmental stages can have a significant impact on crop survival and productivity. Heat stress imposes challenges for legume crops and has deleterious effects on the morphology, physiology, and reproductive growth of plants (Hatfield and Prueger, 2015).

4.5.2 Leaf gaseous exchange traits

Planting date had a significant effect on leaf gaseous exchange of annual clover and vetch cultivars. The planting date 2 treatment increased intercellular CO_2, transpiration rate and stomatal conductance while decreasing photosynthetic rate. This could be attributed to crops being exposed to higher temperatures throughout their growth and developmental stages when compared to planting date 1. The findings of this study are consistent with the findings of Sita *et al*. (2017a) on lentils and Wilson *et al*. (2012) on pigeon pea. A meta-analysis that has investigated the elevated temperature effects on plant physiology (Martiniello and Teixeira da Silva, 2011; Wang *et al*., 2019; Jing *et al*., 2016), concluded that increased temperatures above the plant threshold induced heat stress in plants. Overall, heat stresses affect nutrient cycling, uptake and availability to plants by hampering different physiological functions of plants.

Cultivars showed a significant variation in terms of leaf gaseous exchange. Resal, Elite, Timok and Dr Baumans had higher Ci values on either a certain planting date or harvest day. Cultivars such as Resal, Laser, Alex, Ellie and Dr Baumans had a higher photosynthetic rate than the rest of the cultivars. Capello, Hanka, Timok, Linkarus and Opolska displayed a higher transpiration rate than other cultivars consistently across the harvest days, planting dates in 2018-2019.

Concerning stomatal conductance, all the cultivars had high stomatal conductance on a certain harvest day. Resal, Elite, Dr Baumans, Hanka, Timok and Linkarus peaked at 91DAP, Alex and Capello at 77DAP, and lastly, Laser and Opolska tended to start at a higher rate fluctuated across the harvest days and peaked at 105DAP. Supporting the current results by Ayalew *et al*. (2022) on cowpea and Chavan *et al.* (2022) on wheat indicated that cultivar variation in leaf gaseous exchange parameters could be due to the genetic makeup and adaptive mechanism of the cultivars to different environmental conditions.

The interaction of planting date, harvest day and cultivar significantly influenced the leaf gaseous exchange. Based on the complexity of stomatal conductance response curves of cultivars under different harvest days and plating dates (Fig. 4.4, 4.5, and 4.6), stomatal conductance displayed to be more sensitive to weather differences in planting dates than intercellular CO_2 concentration, transpiration rate and photosynthetic rate. Several authors indicated that stomatal conductance is the leading response trait to any stress hence more sensitive (von Caemmerer and Evans, 2015; Kumari *et al*., 2021). The explanation highlighted was that stomatal conductance is a key factor that regulates transpiration and photosynthesis rates concurrently, either with a higher transpiration rate or reduced photosynthetic rate or vice versa, responding to changes in external conditions and internal signals (Lawson *et al*., 2010). This background validates the leaf gaseous exchange trends that were observed in this study.

At high stomatal conductance, Resal, Laser, Alex, Elite and Dr Baumans had a higher photosynthetic rate with lower transpiration rates. Contrary to these responses Capello, Hanka, Timok, Linkarus and Opolska displayed a higher transpiration rate with lower photosynthetic rates. According to Urban *et al*. (2017), increased transpiration rate allowed plants to benefit through evaporative cooling to regulate the internal temperature in situations where moisture is not a constraint. The establishment of winter forage crop coincides with the dry season in the Limpopo province as a result irrigation is required. Therefore increasing water use efficiency in the crop is becoming crucial in improving crop productivity under changing climatic conditions. The study found out that both the leaf-level water use efficiency traits, WUEinstantaneous and WUEintrinsic decreased with delayed planting date. This is due to the response observed in the increased stomatal conductance and transpiration rate hypothetically for evaporative cooling to regulate the effect of increased temperature where moisture was not a constraint (Urban *et al*., 2017).

4.5.3 Biomass production

Planting date is also an important determinant for biomass production. Across the three growing seasons, planting date 2 resulted in lower biomass production than planting date 1. This could be because annual clover and vetch cultivars planted on planting date 2 were subjected to higher temperatures throughout their growth and development stages than those planted on planting date 1. Our findings concur with the findings of Chen *et al*. (2006) on winter pea and lentil; Hayden *et al*. (2015) on vetch; Toom *et al.* (2019) on berseem clover, faba bean and field pea who established that biomass was reduced with delayed planting due to genetic variation and exposure to increased temperatures. Reviews and empirical studies on heat stress effects on plant productivity associated low productivity with physiological responses of the crop (Hatfield and Prueger, 2015; Sita *et al*. 2017, Moore *et al.* 2021). The authors indicated that exposure to high temperatures usually results in sun-burning and scorching of leaves and stems, a reduction in chlorophyll biosynthesis, leaf senescence and abscission as well as impaired mitosis and cell elongation which results in poor growth. Hence, leaf expansion and elongation are reduced.

Furthermore, their findings revealed that exposure to high temperatures results in downregulation of photosynthesis due to impaired proper functioning of the photosystem II system, membrane damage, deactivation of enzymes in chloroplasts, protein denaturation, and ultimately impaired protein and carbohydrate synthesis, hence low biomass production.

Plant growth and biomass accumulation are functions of plant cell division, enlargement, and differentiation. Harvest days also had a significant effect on biomass production and accumulation. 91DAP (flower initiation) and 105DAP (50% flowering) yielded the highest biomass production because of the length of the growing season. At this stage, the crop had accumulated the photoassimilates and translocated them into sinks for biomass accumulation. The study done by Teasdale et al. (2004) found that hairy vetch biomass was higher when harvested at flowering than at the vegetative stage.

Biomass production varied significantly between the ten cultivars. Among the ten cultivars, high producers were Resal, Laser, Alex, Elite and Dr Baumans which yielded significantly more biomass than Capello, Hanka, Timok, Linkarus and Opolska, low producers. The significant biomass production differences observed among the cultivars are in agreement with previous findings on common vetch (Larbi *et al*., 2011; Huang *et al.,* 2019) who concluded that the variation in biomass between cultivars is partly attributable to the cultivars' differences in the genetic makeup of the species to which they belong. The correlation results of this study confirmed a positive relationship between biomass production and stomatal conductance and photosynthetic rate and a negative relationship with transpiration rate. Cultivars that are classified as high producers had a higher photosynthetic rate with a low transpiration rate contrary to low producers.

4.5.4 Nodulation response

The nodulation process in legumes is important for biological nitrogen fixation for ecosystem services. The results indicated that planting date, cultivar and harvest day had a highly significant influence on nodulation. Delayed planting resulted in decreased nodule DM. Significant differences in nodulation ability were observed, Hanka was the high module producer and Opolska and Linkarus as lower nodule producers. Peak nodule production was observed at 77DAP, the flower initiation stage. Supporting the results of this study, Pommeresche and Hansen (2017) indicated that nodule activities differ from one plant species to another and the majority of crops reach maximum nodulation around the flowering stage of development.

4.5.5 Nutritive value of shoot DM

Planting date did not have a significant effect on nutritive value traits including, ash, CP, ADF and NDF. However, significant cultivar variations were observed for these traits. Nutritive value was only quantified at 105DAP at 50% flowering. The effect of harvest days concerning crop developmental stages on nutritive value is discussed in the literature review. In agreement with the research findings, significant cultivar variations in the nutritive value are consistent with previous research on common vetch (Huang *et al*., 2020); persian and berseem clover (Balazadeh *et al*., 2020); hairy vetch (Teasdale *et al.*, 2004) as well as hairy and common vetch (Kebede, 2018). The genetic makeup of crops influences cultivar variation. Furthermore, changes in nutritive value were attributed in our study to changes in forage tissue age and maturity depending on growth stages and management.

4.6 CONCLUSION

Planting date, cultivar, and harvest day had significant effects on leaf gaseous exchange, biomass production, nodulation and nutritive value. Planting date 1 in June produced the highest biomass production of better quality across all growing seasons at 105DAP. Late planting exposes the crops to increased temperatures, which negatively affects the leaf gaseous exchange, biomass production and nutritive value. As planting date significantly affects key economic traits in winter annual clover and vetch production, it is critical to choose the optimal planting date to maximize performance and mitigate risks such as thermal stress. Overall, higher stomatal conductance and photosynthetic rate enhanced biomass productivity. For climate change mitigation, breeding cultivars with high thermo-tolerance adaptive capacity is essential. Resal, Alex, Elite, Laser and Dr Baumans showed more consistency in terms of leaf gaseous exchange, biomass production and quality traits under varying climatic conditions and harvest days. These forages have shown huge potential to mitigate the feed gap.

4.7 RECOMMENDATIONS

The clover and vetch biomass production respond to planting dates and harvesting stage. With increasing climate variability, further research on a broader planting window from early autumn and across different environmental conditions is advised before recommendations are made since they are relatively new cultivars in Limpopo province. Further studies of their nitrogen fixation is required to support and increase knowledge on their significance as cover crop for soil fertility improvements.

CHAPTER 5: GROWTH AND NUTRITIONAL COMPOSITION OF FORAGE SORGHUM RESPONSE TO PLANTING DATE, AND SHORT-TERM ROTATION WITH WINTER ANNUAL FORAGE LEGUMES, NITROGEN APPLICATION AND VALIDATION WITH APSIM.

5.1 ABSTRACT

Conservation agriculture (CA) systems are based on minimal soil disturbance, crop residue retention and crop rotation. A no-tillage, short-term rotation experiment was conducted at the University of Limpopo experimental farm to determine the growth and nutritive value of forage sorghum, planted after the winter annual forage legumes in combination with nitrogen (N) application and to validate the performance of APSIM-grain sorghum crop model in simulating forage sorghum growth and biomass production under different N rates. The treatments were planting date (January and February) and N source from inorganic N rates (0 kg N ha^{-1}, 60 kg N ha^{-1}, 120 kg N ha^{-1}, 180 kg N ha^{-1}) and forage legume N residues (Alex, Capello, Dr Baumans, Elite, Hanka, Laser, Linkarus, Opolska, Resal and Timok) arranged in a randomized complete block design with four replicates. The findings of this study showed a significant response of forage sorghum biomass accumulation and nutritive value to planting date. Delayed planting reduced plant height (11%), stem diameter (18%), Leaf Area Index (LAI) (6.7%), chlorophyll content (18%), normalised difference vegetative index (NDVI) (2.5%), photosynthetic rate (38%) and biomass production (8%). Delayed planting further reduced crude protein, acid detergent fiber and N yield. Nitrogen source from inorganic N fertilisation at 60 kg N ha^{-1}, 120 kg N ha$^{-1,}$ 180 kg N ha-1 and residual N from annual clover and vetch cultivars had a significant effect on yield and morphological, physiological and nutritive value parameters of forage sorghum. Generally, legume N residue effects on all the studied parameters of forage sorghum were similar to 60 kg N ha^{-1}. However, the effects differed widely according to the species and cultivar of the legume. The residue of the Resal, Laser, Elite Capelo and Dr Baumans consistently showed greater effects than the other legume residues. They consistently outperformed inorganic 60 kg N ha^{-1} on the most measured parameters. The results confirm that annual clover-forage sorghum and vetch-forage sorghum rotation have huge potential to reduce the cost associated with inorganic N use in forage production systems. Concerning the potential of the APSIM grain sorghum model to simulate forage sorghum shoot dry matter (SDM) and plant height, the model general, performed well and accurately predicted the SDM accumulation and plant height under 60 kg N ha^{-1} and 120 kg N ha^{-1}. However, it underestimated both parameters at 180 kg N ha^{-1} indicating that the application of N up to 180 kg N ha^{-1} does not increase productivity further as a result can be deemed unnecessary.

Keywords: APSIM, forage sorghum, legume N residue, nitrogen.

5.2 INTRODUCTION

Conventional agricultural development has relied heavily on external inorganic fertilizers, but this contributes to increased crop production costs, environmental pollution and soil degradation (Singh and Ryan, 2015; Li *et al*., 2018). The inappropriate and injudicious use of inorganic fertilizers is not compatible with sustainability, maintenance of environmental quality and conservation of natural resources. Consequently, sustainable agricultural production demands that alternative and cheaper sources of nitrogen fertilizer be explored. Conservation agriculture (CA) systems are based on minimal soil disturbance, crop residue retention and crop rotation. Literature has emphasized the importance of CA systems, however, less research had been done to update the existing old literature on CA for forage production systems. Legume-based crop rotation is regarded as a long-term corrective measure for improving soil fertility and crop productivity (Siddique *et al*., 2012; Gan *et al.,* 2015). Biological nitrogen fixation (BNF) on legumes can provide an alternative nitrogen source via nitrogen-fixing bacteria to symbiotically convert atmospheric nitrogen into plant-usable ammonia. The inclusion of legumes into crop production systems has been shown to increase the productivity of companion or subsequent crops (Peoples *et al*., 2009).

Nitrogen is an essential macronutrient, highly required for the growth and development of crops. It is an important component in so many physiological processes such as nutrient uptake, amino acid, and protein synthesis, chlorophyll formation and photosynthesis (Wang *et al*., 2016). Current recommendations for producing optimal forage yields of sorghum-Sudan grass hybrids suggest the application of 50 to 100 kg N ha^{-1}. However, in real-life situations, some farmers apply higher N rates with the idea of increasing production. Empirical-based evidence is required to guide farmers' N use practices and find sustainable inorganic N substitutes.

The forage production sector experiences significant seasonal fluctuations in Limpopo province, particularly during the winter and early spring seasons, when feed shortages are at their peak. Increasing the productivity of summer forage crops in order to address the winter forage shortage. Forage sorghum (*Sorghum bicolor* (L.) Moench) is an annual, warm-season forage crop following a C4 photosynthetic pathway (Jirim *et al*., 2013). Desirable traits of forage sorghum include its adaptation to harsh environments with limited rainfall, high temperatures and low soil fertility (Afzal *et al*., 2012), high water and nutrient use efficiency and high biomass production potential (Bollam *et al*., 2021), which makes it an important livestock feed in several arid and semi-arid climatic regions (Deep *et al*., 2019). It is a multi-purpose crop that can be utilized in different forms and at different developmental stages of growth, such as green grazing pasture, hay, haylage, silage, and green chop. These characteristics provide considerable flexibility for forage and livestock producers in managing their resources and responding to the critical needs of their livestock. However, its productivity still depends on the application of proper agronomic management practices such as planting date, fertilization and harvest time to optimize higher biomass production of adequate quality required for sustainable livestock production. There, utilizing the summer rainy season and alternative nitrogen sources for low-cost fodder production from high-producing summer grasses such as forage sorghum is critical.

In addressing the feed gap challenges, the transition to high livestock productivity requires efficient planning and management decisions within the production system. One such planning and management decision is the ability of managers to properly

estimate the fodder productivity of the pastures available on the farm to avert the winter feed gap risks. Estimating crop productivity using crop models such as Agricultural Production Systems Simulator (APSIM) is becoming essential. APSIM is one of the tools that can form the basis of decision-support systems for farmers in evaluating the potential agronomic management adaptations and for forage yield estimations on the farms. A benefit of such models is that they can predict crop growth and yield with considerable confidence without prolonged and costly experimentation. Crop growth simulation models that include the soil-plant-atmosphere complex are increasingly being used to forecast the effects of climate change on different crop species (Druille *et al*., 2020). APSIM is a useful tool for grain sorghum growth simulations and previous work done to validate APSIM had produced very satisfactory results. However, research on the development of specific forage sorghum model and simulations is
currently not available. The objectives of the study were to determine the growth and nutritive value of forage sorghum, planted after the winter annual legumes in combination with nitrogen application in a short-term rotation and to validate the performance of the APSIM-grain sorghum crop models in simulating forage sorghum growth and biomass production under different N rates.

5.3 MATERIALS AND METHODS

5.3.1 Description of the study site

The study site was described in Chapter 4, refer to 4.3.1. The study's initial crop was *Eragrostis tef* (Teff grass), which was planted in January and February of 2019 and 2020. Termite infestation halted crop growth at the seedling stage, hence no data was collected. These resulted in changing the crop to *Sorghum bicolor* (L.) Moench (forage sorghum).

5.3.2 Soil sampling and analysis

Soil samples at the experiment site were collected before planting at the depths of 0–15 cm and 15–30 cm using the procedure which was described in Chapter 4, refer to 4.3.3. The physical and chemical properties of the soils before planting are indicated in Table 5.1. The soil of the experimental plots was silt clay having a pH of

7.54 and 7.45. Forage sorghum annual clover and vetch species prefer well-drained soils, sandy to loam with a neutral to slightly alkaline pH (7-8) for optimum growth.

Table 5.1 Soil chemical and physical properties before pasture establishment in 2021

Soil properties	**Plating date 1**
pH(KCl)	7.59
N (%)	0.19
P (mg/L)	27.6
K (mg/L)	390.5
Ca (mg/L)	920
Mg (mg/L)	594
Zn (mg/L)	2.45
Mn (mg/L)	15.5
Cu (mg/L)	3.1
Org. C (%)	0.89
Clay (%)	32.5
Silt (%)	16
Sand (%)	51

5.3.3 Experimental design and treatments

The experimental design was a split-plot in a randomized complete block design (RCBD) replicated four times and comprised 28 treatments: two planting dates and 14 sources of nitrogen. The planting date was the main plot (January and February 2021) and the N sources were the sub-plots. The N sources comprised four inorganic N levels 0 kg N ha^{-1}, 60 kg N ha^{-1}, 120 kg N ha^{-1} and 180 kg ha^{-1} as well as residual N from ten preceding winter forage annual legumes. The inorganic N levels were from Urea. The ten preceding legumes include the clover and vetch cultivars from the previous season in a rotation system. The total number of experimental units was 54 per planting date.

5.3.4 Crop husbandry

Winter annual forage legumes were planted on separate plots and were harvested at 50% flowering at the height of 5 cm from the ground. After their harvest, all residues were retained on each plot, the mean N percentage of legume crop residue is presented in Table 5.2. Plots were not tilled and forage sorghum cv., Kow Kandy was planted on 22 January and 12 February 2021 on all the plots to evaluate the rotation effect of the previous legumes. The N treatment was applied in the form of Urea as per treatment, banded along the rows. Each plot received phosphorus in a form of superphosphate (10.5% P) at 30 kg P per ha, based on pre-plant soil fertility analysis. The plot size was 5 m × 3 m, with the 45 cm inter-row spacing. Seeds were planted with a hand drill at the seeding rate of 10 kg ha^{-1}. Standard crop management practices such as weeding were monitored and done when necessary throughout the cropping season.

Table 5.2 Mean N % of legume residue

Cultivars	N %
Alex	3.33
Dr Baumans	3.12
Capello	2.91
Ellite	3.31
Hanka	2.83
Laser	3.52
Linkarus	2.45
Opolska	2.35
Resal	3.60
Timok	2.99

5.3.5 APSIM simulation

5.3.5.1 Model set up

Agricultural Production System Simulator (APSIM) version 7.10 was used in this study to simulate the effect of nitrogen levels on the growth and biomass of forage sorghum. Crop simulations were developed using the continuous sorghum model in APSIM (previous work (Kholova *et al*., 2014). The weather (met) and management modules were also used as inputs in the model. The met (Syfekuil met) module data used in study was obtained from the South African Weather Service, Institute of Climate Information. The database contained 2020/2021 daily hydro-climatological data such as daily rainfall, minimum and maximum temperatures, and solar radiation (Figure 5.2). It is a critical input parameter because it controls all weather variables.

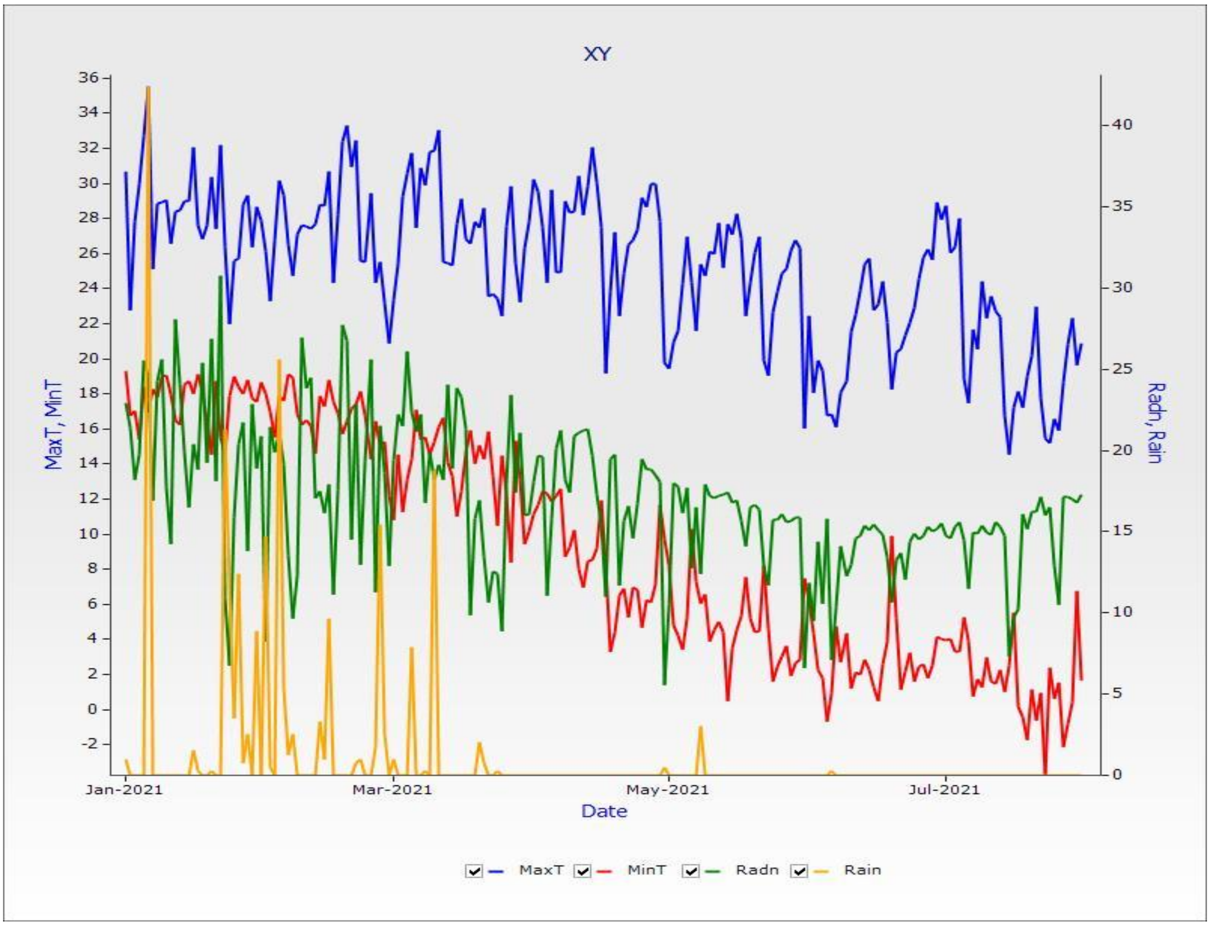

Figure 5.1 Climatological data used for simulations.

The manager folder contains crop management module information like when to plant and what cultivar to use. Furthermore, site information (latitude, longitude, altitude) was also used to run the model. The Syfekuil soils were used to set up the APSIM model and the soil parameterization values used for the simulations are shown in Table 5.3. Initial water was set at 50%.

Table 5.3 Soil physical properties for estimated bulk density (BD), lower limits of available soil water for each crop limit (LL), drained upper limits (DUL).

Depth	BD	AirDry	LL15	DUL	SAT	Sorghum LL	Sorghum KL	Sorghum XF
(cm)	(g/cc)			(mm/mm)			(/day)	(0-1)
0-15	1.45	0.11	0.11	0.15	0.403	0.11	0.06	1.00
15-30	1.45	0.11	0.11	0.156	0.403	0.11	0.06	1.00
30-60	1.45	0.11	0.11	0.157	0.403	0.11	0.06	1.00
60-90	1.45	0.11	0.11	0.157	0.403	0.11	0.06	1.00
90-120	1.45	0.11	0.11	0.157	0.403	0.11	0.06	1.00
120-150	1.45	0.11	0.11	0.157	0.403	0.11	0.06	1.00
150-180	1.45	0.11	0.11	0.157	0.403	0.11	0.00	1.00

Forage sorghum cultivar Kow Kandy used in the trial was not available in the APSIM model, therefore based on the thermal time required to complete the different physiological stages the “medium cultivar” grain sorghum was selected as a template and modified to derive Kow Kandy cultivar specific parameters. Using the trial data, the “medium cultivar” was re-parameterized for phenology and canopy development to simulate plant height and biomass production (Table 5.4). The rest of the various properties were the same as the default properties of the medium cultivar used as a template.

Table 5.4 APSIM calibration parameters and values made to medium cultivar for Kow Kandy forage sorghum cultivar.

Apsim parameter	Description	Unit	Default	0N	60N	120N	180N
<rue>	Radiation use efficiency	g bio/MJ	1.25	1.25	1.25	0.65	0.65
<frac_stem2flower>	Fraction of dm allocated to stem that goes to developing head		0.30	0.90	0.90	0.35	1.90
<dm_leaf_init>	Leaf weight at emergence	g/plant	0.10	1.10	1.60	1.00	1.70

<dm_root_init>	Root weight at emergence	g/plant	0.10	1.20	1.30	1.00	1.00
<dm_stem_init>	Stem weight at emergence	g/plant	0.10	1.20	1.50	1.00	1.70
<transp_eff_cf>	Transpiration efficiency coefficient	kpa	0.01	1.00	1.00	1.00	1.00
<svp_fract>	Vapour Pressure Deficit (VPD) fraction		0.75	0.15	0.15	0.10	0.15

The field data was derived from the trial conducted to measure the growth and nutritional composition of forage sorghum under planting date and short-term rotation with winter annual legumes in combination with nitrogen application. The shoot DM accumulation and plant height dataset from planting date 1 and nitrogen level treatments was used for calibration of the model and was excluded from the validation. Forage sorghum was harvested when grains were at the soft dough stage. As a result, the model was set to report the selected variables daily to extract simulated data per day after planting. This enabled the simulation to harvest the crop on the same days after planting as the observed. The determination of the parameters was done by graphically matching model output against observed results of shoot DM and plant height as illustrated in Figure 5.3 and 5.4, respectively.

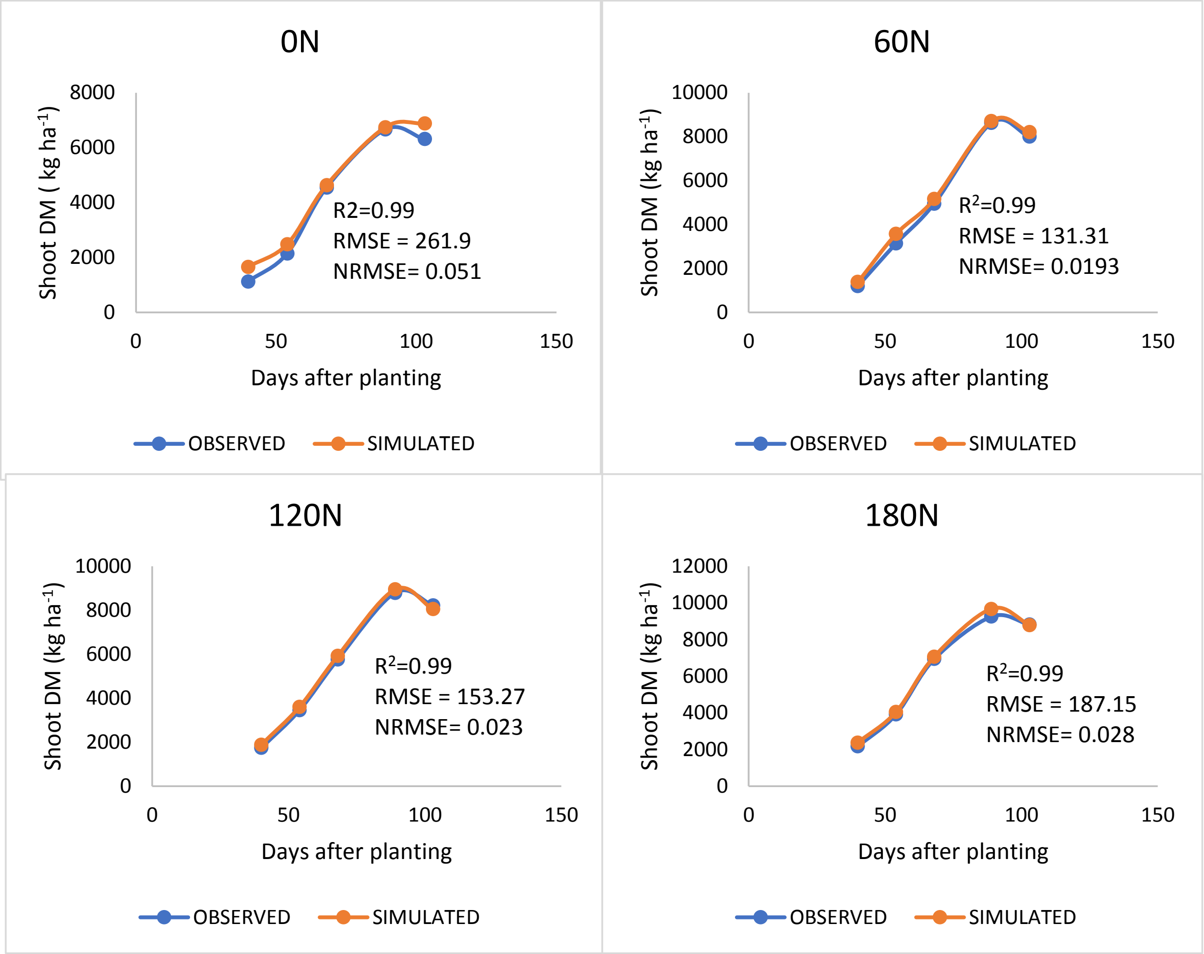

Figure 5.2 Calibration output for forage sorghum shoot dry matter yield compared simulated orange lines and observed blue lines under N levels 0 kg N ha^{-1}, 60 kg N ha^{-1}, 120 kg N ha^{-1} and 180 kg N ha^{-1}.

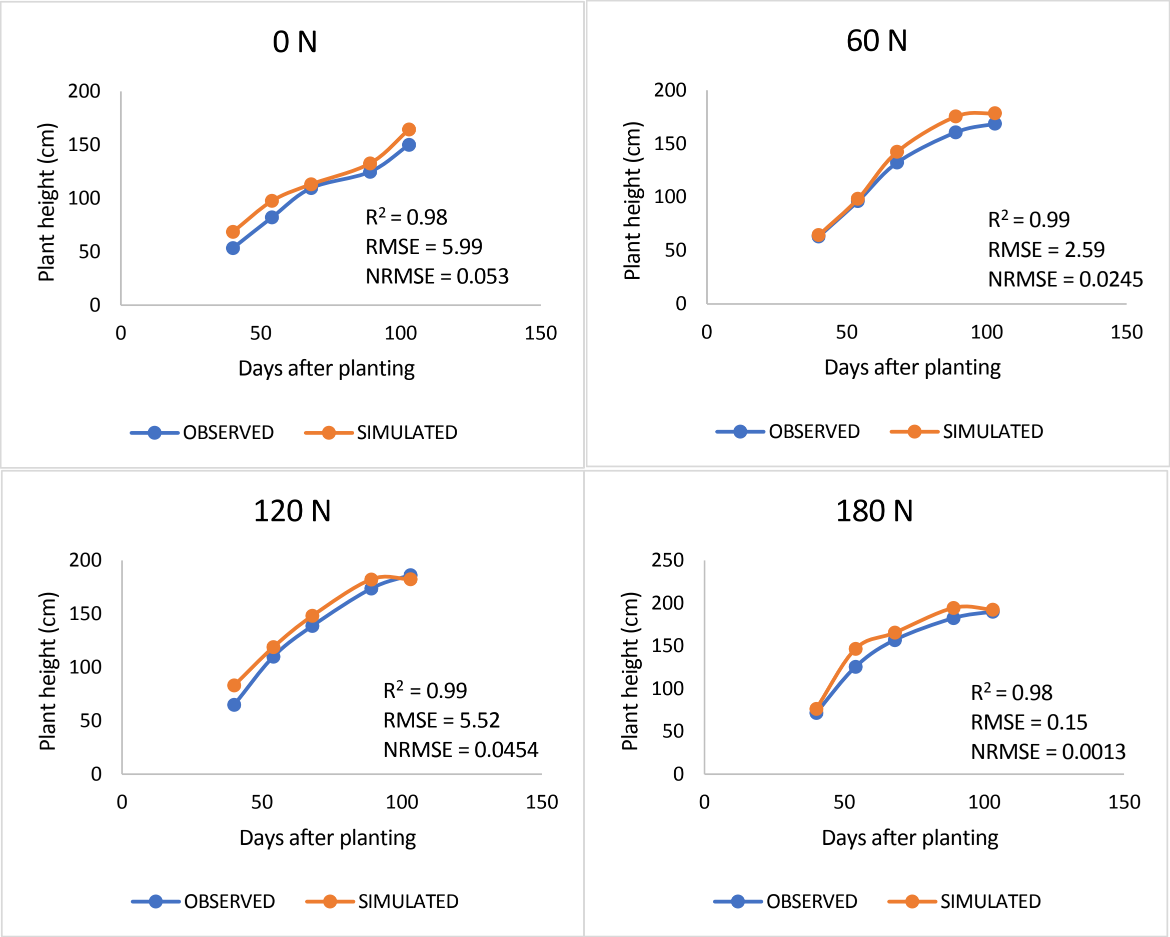

Figure 5.3 Calibration output for forage sorghum plant height compared simulated orange lines and observed blue lines under 0 kg N ha^{-1}, 60 kg N ha^{-1}, 120 kg N ha^{-1} and 180 kg N ha^{-1} levels.

5.3.6 Data collection

Growth and physiological parameters were collected biweekly from 40DAP until 103Days including plant height, stem diameter, leaf area index (LAI), Chlorophyll content, NDVI, photosynthetic rate (A) and biomass production. Plant height was measured on five plants per plot using a meter-scale from the surface of the soil to the tip of the shoot apex. Average plant height was calculated in centimeters. Stem diameter was collected from five plants per plot using a vernier calliper (mm) which was placed around the stem of the crop. Leaf area index (LAI) was measured using AccuPAR LAI Ceptometre LP-80 (D Decagon Devices, Inc., Pullman, WA, USA) on middle rows of sorghum plots between 10:00 a.m. and 1:00 p.m. The Normalized difference vegetation index (NDVI) was measured with a portable spectroradiometer with an active sensor (GreenSeeker handheld crop sensor, Trimble, USA) scanning with the sensor held perpendicularly to the canopy and 0.5–0.6 m above the top canopy. Chlorophyll content was determined by the SPAD 502 plus instrument by measuring the absorbance of the leaf in two wavelength ranges (Blue 400-500 nm and Red 600-700 nm). The readings were taken by inserting a leaf and closing the measuring head. Using these two absorbance ranges, the meter calculated a numerical SPAD value.

The photosynthetic rate was recorded using LCi-SD UltraCompact Photosynthesis System (ADC Bio Scientific, Hoddesdon, UK) between 10:00 a.m. and 1:00 p.m. Biomass production was measured by crop destructive method from 1.0 m x 1.0 m quadrats, manually cutting the crops at the height of 5 cm above-ground. Samples were dried at 60°C until constant weight for the determination of dry mass. For Herbage quality analysis, the dried samples collected for shoot DM determination at 103DAP (soft dough stage) were milled through a 1 mm screen using a hammer mill to determine the nutritive value of forages. The nitrogen content was traditionally analyzed by the Kjeldahl procedure (Van Soest, 1991), and crude protein (CP) content was calculated from the N content (CP = N × 6.25). The ash, neutral detergent fiber (NDF) and Acid detergent fiber (ADF) were measured using standard processes of the Association of Official Analytical Chemists (AOAC 1990). Plant nitrogen yield was calculated by multiplying the total nitrogen concentration in shoots with the respective dry matter at the grain soft dough stage.

5.3.7 Data analysis

Data were analysed with the Statistical Analysis System 9.4 (SAS 9.4) software using the standard procedure of analysis of variance (ANOVA) to determine the effects of planting date, nitrogen source and harvest day on the parameters studied. Data were analysed for the 2020 growing season. Statistical tests were considered significant at the $P \leq 0.05$ level. Post Hoc comparisons for observed means were compared at a probability level of 5% using Duncan’s Multiple Range Test (DMRT).

To assess the performance of the crop simulation model, the observed and simulated shoot DM accumulation and plant height were compared using linear regression analysis. Root mean square error (RMSE) and its normalization (NRMSE) were used to evaluate the model’s performance as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n}}$$

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

Where: n is the number of replications of each planting date experiment, where Si is the simulated value of the variable, Oi is the observed value of the variable. Y max and Ymin are the observed values.

Lower RMSE indicates a good model performance, NRMSE closer to 0 shows high model accuracy, R^2 closer to 1 indicates a good relationship between simulated and observed means.

5.4 RESULTS AND DISCUSSIONS

5.4.1 Weather results

The experimental site had daily average minimum and maximum temperatures of 12 °C and 27 °C, respectively, with total precipitation of 226 mm in the growing period between January and June 2021 (Figure 5.5). Assessment of the climatic conditions of the experimental site showed the appropriateness of forage sorghum cultivation.

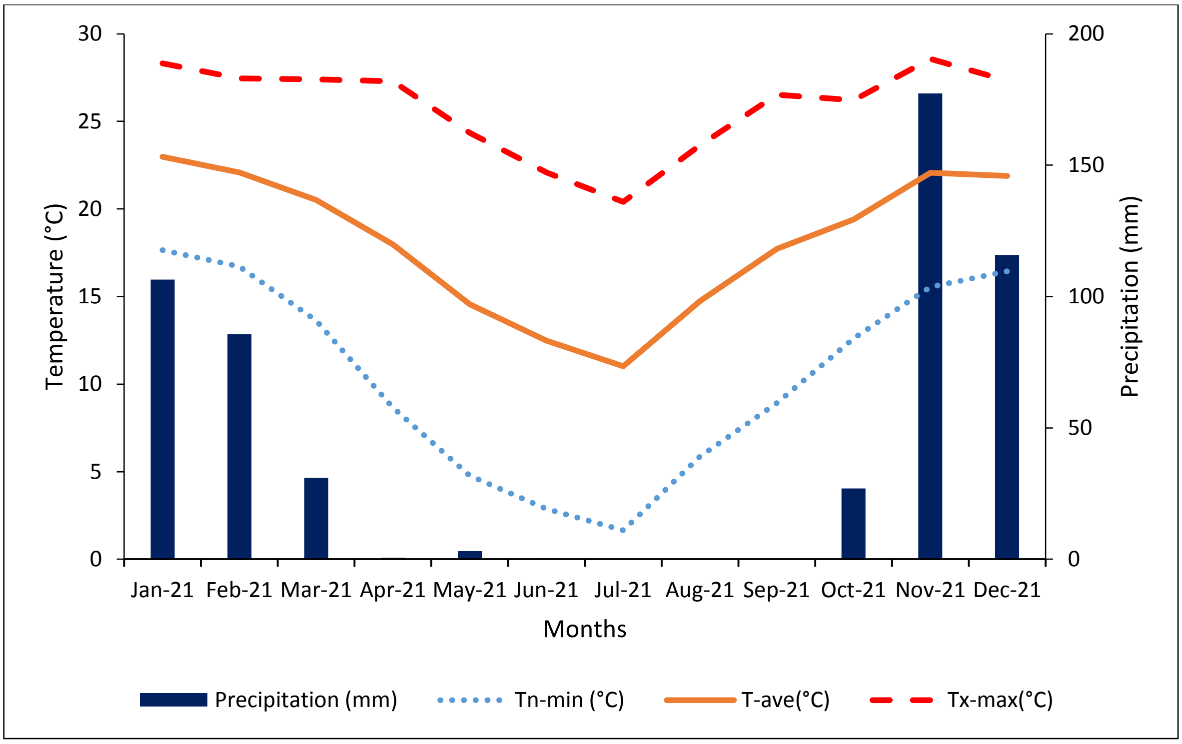

Figure 5.4 Syferkuil daily precipitation, maximum and minimum temperature during 2021 growing seasons.

5.4.2 Analysis of Variance (ANOVA) for morphology physiological and yield responses of forage sorghum to planting date and nitrogen source

The summarised ANOVA presented in Table 5.5 indicated that planting date and N source significantly ($P < 0.001$) influenced the morphological parameters such as plant height (PH) and stem diameter (SD), and all the physiological parameters measured, namely: leaf area index (LAI), chlorophyll content (CC), normalized difference vegetation index (NDVI), photosynthetic rate (A), as well as shoot dry matter (SDM) as a yield parameter of forage sorghum. Planting date by N source interaction was only significant on stem diameter, leaf area index, chlorophyll content and shoot dry matter.

Table 5.5 Analysis of Variance (ANOVA) for effects of planting date (PD), nitrogen source (NS) and their interaction (PD x NS) on morphological, physiological and yield traits of forage sorghum.

	Morphological	Physiological parameters	Yield

		parameters						
Source	DF	PH	SD	LAI	CC	NDVI	A	SDM
Planting Date(PD)	1	***	***	***	***	*	***	***
Nitrogen source (NS)	13	***	***	***	***	***	***	***
PD x NS	13	ns	***	***	***	ns	ns	***

PH-plant height, SD-stem diameter, LAI-leaf area index, CC-chlorophyll content, NDVI-Normalized difference vegetation index, A-photosynthetic rate, SDM-shoot dry matter. Letters designate significant differences between cultivars *** indicate highly significant difference $P < 0.001$, ** indicate significant differences $P < 0.01$, * indicate significant differences $P < 0.05$.

5.4.3 Planting date effect on morphological, physiological and yield parameters of forage sorghum.

All the parameters were significantly higher ($P \leq 0.05$) in PD 1 compared with PD 2. A decrease in plant height (11%), stem diameter (18%), LAI (6.7%), chlorophyll content (18%), NDVI (2.5%), photosynthetic rate (38%) and biomass production (8%) was observed when planting was delayed by three weeks from 22 January (PD 1) to 12 February (PD 2) (Table 5.6).

Table 5.6 Plant height, stem diameter, LAI, chlorophyll content, NDVI, photosynthetic rate and shoot dry matter of forage sorghum as influenced by planting date.

	Morphological parameters		**Physiological parameters**				**Yield**
Variable	PH (cm)	SD (mm)	LAI (m^2m^{-2})	CC	NDVI	A	SDM (kg ha^{-1})
PD 1	123.80 ^{a}	13.18 ^{a}	2.34 ^{a}	41.32 ^{a}	0.44 ^{a}	12.46 ^{a}	5020 ^{a}
PD 2	110.43 ^{b}	10.79 ^{b}	2.19 ^{b}	33.86 ^{b}	0.43 ^{b}	7.73 ^{b}	4607 ^{b}
LSD (0.05)	1.4503	0.2307	0.0133	0.8234	0.0097	0.6788	86.183

Numbers represent the means. Letters designate significant differences. Means with the same letters within the columns are not significant from each other at a 5% probability level. PD - planting date, PH - plant height, SD -stem diameter, LAI - leaf area index, CC - chlorophyll content, NDVI-normalized difference vegetation index A - photosynthetic rate, SDM - shoot dry matter.

Morphological parameters such as plant height and stem diameter are thought to be a good predictor of forage crop performance, including forage sorghum (Bhusal *et al*., 2017). Plant height and stem diameter were decreased by late planting in this study. This can be attributed to the shorter growing season and low temperatures. The findings were in line with the study by Shin *et al*. (2015), in which it was reported that plant height and stem diameter decreased with delayed planting date. Concerning LAI the results of the study are in agreement with those of Jirim *et al.* (2013) who indicated that earlier planting dates exhibited a significantly higher LAI value. The shoot dry matter results of this study concur with Zhang *et al.* (2017) who found that early planting date yielded the highest biomass in forage sorghum. In their study delayed planting reduced shoot dry matter by more than 15%. The lower shoot dry matter in PD 2 could be attributed to the fact that the plants received markedly lower precipitation during the whole period of their development. The lesser availability of water might be the reason for the clear decline in SDM yield. Additionally, a reduced photosynthetic activity was observed when the planting date was delayed. This could have also contributed to the low yield produced by PD 2.

5.4.4 Nitrogen (N) source effect on morphological, physiological and yield parameters of forage sorghum.

From the statistical ANOVA (Table 5.5) it was clear that N source treatment had a highly significant effect ($P < 0.001$) on all the studied morphological, physiological and yield parameters of forage sorghum.

Plant height

Nitrogen source had a significant effect on forage sorghum plant height ($P < 0.001$) (Figure 5.6). Inorganic 180 kg N ha^{-1} produced significantly the tallest plants with a mean height of 140 cm followed by plants that received 120 kg N ha^{-1} (125 cm). The impact of the residual N from the previous legumes on forage sorghum height was generally similar except for those following Dr Baumans, Laser, Linkarus, and Opolska which were higher than those following Capello, Elite, and Resal. It was also observed that the residual effect of 70% of the legumes was not different from the forage sorghum plants fertilised at 60 kg N ha^{-1}. The height of all the sorghum plants following a previous legume cover crop exceeded that of the unfertilised plants. Similar findings on the effect of N source on succeeding sorghum were reported by Shuaibu *et al.* (2015), who found that growing sorghum after cowpea and soybean produced significantly ($P \leq 0.01$) taller plants than when the land was left fallow. Similarly, Daramy *et al*. (2015) found the significant effect of N source (cowpea residues and N) on succeeding maize.

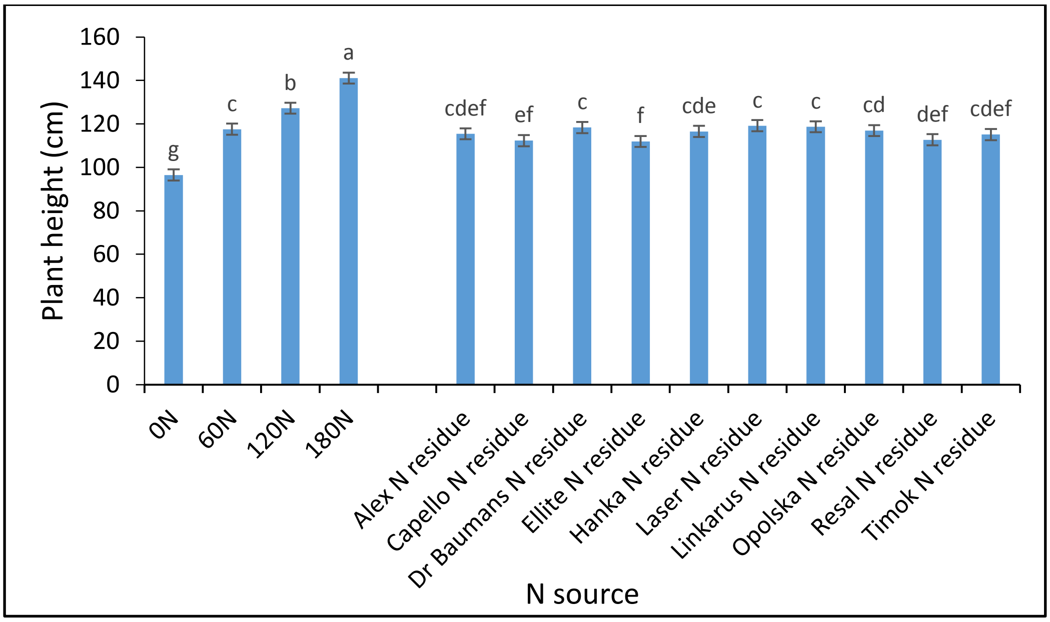

Figure 5.5 The effect of N source on forage sorghum plant height.

Stem diameter

Stem diameter was significantly influenced by the N source ($P < 0.001$) (Figure 5.7) ranging from 11 mm to 14 mm in the N fertilised plants and 11 mm to 13 mm in plants following the residual cover crops. Inorganic fertiliser application at 180 kg N ha^{-1} produced the thickest plants with a mean diameter of 14 mm. This was followed by the application of 120 kg N ha^{-1}, which gave a similar stem diameter as Resal N residue. The findings of this study support the findings of Jung et al. (2016), who reported that
stem diameter increased with increasing N fertility rates.

Alex N residue produced the stem diameter which was significantly higher than inorganic 60 N kg ha^{-1}. The stem diameter of all other legume N residues differed significantly from each other. Sixty percent of the sorghum plants with residual effects were however similar to the unfertilised plants.

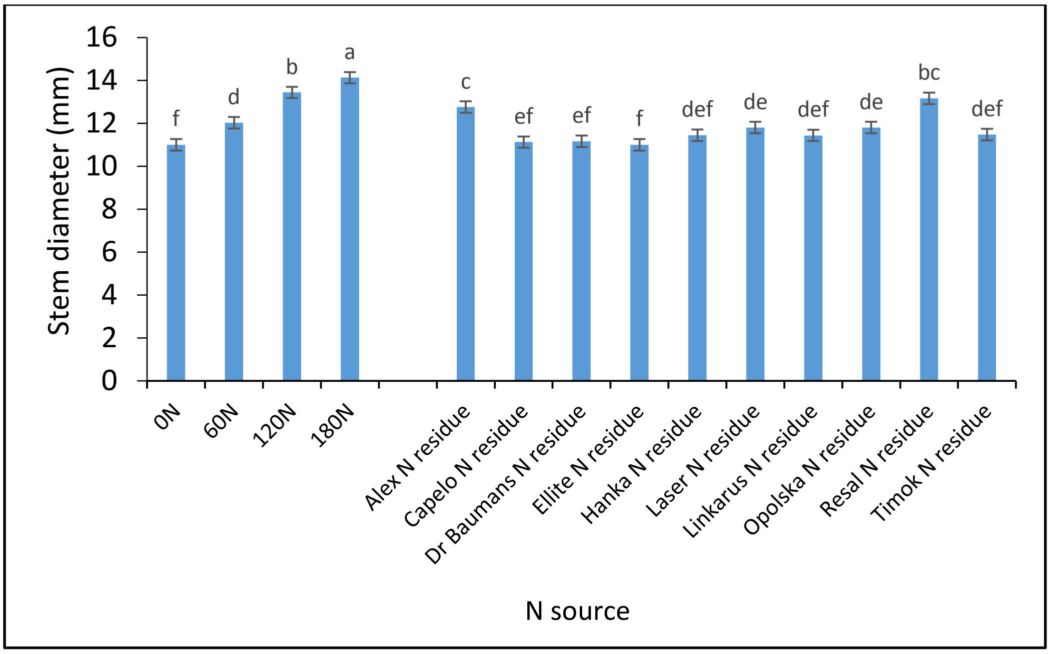

Figure 5.6 The effect of N source on forage sorghum stem diameter.

Leaf area index **(LAI)**

The leaf area index (LAI) is a structural property of the crop canopy that predicts photosynthesis and can be used as a reference tool for crop growth measurements (Nazeri, 2021). The nitrogen source significantly affected the leaf area index ($P < 0.001$) (Figure 5.8). Inorganic 180 kg N ha^{-1} produced significantly the highest LAI followed by inorganic 120 kg N ha^{-1}, with mean values of 2.88 and 2.52 m^{2}m^{-2}, respectively. LAI under Laser and Resal residual N was third and significantly higher than that of inorganic 60 kg N ha^{-1} and all other legume N residues. LAI was similar for inorganic 60 kg N ha^{-1}, Alex, Elite and Capello N residues. LAI for Linkarus, Opolska and Timok N residues was significantly the lowest when compared with other legume N residues, however significantly higher than that of 0 kg N ha^{-1}. The results concur with the findings by Olugbemi and Ababyomi (2016) who reported that LAI increased with increase in nitrogen fertilizer rate in sweet sorghum. In contrary, Shamme *et al*. (2015) observed that there was no discernible effect of nitrogen fertilizer rates on leaf area index of sorghum.

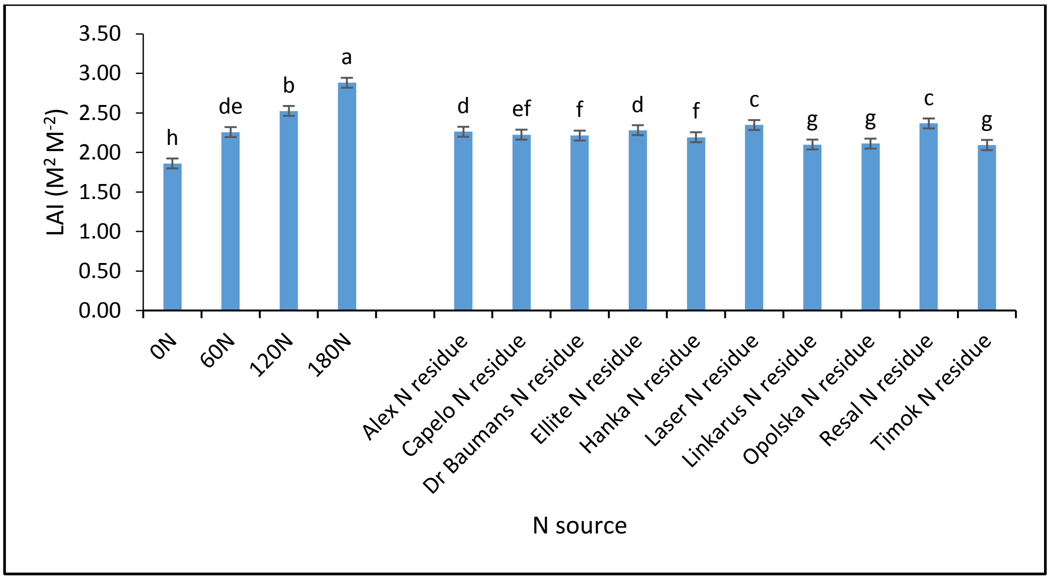

Figure 5.7 The effect of N source on forage sorghum leaf area index (LAI).

Chlorophyll content (SPAD units)

The effect of the N source was highly significant on the chlorophyll content ($P < 0.001$). (Figure 5.9). Inorganic 180 kg N ha^{-1} and 120 kg N ha^{-1} application had similar but significantly the highest chlorophyll content of about 48.58 followed by an application rate of 60 kg N ha^{-1}. Similar findings were reported by Jung et al. (2016), who found that SPAD values increased with increasing N application rates. The chlorophyll content of all the forage sorghum following the forage legumes was significantly lower than the N-fertilised plants but greater than the unfertilised plants. Chlorophyll content for Hanka N residue was third and significantly the highest among other legume residues.

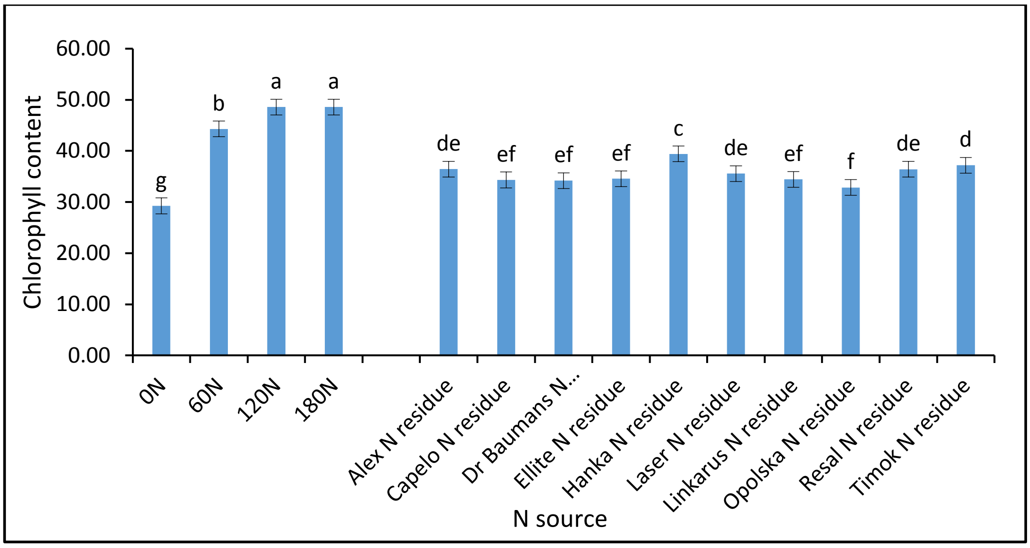

Figure 5.8 The effect of N source on forage sorghum chlorophyll content.

NDVI

Nitrogen source had a significant effect on the NDVI ($P < 0.001$) (Figure 5.10). NDVI was highest at inorganic 180 kg N ha^{-1} (0.61) application followed by 120 kg N ha^{-1}). NDVI for Alex and Resal residual N were at par with inorganic 60 kg N ha^{-1} and significantly higher than all other legume N residues. The rest of the legume N residue were generally similar except for Baumans, Linkarus and Opolska which had NDVI values lower than the rest. All the N source treatments had significantly higher NDVI than the control, 0 kg N ha^{-1} at 0.30. The results are in agreement with work reported by Cavalcante et al. (2018) using the N uptake curve for sorghum, which showed that at higher N rates, plants were more greener and yielded higher NDVI values.

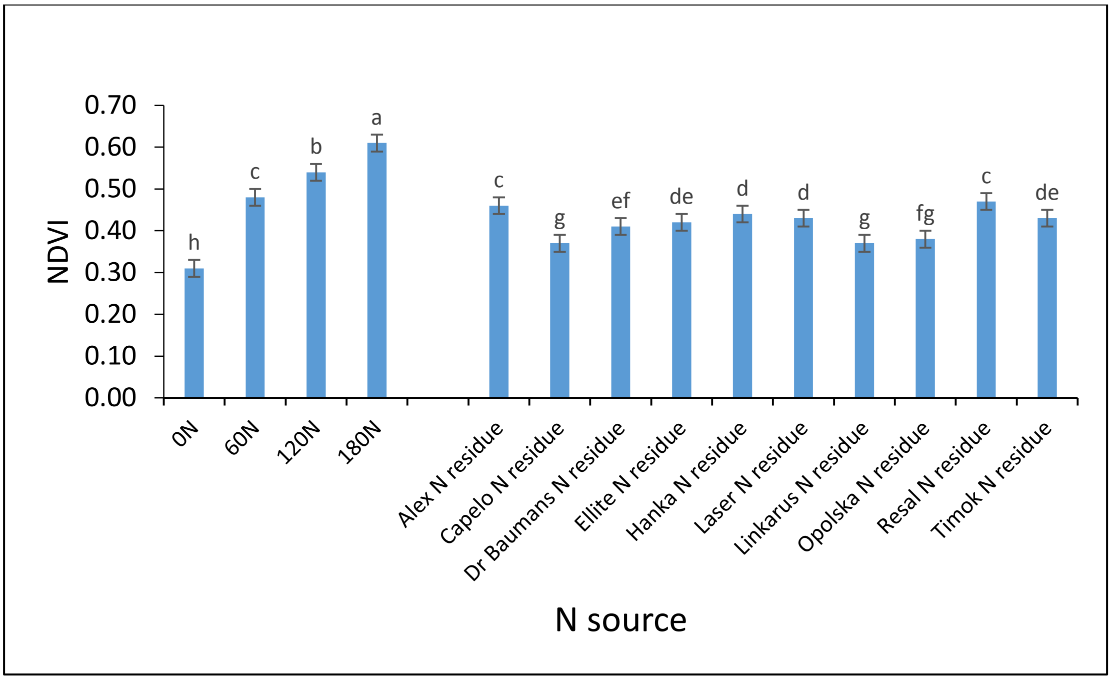

Figure 5.9 The effect of N source on forage sorghum NDVI.

Photosynthetic rate

The nitrogen source had a significant effect on the photosynthetic rate ($P < 0.001$) (Figure 5.11). However, the photosynthetic rate did not differ significantly among plants receiving 180 kg N ha^{-1}, 120 kg N ha^{-1} and 60 kg N ha^{-1} and all were similar to that of Alex and Resal legume N residue. Overall, the photosynthetic rates of sorghum following the forage legume N residue were similar except that after Timok which was lower than that following Alex. Photosynthetic rate of plant under Timok residues was not significantly different from the control forage sorghum plants, 0 kg N ha^{-1}. The findings of this study concur with earlier studies by Maranville and Madhavan (2002) in grain sorghum, which indicated that N deficiency reduced photosynthetic rate of plants. Similar conclusions were drawn in Zhao *et al*. (2005).

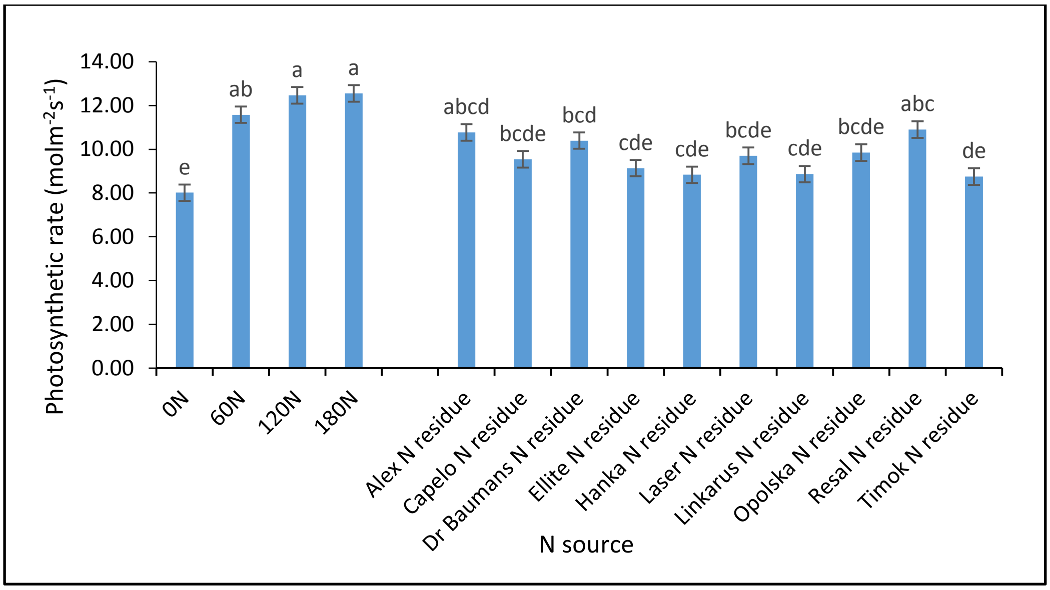

Figure 5.10 The effect of N source on forage sorghum photosynthetic rate.

Shoot dry matter (SDM)

Nitrogen source significantly influenced shoot dry matter accumulation ($P < 0.001$) (Figure 5.12). SDM was significantly the highest at inorganic 180 kg N ha^{-1} (5946 kg ha^{-1}), followed by inorganic 120 kg N ha^{-1} (5387 kg ha^{-1}). SDM produced by inorganic 60 kg N ha^{-1} was the third and similar to most legume N residue including Resal, Capelo, Dr Baumans, Elite, Hanka, Laser, and Opolska with the SDM ranging between 5057 kg ha^{-1} and 4704 kg ha^{-1}. Thus, 70% of the sorghum plants following the forage legumes produced dry matter which was equivalent to plants receiving 60 kg N ha^{-1}. The lowest SDM was observed in the control plants, 0 kg N ha^{-1} yielding 3714 kg ha^{-1}. Similar findings were reported by Mahama *et al*., (2014) who found that biomass increased linearly with increasing N fertilizer rates. Overall, forage sorghum grown with different N sources outgrew the unfertilized control. This is because the fertilizer provided the plants with the nutrients they needed for healthy growth. The findings of this study support the findings of Addai and Alimiyawo (2015), who reported that sorghum, like other crops, requires an adequate supply of nutrients, particularly nitrogen, for growth. Legume N residues were able to satisfy the N demand of forage sorghum during its vegetative growth stage until the grain soft dough stage. This is in accordance with Samarappuli *et al*. (2014). Who observed that the presence of a leguminous cover crop preceding the forage crop had a clear effect on biomass when compared with the control. This indicates that substituting inorganic N fertilizer with organic N from forage legumes can reduce N cost in the forage production system.

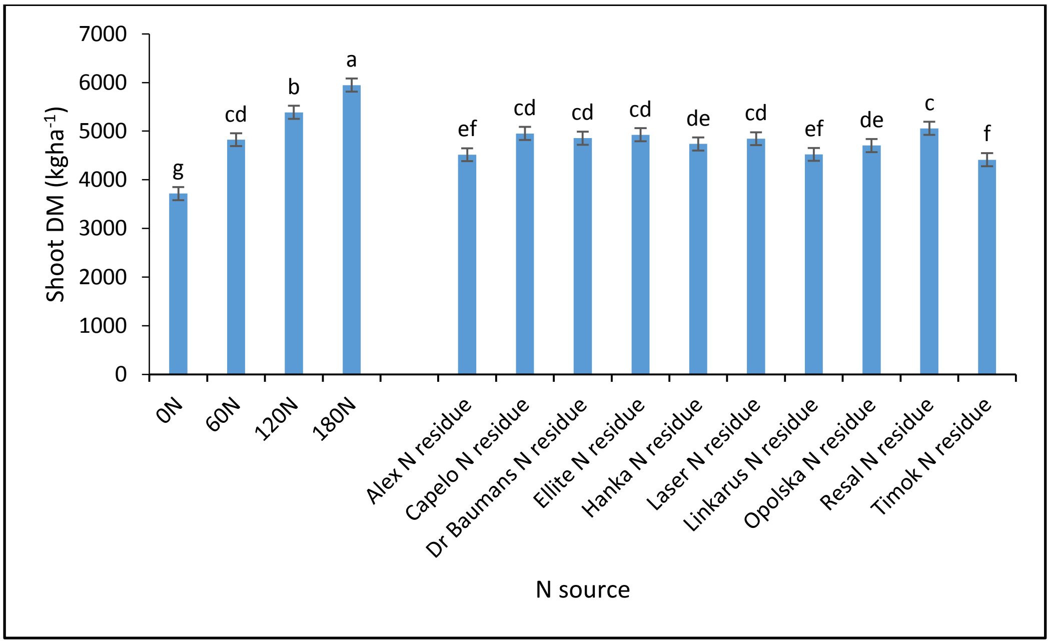

Figure 5.11 The effect of N source on forage sorghum shoot dry matter.

5.4.5 Planting date by nitrogen source interaction effects on selected morphology, physiological and yield parameters of forage sorghum.

According to statistical ANOVA (Table 5.5), the planting date by nitrogen source interaction had a highly significant effect ($P < 0.001$) on stem diameter, LAI, chlorophyll content and shoot dry matter only.

Stem diameter

Stem diameter was significantly ($P < 0.01$) influenced by the interaction effect of planting date and N source across the growing season (Figure 5.13). It was found to progressively increase with increasing N sources from 40 DAP to 103 DAP for both planting dates 1 and 2. Stem diameter at 40 DAP ranged between 7.00 and 9.62 mm and between 5 and 8 mm for PD 1 and PD 2 respectively, while at 103 DAP it ranged between 15.00 and 18.5 mm and between 9.75 and 17 mm for PD 1 and PD 2 respectively. Generally, between 68 DAP and 103 DAP, inorganic 180 kg N ha^{-1} yielded the highest stem diameter followed by either inorganic 120 kg N ha^{-1} or Resal and Alex N residues and lastly 60 kg N ha^{-1} across the two planting dates.

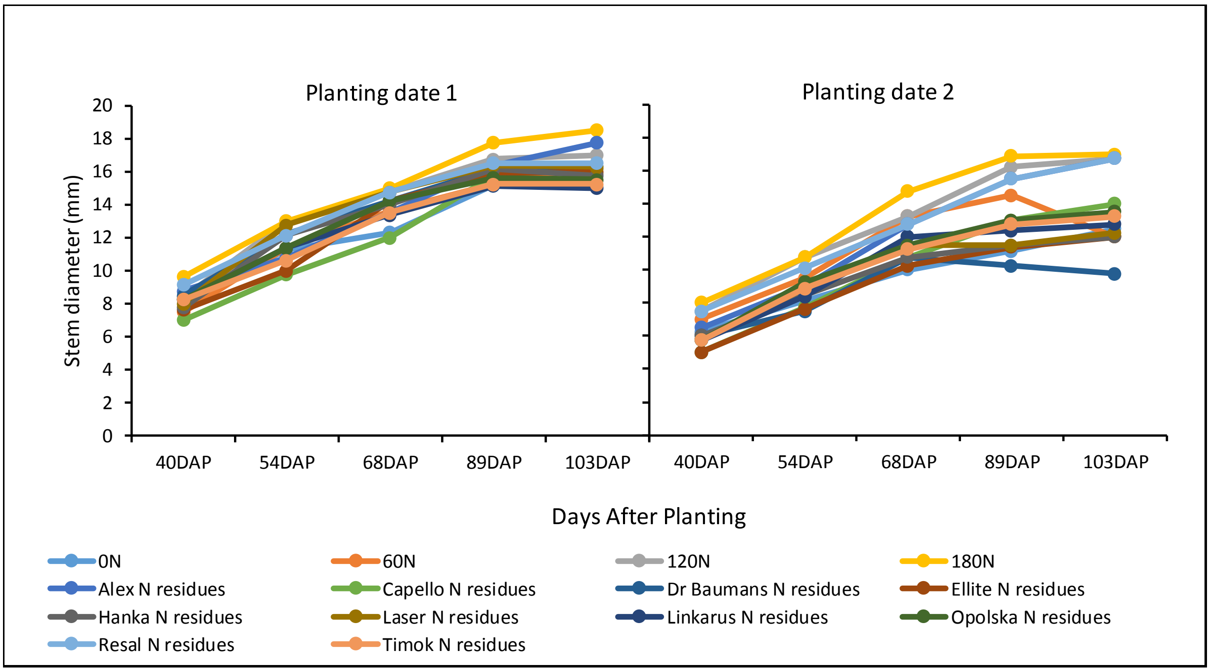

Figure 5.12 Changes in stem diameter of forage sorghum as influenced by planting date and N source interaction.

LAI

LAI of forage sorghum was significantly ($P < 0.01$) influenced by the interaction of planting date and N source from 40 DAP until 103 DAP (Figure 5.14). LAI was found to progressively increase with an increase in growth from 40 DAP until 89 DAP and declined at 103 DAP under PD 1 while under PD 2, the decline was observed from 89 DAP. LAI at 40 DAP ranged from 0.64 to 1.41 m^2m^{-2} and from 0.55 to 1.22 m^2m^{-2} for PD 1 and PD 2, respectively, while at 103 DAP it ranged between 2.69 and 4.00 m^2m^{-2} and between 1.78 and 2.77 m^2m^{-2} for PD 1 and PD 2, respectively. Generally, throughout the growth stages, inorganic 180 kg N ha^{-1} application yielded significantly high LAI followed by inorganic 120 kg N ha^{-1}. Thirdly Resal and Alex N residues yielded higher than 60 kg N ha^{-1} across the two planting dates. Across the two planting dates, LAI under the control, 0 kg N ha^{-1} was the least.

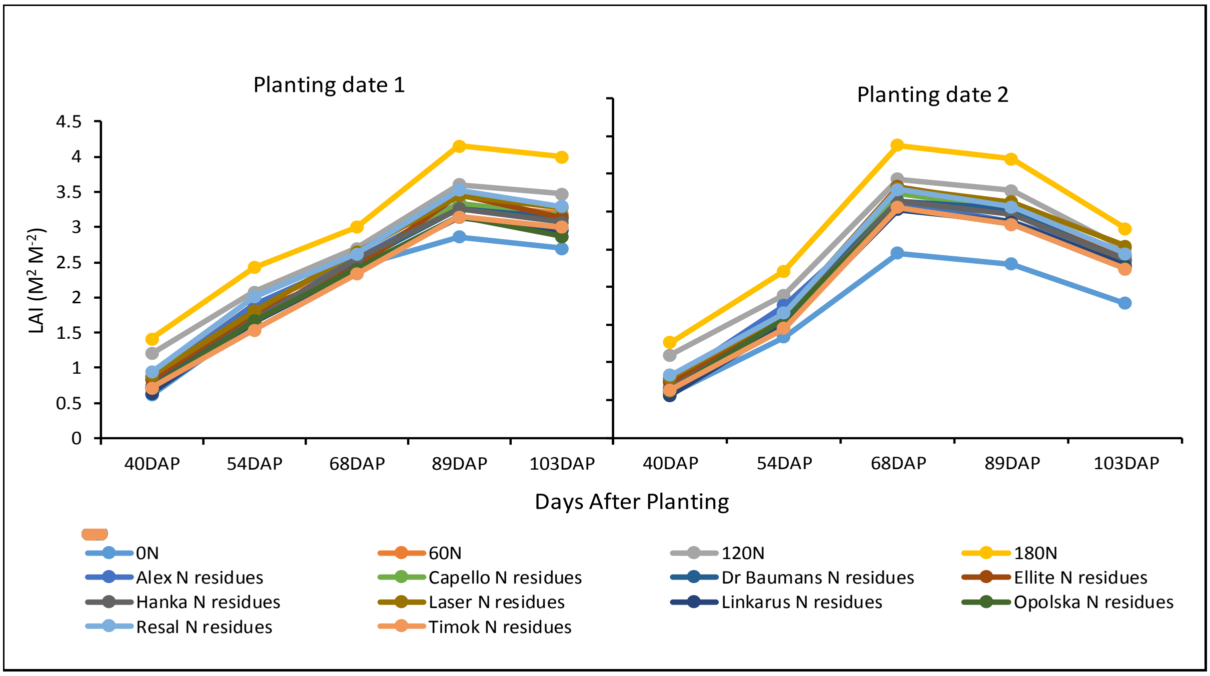

Figure 5.13 Changes in LAI of forage sorghum as influenced by planting date and N source interaction.

Chlorophyll

Chlorophyll content of forage sorghum was significantly ($P < 0.01$) influenced by the interaction effect of planting date and N source from 40 DAP to 103 DAP (Figure 5.15). The chlorophyll content of forage sorghum was found to differ significantly between different N sources and continued to fluctuate during the growing period. Chlorophyll content was high at 54 and 89 DAP, while inorganic 180 kg N ha^{-1} yielded the highest chlorophyll content, followed by inorganic 120 kg N ha^{-1} and 60 kg N ha^{-1}. Chlorophyll content from the legume N residues was significantly higher than that of 0 kg N ha^{-1}.

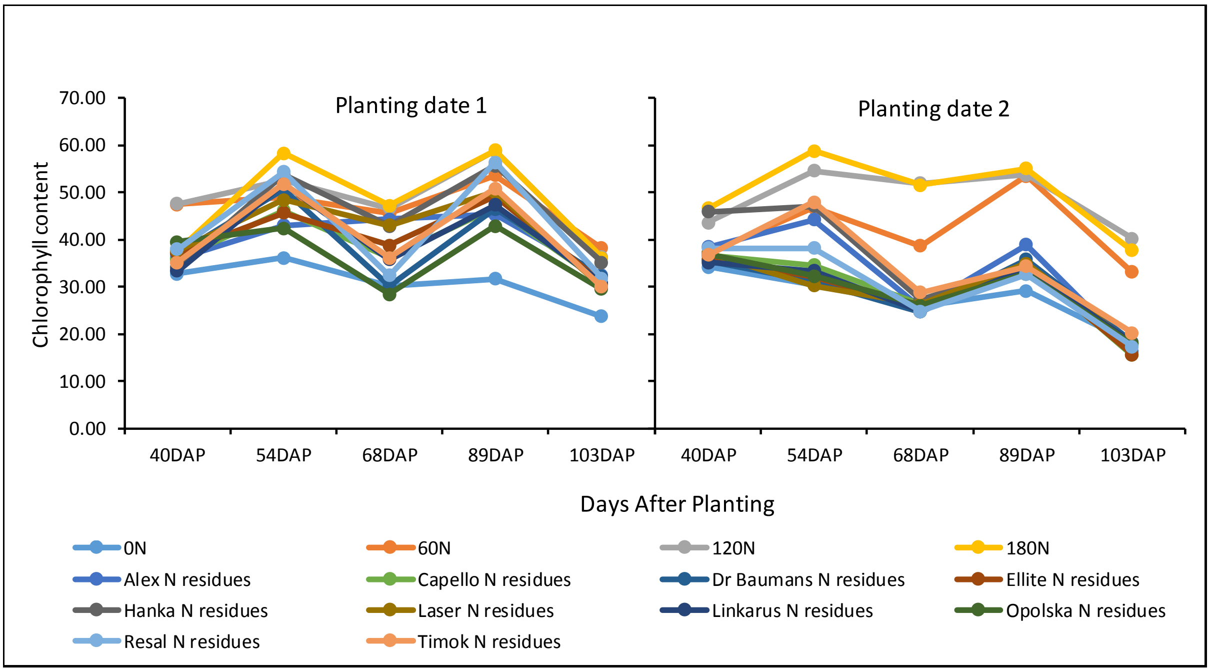

Figure 5.14 Changes in the chlorophyll of forage sorghum as influenced by planting date and N source interaction.

Shoot dry matter (SDM)

The shoot dry matter of forage sorghum was significantly ($P < 0.01$) affected by the interaction effect of planting date and N source across the growing season (Figure 5.16). SDM significantly increased linearly with increased organic N rates, with the application rate of 180 kg N ha^{-1} producing the highest SDM, followed by 120 kg N ha^{-1} throughout the growing season and across the two planting dates. Across the sampling dates, SDM at 60 kg N ha^{-1} was similar to that of Laser, Capelo, Resal and Elite N residue under PD 1 while similar with Dr Baumans, Elite, Resal and Capelo under PD 2. At 89 DAP and 103 DAP, SDM of all legume N residues was significantly higher than that of inorganic 60 kg N ha^{-1} under PD 1.

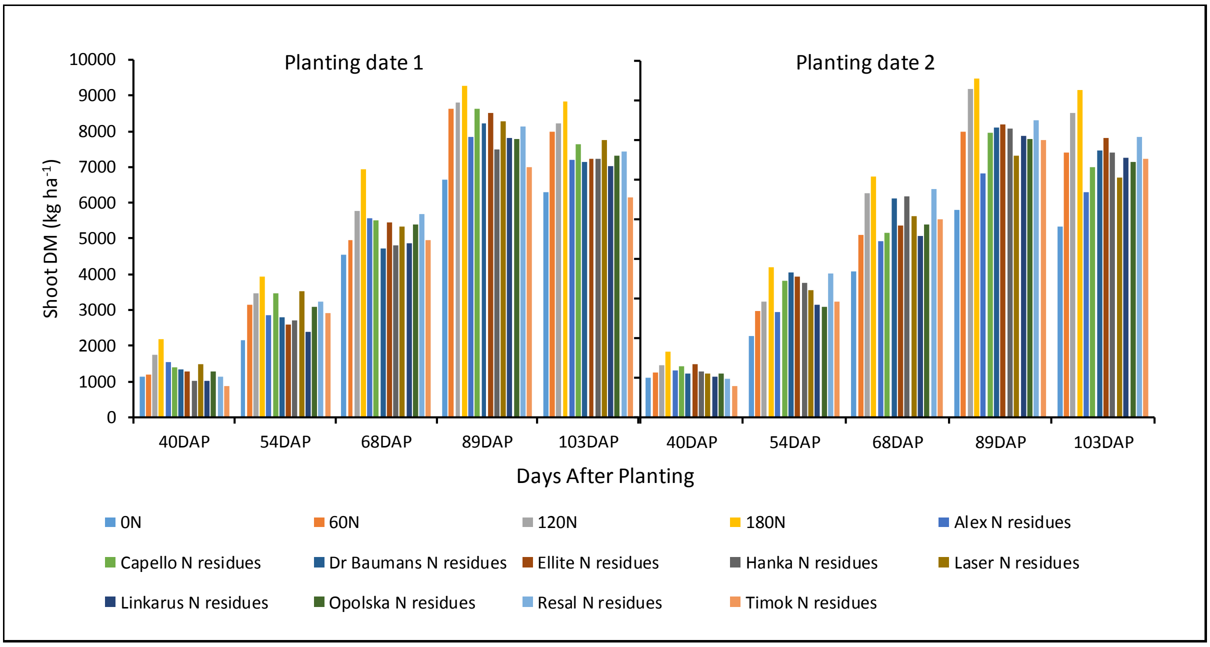

Figure 5.15 Changes in the chlorophyll of forage sorghum as influenced by the interaction.

Nutritive value

The effect of planting date and N source on the nutritive value of forage sorghum which was harvested at the grain soft dough stage of growth is shown in Table 5.7. Forage sorghum nutritive value results (Table 5.7) indicated that CP was significantly affected by planting date, with a significantly higher concentration occurring in PD 1 (12.83%) compared to PD 2 (11.90%). The findings of this study differ from the ones reported by Zhang *et al*. (2017), who found that planting date showed no significant effect on CP. Protein supply is one of the major factors that influence the productivity of animals which is effective to build assets and increase livestock productivity in terms of yield and quality both. Ash content was not significantly affected by planting date, 11.90% and 11.92% for PD1 and PD 2 respectively. Ash contents of forage sorghum varieties were reported as between 6.15 and 13.08% by Chakravarthi *et al*. (2017).

Neutral detergent fibre content was not significantly affected by planting date. A delay in the planting date significantly increased ADF, with values of 32.94% and 33.55% for PD 1 and PD 2, respectively. These findings are in accordance with Carmi *et al*. (2006) and Marsalis *et al*. (2010), who reported that planting date did not affect the NDF contents of sorghum, but are in contrast with observations in corn

(Widdicombe and Thelen 2002). Protein yield was significantly higher in PD 1 (172.03 kg ha^{-1}) compared to PD 2 (138.5 kg ha^{-1}). Regarding the effects of N source on nutritive value parameters, the results showed that inorganic N fertilizer and legume N residues influenced nutritive value parameters. There were significant differences in crude protein contents of forage sorghum as influenced by N source treatment. A significantly higher crude protein content (13.71 %) was obtained under inorganic 180 kg N ha^{-1} and 120 kg N ha^{-1} relative to the other N treatments. Within the inorganic N fertiliser treatment, the lowest crude protein content of 11.54 % was recorded under the control treatment, 0 kg N ha^{-1}. Ash content differed significantly across the N source treatment, ranging between 10.35% and 13.76%. Inorganic 60 kg N ha^{-1} produced the higher ash content while the least was observed from Hanka N residue.

There was no significant difference in % NDF of forage sorghum when analyzed across the different N sources, except at 180 kg N ha^{-1} which was lower than most of the forage legume sources. The NDF values ranged from 62.55% to 64.76%. Nitrogen source treatment significantly influenced the ADF which ranged between 34.76% and 31.58%. Inorganic 180 kg N ha^{-1}, Hanka, Linkarus, Opolska and Timok N residues yielded significantly similar ADF which was the highest. Dr Bauman and Resal N residue yielded the lowest ADF value (32.48 and 31.58 respectively) which was not significantly lower than the majority of the legume N residues and even inorganic 120 kg N ha^{-1} and 60 kg N ha^{-1}. Protein yield was significantly influenced by N sources. Inorganic 180 kg N ha^{-1} produced significantly the highest protein yield of 292.47 kg ha$^{-1,}$ followed by inorganic 120 kg N ha-1. 60 kg N ha^{-1} had a similar effect as the majority of the legume N residues. The lowest protein yield was observed from Timok N residue (105.19 kg ha^{-1}). Protein supply is one of the major factors that influence the productivity of animals which is effective in building assets and increasing livestock productivity in terms of yield and quality or both. Livestock feed is regarded as high quality when crude protein (CP) is high and when crude fiber, including both acid detergent fiber (ADF) and neutral detergent fiber (NDF), is low. Forages with CP content above 8% and ADF and NDF content below 45 and 65%, respectively, are recommended for livestock feed purposes. The stage of growth is among the crucial factors that influence the nutritional value of fodder (Fariani *et al*., 1994). Generally, the forage sorghum produced under clover and vetch rotation systems have great potential to meet the nutrient requirements of all the classes of sheep (National Research Council, 2016).

Table 5.7 Nutritive value of forage sorghum as influenced by planting date and nitrogen source.

Planting date	CP (%)	Ash (%)	NDF (%)	ADF (%)	N Yield (kg ha^{-1})
PD1	12.83 ^{a}	11.90 ^{a}	64.11 ^{a}	32.94 ^{b}	172.03 ^{a}
PD2	11.90 ^{b}	11.92 ^{a}	64 ^{a}	33.55 ^{a}	138.5 ^{b}
LSD (P ≤ 0.05)	**0.35**	**0.49**	**0.58**	**0.48**	**14.07**
N Source	CP (%)	Ash (%)	NDF (%)	ADF (%)	N Yield (kg ha^{-1})
0 N	11.54 ^{d}	12.65 ^{abc}	63.55 ^{ab}	32.90 ^{dc}	137.58 ^{cde}
60 N	12.73 ^{c}	13.76 ^{a}	64.03 ^{ab}	32.40 ^{de}	147.68 ^{dc}
120 N	13.71 ^{b}	12.69 ^{abc}	64.01 ^{ab}	32.47 ^{de}	209.71 ^{b}
180 N	14.87 ^{a}	13.08 ^{ab}	62.55 ^{b}	34.76 ^{a}	292.47 ^{a}
Alex N residue	12.21 ^{cd}	12.89 ^{ab}	64.29 ^{a}	33.15 ^{cd}	164.63 ^{c}
Capello N residue	11.98 ^{cd}	11.33 ^{cdef}	64.33 ^{a}	33.3 ^{cbd}	162.26 ^{c}
Dr Baumans N residue	11.88 ^{cd}	11.88 ^{bcde}	63.86 ^{ab}	32.48 ^{de}	140.83 ^{cde}
Elite N residue	12.21 ^{cd}	11.5 ^{cdef}	64.76 ^{a}	33.41 ^{bcd}	155.94 ^{dc}
Hanka N residue	12.09 ^{cd}	10.35 ^{f}	64.12 ^{a}	33.49 ^{abcd}	124.29 ^{de}
Laser N residue	12.06 ^{cd}	12.36 ^{bcd}	63.42 ^{ab}	33.00 ^{cd}	158.54 ^{dc}
Linkarus N residue	12.05 ^{cd}	10.6 ^{def}	64.33 ^{a}	34.12 ^{abc}	109.15 ^{e}
Opolska N residue	11.89 ^{cd}	10.57 ^{f}	64.30 ^{a}	34.46 ^{ab}	137.12 ^{cde}
Resal N residue	12.25 ^{cd}	11.96 ^{bcd}	64.75 ^{a}	31.58 ^{e}	128.34 ^{cde}
Timok N residue	11.73 ^{d}	11.15 ^{def}	64.51 ^{a}	33.95 ^{abc}	105.19 ^{e}
LSD(P ≤ 0.05)	**0.94**	**1.29**	**1.53**	**1.28**	**37.23**

Letters represent significant differences. Means with the same letters within the columns are not significant from each other at a 5% probability level. Significance levels: *P < 0.05, ***P < 0.001, ns = not significant. CP-Crude protein, NDF-Neutral detergent fibre, ADF-Acid detergent fibre.

5.4.6 APSIM Validation

Shoot Dry Matter (SDM)

Shoot DM was well simulated for all the N rates as evidenced by the range of values for the correlation coefficient (R^2: 0.95 – 0.98), NRMSE (0.072 – 0.1147) (Figure 5.17). Furthermore, the model was able to accurately simulate the trend of SDM accumulation over the growing season. Similar observations on the accuracy of the model to predict biomass were reported by Chimonyo *et al.* (2016). However, the measured and simulated SDM was well estimated in the early stages of growth in all the treatments, but later in the season, the model simulated a slightly lower SDM than the measured SDM for the control treatment (0 kg N ha^{-1}) and 180 kg N ha^{-1}. The model was able to accurately simulate shooting DM around 50DAP for forage sorghum under 0N and 180N as well as at around 100DAP for 60N and 120 N treatments. Simulated SDM increased linearly with increased N rate. However, it is important to note that at 180 kg N ha^{-1}, the model predicated biomass up to 7700 kg ha^{-1} which was similar to 120 kg N ha^{-1}. This means that according to the model an N rate increase up to 180 kg N ha^{-1} is not necessary.

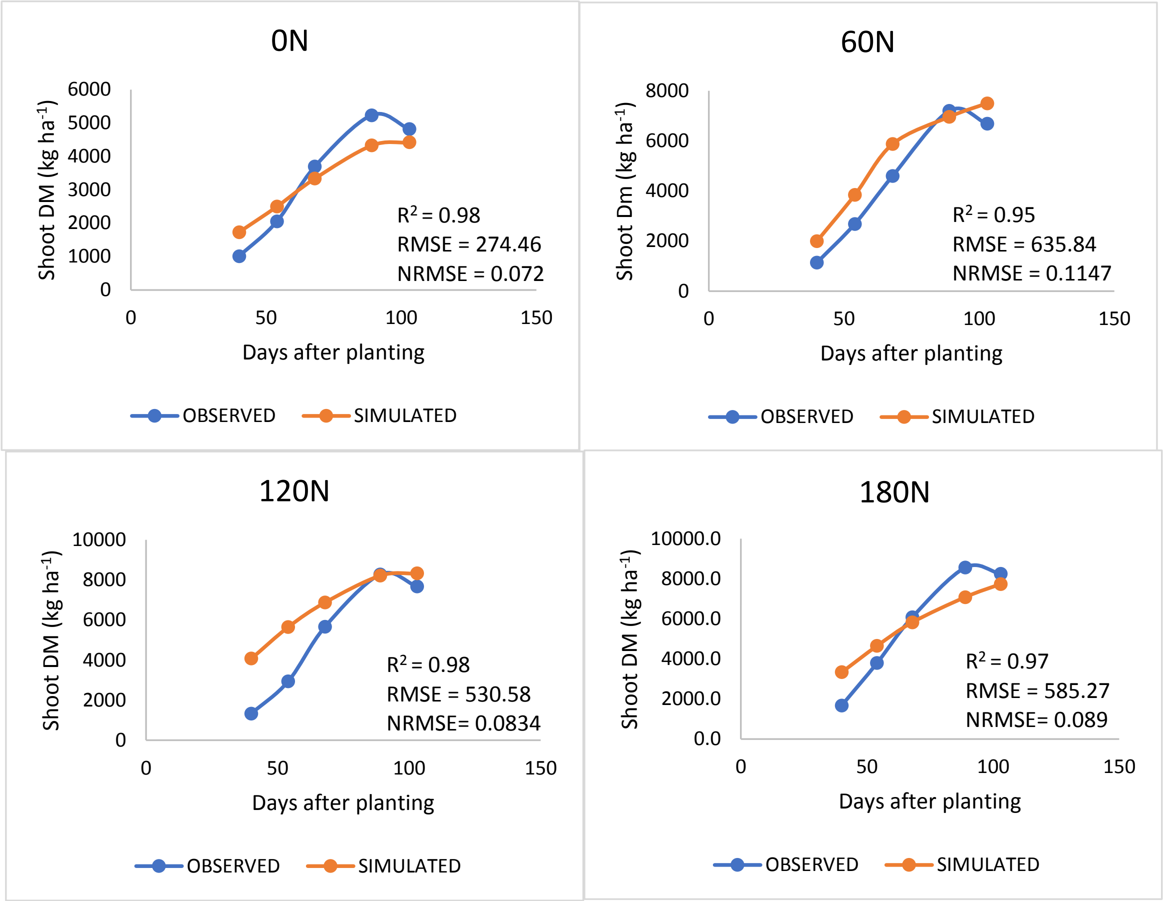

Figure 5.16 Validation output for biomass.

Plant height

The model achieved a successful simulation for plant height, at 60 kg N ha^{-1}, 120 kg N ha^{-1} and 180 kg N ha^{-1} as demonstrated by the range of values for the correlation coefficient (R^2: 0.95 – 0.99) and (NRMSE: 0.023 – 0.104) (Figure 5.18). Plant height comparisons under these N rates showed a high correlation, low error and a good agreement between measured and simulated data, indicating a good validation. However, the model underestimated plant height at 0 kg N ha^{-1}, R^2: 0.91 and NRMSE: 0.101. Simulated plant height increased linearly with increasing N rates. Similar to SDM simulation at 180 kg N ha^{-1}, the model predicated biomass plant height of about 170 cm which was similar to that of 120 kg N ha^{-1}, indicating that the application on N to 180 kg N ha^{-1} is not necessary.

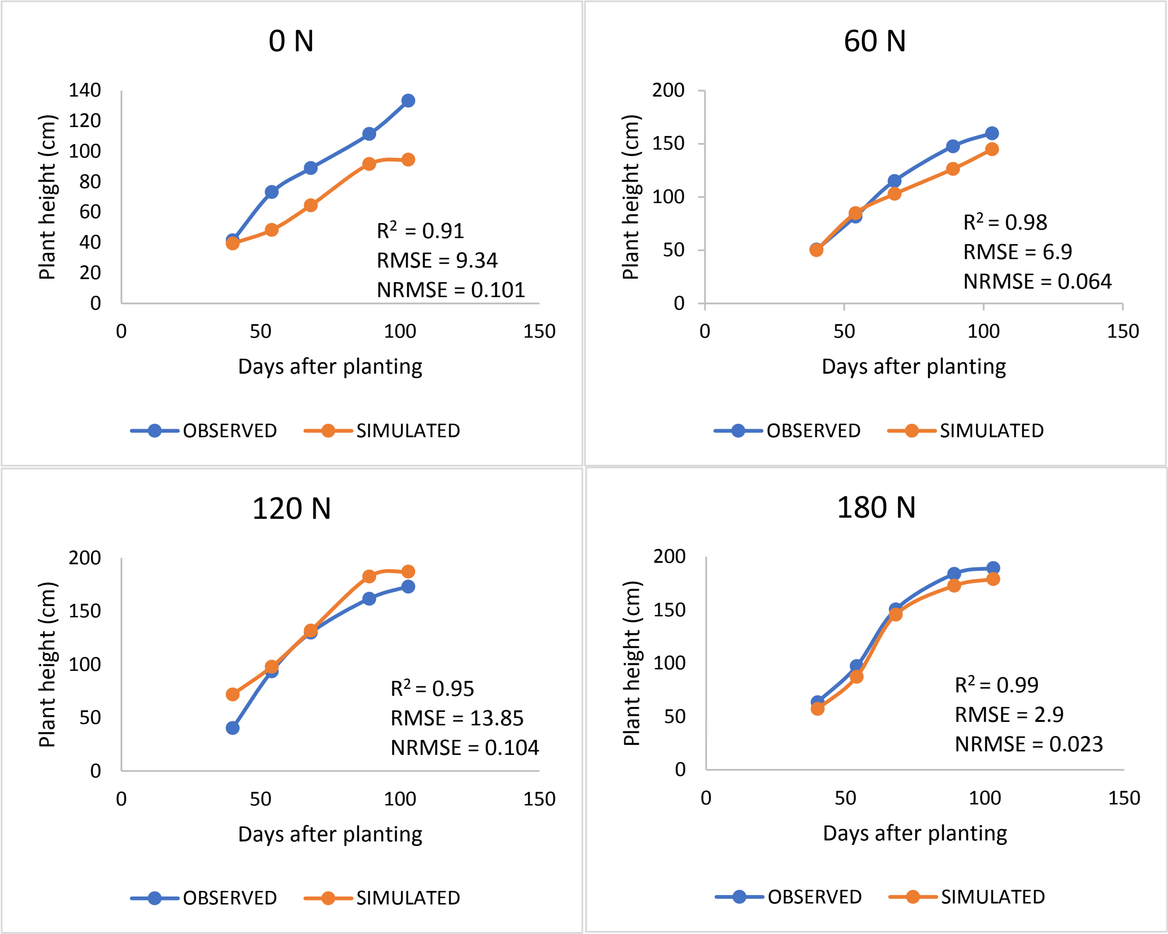

Figure 5.17 Validation output for plant height.

Limitations of APSIM modeling observed in this study

Crop models require an adequate amount of input data, which was not available in our case due to crop failures as a result of termite infestation. Furthermore, parameterization of N dynamics within the N model required experimental data on minimum, maximum and critical leaf, stem or shoot N concentration at different phenological stages and N translocation rate which was also not available due to financial constraints to analyze N at different phenological stages (Soufizadeh *et al*., 2018). Hence, the calibration parameters (Table 5.4) used in this study were those that are associated with canopy development and biomass accumulation only.

5.5 CONCLUSIONS

The most critical decisions affecting pasture productivity and sustainability are planting date and soil fertility management. Findings of this study indicated that delaying the planting date by three weeks had a negative effect on morphological, physiological, yield and nutritive value parameters of forage sorghum across species and sampling stages. Nitrogen source from inorganic N at 60 kg N ha$^{-1,}$ 120 kg N ha^{-1}, 180 kg N ha^{-1} and residual N from annual clover and vetch cultivars had a significant effect on morphological, physiological, yield and nutritive value parameters of forage sorghum. Generally, legume N residue effects on all the studied parameters of forage sorghum were similar to 60 kg N ha^{-1}. However, the effects differed widely according to the species and cultivar of the legume. Resal, Laser, Elite Capelo and Dr Baumans N residue consistently showed greater effects on all the measured parameters than other legume residues. They consistently outperformed inorganic 60 kg N ha^{-1} on most of the measured parameters. The results confirm that annual clover-forage sorghum and vetch-forage sorghum rotation have huge potential to reduce the cost associated with inorganic N use in forage production systems. With regard to the potential of the APSIM grain legume model to simulate forage legume DM and plant height, in general, the model performed well and accurately in predicting the SDM accumulation and plant height under 60 kg N ha^{-1} and 120 kg N ha^{-1}. However, it underestimated both these parameters at 180 kg N ha^{-1} indicating that the application on N up to 180 kg N ha^{-1} is not necessary.

5.6 RECOMMENDATIONS

Results from this short-term study demonstrated that crop residue retention is critical in improving the productivity of the succeeding crop. Therefore, long-term annual clover-forage sorghum and vetch-forage sorghum rotation studies are required to build up knowledge of the ecological and economic benefits of incorporating these legumes into rotation systems. Furthermore, the build-up of knowledge is required for developing the models specific for forage crops under the agro-ecological condition of South Africa. Resal, Laser, Elite Capelo and Dr Baumans N residue consistently showed greater effects on forage sorghum parameters and can therefore be recommended for conservation agricultural practices such as crop rotations.

CHAPTER 6: GENERAL CONCLUSION AND RECOMMENDATIONS

This section addresses all the objectives of the study and also summarises findings generated from the study as well as recommendations for possible future research relating to the study area.

Objective 1: Assess the factors affecting the adoption of winter annual legumes by sheep farmers in addressing winter forage gaps in the Limpopo Province and investigate the question “Does production practices of communal and smallholder sheep farmers of Limpopo Province contribute to feed gaps”?
Hypothesis: Sheep farmers in the Limpopo Province have not adopted winter annual legumes to address winter forage gaps.
Conclusion: The dominant feed resource which the majority of the sheep farmers interviewed rely on within the two farming systems was natural grasses that grow in the rangelands, roadsides, fallow lands around homesteads and browse plants during all seasons. As a result, farmers experienced feed shortages from mid-May to September before the first rain and about 38% of farmers perceived the extent of the feed gap to be between medium to very high. The hypothesis of the study is rejected because about 25% of the sheep farmers practice on-farm forage production on an average of 0.5 to 1 ha. The adoption of on-farm forage legume production has a critical potential role in alleviating feed gaps for proper fodder flow and fodder bank development. Survey results have determined that factors such as gender, farming experience, knowledge of forage legume production, source of income, membership in farmer associations, access to extension services and farm size all exert a significant positive influence on the decision to adopt on-farm forage legume production. Additionally, the perceived barriers to adopting on-farm forage production identified by this study were low institutional support, lack of resources, lack of knowledge, shortage of water and objectives of the farmer.

Recommendation: To overcome the above-mentioned barriers, the adoption of on-farm forage production depends on the priorities and associated activities of a wide variety of stakeholders, including multiple levels of government (provincial–district–local). Dialogue between stakeholders should consider the determining factors and identified barriers to the adoption of on-farm forage production in planning and developing enabling environments, vital policies, strategic programs and much-needed investments. The required activities to reduce the identified barriers should include increased institutional support such as accessibility of extension services, initiation of sheep farmer associations, increased awareness and training sessions and including forage production resources in government farmer support programs. The promotion of on-farm forage production should be backed up by empirical evidence that the forage pastures are adapted to the local climatic and soil conditions.

Objective 2: Measure the leaf gaseous exchange, biomass production, biological nitrogen fixation and nutritive value of no-till winter annual vetch and clover cultivars under different planting dates for climate change adaptation.

Hypothesis: Planting date does not affect the leaf gaseous exchange, biomass production, biological nitrogen fixation and nutritive value of no-till winter annual vetch and clover cultivars.

Conclusion: The study revealed that planting date, cultivar and harvest day had significant effects on leaf gaseous exchange, biomass production, nodulation and nutritive value. Therefore the hypothesis of the study is rejected. Planting date 1 in June produced the highest biomass production of adequate quality at 105DAP. Late planting exposes the crops to increased temperatures, which negatively affected the leaf gaseous exchange, biomass production and nutritive value. Overall, higher stomatal conductance and photosynthetic rate enhanced biomass productivity. For climate change mitigation, breeding cultivars with high thermo-tolerance adaptive capacity is essential. Resal, Alex, Elite, Laser and Dr Baumans showed more consistency in terms of leaf gaseous exchange, biomass production and quality traits under varying climatic conditions and harvest days. These forages have shown huge potential to mitigate the feed gap. Due to their ability to fix atmospheric nitrogen in symbiosis with Rhizobium bacteria, legumes are valuable forage cover crops recommended for soil improvement in rotational cropping.

Recommendation: The clover and vetch biomass production respond to planting dates and harvesting stage. With increasing climate variability, further research on a broader planting window from early autumn and across different environmental conditions is advised before recommendations are made since they are relatively new cultivars in Limpopo province. Further studies of their nitrogen fixation are required to support and increase knowledge of their significance as a cover crop for soil fertility improvements.

Objective 3: Determine the growth and nutritive value of forage sorghum, planted after the winter annual legumes in combination with nitrogen application in a short-term rotation and validation of forage sorghum growth with APSIM.

Hypothesis: The growth and nutritive value of forage sorghum are not influenced by preceding winter annual vetch and clover cultivars and nitrogen application in a short-term rotation. Experimental results on the performance of no-till forage sorghum under different planting dates and N levels will not differ from the APSIM simulation result.

Conclusion: The findings of objective three of this study indicated that delaying the planting date by three weeks had a negative effect on morphological, physiological, yield and nutritive value parameters of forage sorghum. Nitrogen source from inorganic N at 60 kg N ha^{-1}, 120 kg N ha^{-1}, 180 kg N ha^{-1} and residual N from annual clover and vetch cultivars had a significant effect on morphological, physiological, yield and nutritive value parameters of forage sorghum. As a result, the hypothesis of the study is rejected. Generally, legume N residue effects on all the studied parameters of forage sorghum were similar to 60 kg N ha^{-1}. However, the effects differed widely according to the species and cultivar of the legume. Resal, Laser, Elite Capello and Dr Baumans N residue consistently showed greater effects than other legume residues and can be incorporated in crop rotation system. With regard to the evaluation of the potential of the APSIM grain legume model to simulate forage legume DM and plant height, in general, the model performed well and accurately in predicting the SDM accumulation and plant height under 60 kg N ha^{-1} and 120 kg N ha^{-1}. However, it underestimated both these parameters at 180 kg N ha^{-1} indicating that the application on N up to 180 kg N ha^{-1} is not necessary.

Recommendation: Results from this short-term study demonstrated that crop residue retention is critical in improving the productivity of the succeeding crop. Therefore, long-term annual clover-forage sorghum and vetch-forage sorghum rotation studies are required to build up knowledge on the ecological and economic benefits of incorporating these legumes in rotation systems. Furthermore, the build-up of knowledge is required for developing the models specific for forage crops under the agro-ecological condition of South Africa.

REFERENCES

Abebe, A.S., Alemayehu, K., Johansson, A.M. and Gizaw, S. 2020. Breeding practices and trait preferences of smallholder farmers for indigenous sheep in the northwest highlands of Ethiopia: Inputs to design a breeding program. *PLoS ONE,* 15: e0233040. https://doi.org/10.1371/journal.pone.0233040

Adams, F., Ohene-Yankyera, K., Aidoo, R. and Abawiera Wongnaa, C. 2021. Economic benefits of livestock management in Ghana. *Agricultural Economics*, 9: 17. https://doi.org/10.1186/s40100-021-00191-7

Afzal, M., Ahmad, A. and Ahmad, H. 2013. Effect of nitrogen on growth and yield of sorghum forage (Sorghum Bicolor (L.) under three cuttings system. *Cercetari Agronomice in Moldova*, 45: 57-64. https://doi.org/10.2478/v10298-012-0065-y

Agholor, A.I. 2014. Analysis of decision making in smallholder irrigation practice: a case study of Shiloh and Zanyokwe irrigation schemes in central Eastern Cape, South Africa. Ph.D. Thesis, University of Fort Hare, Alice, South Africa.

Alary, V., Aboul-Naga, A., El Shafie, M., Abdelkrim, N., Hamdon, H., Metawi, H. 2015. Roles of small ruminants in rural livelihood improvement—Comparative analysis in Egypt. *Revue d'élevage et de médecine vétérinaire des pays tropicaux*, 68: 79-85.

Aliber, M., Baiphethi, M., de Satge, R., and Denison, J. 2010. Strategies to support South African smallholders as a contribution to government's second economy strategy, Situation analysis, fieldwork findings and main conclusions. *Institute for Poverty, Land and Agrarian Studies Research Report*, 1: 28.

Aliber, M., Maluleke, T., Manenzhe, T., Paradza, G. and Cousins, B. 2013. Land reform and livelihoods: trajectories of change in northern Limpopo province, South Africa. HSRC Press, Cape Town.

Amejo, A.G., Gebere, Y.M., Dickoefer, U., Kassa, H., Tana, T. and Lawrence, P. 2018. Herd dynamics and productivity performance modeling of livestock in smallholder crop-livestock systems in Southwestern Ethiopia. *Journal of Veterinary Science and Animal Husbandry*, 3: 17-24.

Anderson, W.K., Brennan, R.F., Jayasena, K.W., Micic, S., Moore, J.H. and Nordblom T. 2020. Tactical crop management for improved productivity in winter-dominant rainfall regions: a review. *Crop and Pasture Science,* 71: 621-644. https://doi.org/10.1071/CP19315

Anderson, J.M. and Ingram, J.S.I. 1993. Microbial biomass. In tropical soil biology and fertility: A handbook of methods, 2nd ed.; Anderson, J.M., Ingram, J.S.I., Eds. CAB International: Wallingford, UK, pp. 68-70. ISBN 0-85198-821-0.

AOAC ((2005) Official Methods of Analysis. 15th Edition, Association of Official Analytical Chemists, Arlington. USA.

Aramburu F.A., Monzon, J.P., Mercau, J.L., Taboada, M., Andrade, F.H., Hall, A.J., Jobbagy, E., Cassman, K.G. and Grassini, P. 2015. Potential for crop production increase in Argentina through closure of existing yield gaps. *Field Crop Research,* 184: 145-154. http://dx.doi.org/10.1016/j.fcr.2015.10.001.

Assefa, F., Tigistu, T. and Lambebo, A. 2015. Assessment of the Production System, Major Constraints and Opportunities of Sheep Production in Doyogena Woreda, Kembata Tambaro Zone, Southern Ethiopia. *Journal of Biology, Agriculture and Healthcare*, 5: 37-41. www.iiste.org

Ayalew, T., Yoseph, T., Högy, P. and Cadisch, G. 2022. Leaf growth, gas exchange and assimilation performance of cowpea varieties in response to Bradyrhizobium inoculation. *Heliyon*, 8: e08746. https://doi:10.1016/j.heliyon.2022.e08746

Ayele, S., Duncan, A., Larbi, A. and Khanh, T.T. 2012. Enhancing innovation in livestock value chains through networks: lessons from fodder innovation case studies in developing countries. *Science and Public Policy*, 39: 333-346. https://doi.org/10.1093/scipol/scs022

Ayele, J., Tolemariam, T., Beyene, A., Tadese, D.A. and Tamiru, M. 2021. Assessment of livestock feed supply and demand concerning livestock productivity in Lalo Kile district of Kellem Wollega Zone, Western Ethiopia. *Heliyon*, 7: e08177. https://doi.org/10.1016/j.heliyon.2021.e08177

Balazadeh, M., Zamanian, M., Golzardi, F. and Torkashvand, A.M. 2021. Effects of limited irrigation on forage yield, nutritive value and water use efficiency of Persian Clover (Trifolium Resupinatum) compared to Berseem clover (Trifolium

Alexandrinum). *Communications in Soil Science and Plant Analysis*, 52: 1927-1942. https://doi.org/10.1080/00103624.2021.1900228

Baxter, L.L., Grey, T.L., Tucker, J.J., Hancock, D.W., Baxter, L.L., Grey, T.L. and Hancock, D.W. 2019. Optimizing Temperature Requirements for Clover Seed Germination-NC-ND. *Agrosystems, Geosciences and Environment*, 2:180059. https://doi.org/10.2134/age2018.11.0059

Belay, D., Tegegne, A. and Hegde, B.P. 2012. Smallholder livestock production system in Dendi district, Oromia regional state, Central Ethiopia. *Global Veterinaria*, 8: 472-479. https://www.idosi.org/gv/GV8(5)12/8.pdf

Belay, G. and Negesse, T. 2018. Feed resource availability and their nutrient contribution for livestock evaluated using feed assessment Tool (FEAST) in Burie Zuria District, North Western Ethiopia. *Agricultural Research and Technology*, 17: 556022. http://dx.doi.org/10.19080/ARTOAJ.2018.17.556022

Bell, L., Moore, A. and Thomas, D. 2018. Integrating diverse forage sources reduces feed gaps on mixed crop-livestock farms. *Animal,* 12: 1967-1980. https://doi.org/10.1017/S1751731117003196

Ben Salem, H. 2010. Nutritional management to improve sheep and goat performances in semiarid regions. *Revista Brasileira de Zootecnia*, 39: 337-347.

Berihulay, H., Abied, A., He, X., Jiang, L., Ma, Y. 2019. Adaptation mechanisms of small ruminants to environmental heat stress-A review. *Animals*, 75: 1-9.

Beshir, H. 2014. Factors affecting the adoption and intensity of use of improved forages in the north east Highlands of Ethiopia. *American Journal of Experimental Agriculture,* 4: 12-27. https://doi10.9734/AJEA/2014/5481

Bettencourt, E.M., Tilman, V.M., Henriques, P.D.S., Narciso, V. and Carvalho, M.L.S. 2013. The economic and sociocultural role of livestock in the wellbeing of rural communities of Timor-Leste. CEFAGE-UE working Paper 2013/01.

Bhoya, M., Chaudhari, P.P., Raval, C.H. and Bhatt, P.K. 2014. Effect of nitrogen and zinc on growth and yield of fodder sorghum [Sorghum bicolor (L.) Moench] varieties. *International Journal of Agricultural Sciences*, 10: 294-297.

Bhusal, N., Pahuja, S.K., Vats, A.K., Srivastava, A. and Kumar, R.S. 2017. Morphological characterization of forage sorghum genotypes for its various DUS traits. *Journal of Applied and Natural Science*. 9: 912-919.

Blignaut, J. N., De Wit, M.P., Knot, J., Midgley, S., Crookes, D.J., Drimie, S. and Nkambule. N.P. 2014. Sustainable agriculture: A viable option for enhanced food and nutritional security and a sustainable productive resource base in South Africa: An investigation. Baseline Review. Prepared for the Development Bank Southern Africa, Pretoria: ASSET Research.

Bollam, S., Romana, K.K., Rayaprolu, L., Vemula, A., Das, R.R., Rathore, A., Gandham, P., Chander, G., Deshpande, S.P. and Gupta, R. 2021. Nitrogen use efficiency in Sorghum: exploring native variability for traits under variable n-regimes. *Frontiers in Plant Science,* 12: 643192. https://doi.org/10.3389/fpls.2021.643192

Boswell, R.J., Lonati, M., Fletcher, A., Moot, D.J. and Lucas, C.C. 2003. The ecology of four annual clovers adventive in New Zealand grasslands. *Legumes for Dryland Pastures*, 11: 175-184.

Bumb, I., Garnier, E., Bastianelli, D., Richarte, J., Bonnal, L., and Kazakou, E. 2016. Influence of management regime and harvest date on the forage quality of rangelands plants: the importance of dry matter content. *AoB Plants*, 8: plw045. https://doi:10.1093/aobpla/plw045

Capstaff, N.M. and Miller, A.J. 2018. Improving the yield and nutritional quality of forage crops. *Frontiers in Plant Science*, 9: 535. https://doi.org/10.3389/fpls.2018.00535.

Castro-Montoya, J.M. and Dickhoefer, U. 2020. The nutritional value of tropical legume forages fed to ruminants as affected by their growth habit and fed form: A systematic review. *Animal Feed Science and Technology*, 269: 114641. https://doi.org/10.1016/j.anifeedsci.2020.114641.

Cavalcante, T., Castoldi, G., Rodriques, C., Nogueira, M. and Albert, A. 2018. Macro and micronutrients uptake in biomass sorghum. *Pesquisa Agropecuária Tropical*, 48: 364-373. https://doi.org/10.1590/1983-40632018v4851874

Chakravarthi, M.K., Ravindra, Y., Reddy, K., Sarjan, A., Ravi, B., Punyakumari and Ekambaram, B. 2017. A study on nutritive value and chemical composition of sorghum fodder. *International Journal of Science, Environment* and *Technology*, 6: 104-109

Chand, S., Singhal, R.K. and Govindasamy, P. 2022. Agronomical and breeding approaches to improve the nutritional status of forage crops for better livestock productivity. *Grass and Forage Science*, 77: 11-32. https://doi.org/10.1111/gfs.12557

Chapman, S.C., Chakraborty, S., Dreccer, M.F. and Howden. S.M. 2012. Plant adaptation to climate change: opportunities and priorities in breeding. *Crop Pasture Science,* 63: 251-268.

Chavan, S. G., Duursma, R. A., Tausz, M. and Ghannoum, O. 2022. Moderate heat stress prevented the observed biomass and yield stimulation caused by elevated CO2 in two well-watered wheat cultivars. *Plant Molecular Biology,* 22: 1-18. https://doi.org/10.1007/s11103-022-01276-7

Chimonyo, V.G.P., Modi, A.T. and Mabhaudhi, T. 2016. Simulating yield and water use of a sorghum–cowpea intercrop using APSIM. *Agricultural Water Management*, *177*: 317-328. https://doi.org/10.1016/j.agwat.2016.08.021

Clack, W., and Minnaar, A. 2018. Rural Crime in South Africa: an exploratory review of ‘farm attacks’ and stock theft as the primary crimes in rural areas. *Acta Criminologica: African Journal of Criminology,* 31: 103-135.

Clifford, S.C., Kadzere, I., Jones, H.G. and Jackson, J.E. 1997. Field comparisons of photosynthesis and leaf conductance in Ziziphus mauritiana and other fruit tree species in Zimbabwe. *Trees-Structure and Function*, 11: 449-454.

Cloete, S.W.P., Olivier, J.J., Sandenbergh, L. and Snyman, M.A. 2014. The adaption of the South Africa sheep industry to new trends in animal breeding and genetics: A review. *South African Journal of Animal Science*, 44: 307-321.

Cousins, B. 2010. 'What is a ‘Smallholder’? Class-Analytic Perspectives on Small-Scale Farming and Agrarian Reform in South Africa'. Cape Town: Institute for Poverty, Land and Agrarian Studies.

Dabney, S.M., Delgado, J.A., Meisinger, J.J., Schomberg, H.H., Liebig, M.A., Kaspar, T., Mitchell, J. and Reeves, W. 2010. Using cover crops and cropping systems for nitrogen management. *Advances in nitrogen management for water quality*, 66: 231-82.

DAFF, Department of Agriculture, Forestry and Fisheries. 2019. Abstract of Agricultural Statistics, Directorate Statistics and Economic Analysis. Pretoria, Republic of South Africa.

DAFF, Department of Agriculture, Forestry and Fisheries. 2019. Trends in the Agricultural Sector. Directorate Statistics and Economic Analysis. Pretoria, Republic of South Africa.

DAFF, Department of Agriculture, Forestry and Fisheries. 2021. Trends in the Agricultural Sector. Directorate Statistics and Economic Analysis. Pretoria, Republic of South Africa.

Daramy, M., Sarkodie-Addo, J. and Dumbuya, G. 2016. The effects of nitrogen and phosphorus fertilizer application on crude protein, nutrient concentration and nodulation of cowpea in Ghana. *ARPN Journal of Agricultural and Biological Science*, 11: 470-480.

Deep, H., Arya, S., Pummy, K., Pahuja, S.K. and Jayanti T. 2019. Genetic parameters, correlation and path coefficient analysis for fodder yield and quality in forage sorghum. *Green Farming*, 10: 401-406.

Delaby, L., Finn, J., Grange, G. and Horan, B. 2020. Pasture-based dairy systems in temperate lowlands: challenges and opportunities for the future. *Frontiers in Sustainable Food Systems*, 4: 543587.

https://doi.org/10.3389/fsufs.2020.543587ï

Dickinson, E.B., Hyam, G.F.S., Breytenbach, W.A.S., Metcalf, W.D., Basson, W.D., Williams, F.R., Scheepers, L.J., Plint, A.P., Smith, H.R.H., Smith, P.J., Van Vuuren, P.J., Viljoen, J., Archibald, K.P. and Els, J.N. 2004. Kynoch pasture handbook. Kejafa Knowledge Works, Maanhaarrand. South Africa.

Domingues, C.H.D.F., Borges, J.A.R., Ruviaro, C.F., Gomes Freire Guidolin, D. and Rosa Mauad Carrijo, J. 2020.Understanding the factors influencing consumer willingness to accept the use of insects to feed poultry, cattle, pigs and fish in Brazil. *PLoS ONE*, 15: e0224059t. https://doi.org/10.1371/journal.pone.0224059

Duguma, B. and Janssens, G.P.J. 2021. Assessment of Livestock Feed Resources and Coping Strategies with Dry Season Feed Scarcity in Mixed Crop–Livestock Farming Systems around the Gilgel Gibe Catchment, Southwest Ethiopia. *Sustainability*, 13: 10713.
https://doi.org/10.3390/su131910713https://doi.org/10.3390/su131910713

Emmanuel, A.D. 2014. Farmers' perception of agricultural technologies a case of some improved crop varieties in Ghana. Agronomy Journal, 3: 13-16.

Fahad, S., Bajwa, A.A., Nazir, U., Anjum, S.A., Farooq, A., Zohaib, A., Sadia, S., Nasim, W., Wang, D. and Huang, J. 2017. Crop Production under Drought and Heat Stress: Plant Responses and Management Options. *Frontiers in Plant Science,* 8: 1147. https://doi.org/10.3389/fpls.2017.01147

FAO. 2015. Status of the World's Soil Resources – Main Report. FAO: Rome.

FAO. 2017. The Future of Food and Agriculture–Trends and Challenges. Rome: FAO.

FAO. 2020. Biodiversity and the Livestock Sector—Guidelines for Quantitative Assessment—Version 1. Rome: Livestock Environmental Assessment and Performance Partnership (FAO LEAP). https://doi.org/10.4060/ca9295en

Findlay, N. and Manson, A. 2011. Cover crops: what are they and why are they used. Soil Fertility and Analytical Services. Kwa-Zulu Natal Department of Agriculture, Environmental Affairs and Rural Development.

Fourie, P.J., Mahlako, S.R. and Van Der Westhuizen, C. 2018. Assessment of the management practices of emerging sheep production systems in the Eastern Free State: can the extensionist make a difference? *South African Journal of Agricultural Extension*, 46: 57-68. http://dx.doi.org/10.17159/2413-3221/2018/v46n2a463

Frasier, I., Quiroga, A. and Noellemeyer, E. 2016. Effect of different cover crops on C and N cycling in sorghum NT systems. *Science of the Total Environment*, 562: 628-639. https://doi.org/10.1016/j.scitotenv.2016.04.058

Fulkerson, W.J. and Slack, K. 1993. Estimating mass of winter and tropical pastures in the subtropics. *Australian Journal of Experimental Agriculture*, 33: 865-869.

Gebrekiristos, S. and Duguma, B. 2012. Small ruminant production systems in South Western Ethiopia: Rearing practices in urban and peri-urban area of Jimma. Lambert Academic Publishing. Ethiopia

Gebremedhin, B., Ahmed, M.M. and Ehui, S.K. 2003. Determinants of adoption of improved forage technologies in crop-livestock mixed systems: Evidence from the Highlands of Ethiopia. *Tropical Grasslands,* 37: 262-273.

Getnet, A. and Ledin, I. 2001. Effect of variety, soil type and fertilizer on the establishment, growth, forage yield and voluntary intake by cattle of oats and vetches cultivated in pure and stands and mixtures. *Animal feed science and technology,* 92: 95-111.

Giuseppe, P., Francesconi, A.H.D., Stefanon, B., Sevi, A., Calamari, L., Crovetto, G.M. and Ronchi, B. 2017. Sustainable ruminant production to help feed the planet. *Italian Journal of Animal Science*, 16: 140-171.

Gizaw, S., Tegegne, A., Gebremedhin, B. and Hoekstra, D. 2010. Sheep and goat production and marketing systems in Ethiopia: Characteristics and strategies for improvement. IPMS (improving productivity and market success) of Ethiopian

Farmers Project Working Paper 23. ILRI (International Livestock Research Institute), Nairobi, Kenya.

Gizaw, S., Getachew, T., Edea, Z., Mirkena, T., Duguma, G., Tibbo, M., Rischkowsky, B., Mwai, O., Dessie, T., Wurzinger, M., Solkner, J. and Haile, A. 2013. Characterization of indigenous breeding strategies of the sheep farming communities of Ethiopia: A basis for designing community-based breeding programs. ICARDA working paper, Aleppo, Syria.

Gotoh, E., Suetsugu, N., Yamori, W., Ishishita, K., Kiyabu, R., Fukuda, M., Higa, T., Shirouchi, B. and Wada, M. 2018. Chloroplast accumulation response enhances leaf photosynthesis and plant biomass production. *Plant Physiology*, 178: 1358-1369. https://doi.org/10.1104/pp.18.00484

Gul, H., Beena, S., Ahmad, S., Fida, M. and Ijaz. A. 2011. Influence of late planting dates and planting methods on seed production of clovers. *ARPN Journal of Agricultural and Biological Science,* 6: 1-5.

Gwiriri, L.C., Bennett, J., Mapiye, C. and Burbi, S. 2019. 'Unpacking the ‘emergent farmer’ concept evidence from cattle farmers in South Africa'. *Development and Change, International Institute of Social Studies*, 50: 664-686.

Hailemariam, F., Melesse, A and Banerjee, S. 2013. Traditional sheep production and breeding practice in Gamogofa Zone, Southern Ethiopia. *International Journal of Livestock Production Research,* 1: 26-43.

Hatab, A.A., Cavinato, M.E.R. and Lagerkvist, C.J. 2019. Urbanisation, livestock systems and food security in developing countries: A systematic review of literature. *Food Security,* 11: 279-299.

Hatfield, J.L. and Prueger, J.H. 2015. Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, 10: 4-10. https://doi.org/10.1016/J.WACE.2015.08.001

Havlík, P.H., Valin, A., Mosnier, M.J.S., Obersteiner, M., Baker, M.C., Herrero, E. Rufino and M. Schmid. 2013. Crop productivity and the global livestock sector: Implications for land use change and greenhouse gas emissions. *American Journal of Agricultural Economics,* 95: 442-448.

Hayden, Z.D., Ngouajio, M., Brainard, D.C. 2015. Planting date and staggered seeding of rye–vetch mixtures: biomass, nitrogen, and legume winter survival. *Agronomy Journal*. 107: 33-40. https://doi.org/10.2134/agronj14.0237

Henry, B., Eckard, R. and Beauchemin, K. 2018. Review: Adaptation of ruminant livestock production systems to climate changes. *Animal*, 12: 445-456. https://doi.org/10.1017/S1751731118001301

Herrero, M., Grace, D., Njuki, J., Johnson, N., Enahoro, D., Silvestri, S. and Rufino, M.C. 2013. The roles of livestock in developing countries. Animal, 7: 3-18. https://doi.org/10.1017/S1751731112001954

Herrmann, D., Barre, P., Santoni, S., and Julier, B. 2010. Association of a constans-like gene to flowering and height in autotetraploid alfalfa. *Theoretical and Applied Genetics,* 121: 865-876. https://doi:10.1007/s00122-010-1356-z

Holzworth, D.P., Snow,V., Janssen, S., Athanasiadis, I.N., Donatelli, M., Hoogenboom, G., White, J. W. and Thorburn, P. 2015. Agricultural production systems modelling and software: Current status and future prospects. *Environmental Modelling and Software*, *72*: 276-286. https://doi.org/10.1016/j.envsoft.2014.12.013

Huang, Y., Matthew, C., Zhang, Z., and Nan, Z. 2019. Morphological fractions, chemical composition and in vitro digestibility of stover of four common vetch varieties grown on the Tibetan plateau. J*ournal of Animal Physiology and Animal Nutrition*, 103: 1646-1656. https://doi.org/10.1111/jpn.13173

Huang, Y., Coulter, J.A., Zhang, Z. and Nan, Z. 2020. Cultivar and growing degree day accumulation effects on forage partitioning, quality attributes, and nutrient yields, and water use efficiency of common vetch on the Tibetan Plateau. *Archives of Agronomy and Soil Science*, 67: 1539-1553.

https://doi.org/10.1080/03650340.2020.1799985

Huang, Y.F., Gao, X.L., Nan, Z.B. and Zhang, Z.X. 2017. Potential value of the common vetch (Vicia sativa L.) as an animal feedstuff: a review. *Journal of Animal Physiology and Animal Nutrition*, 101: 807-823. https://doi.org/10.1111/jpn.12617

Hulela, K. 2010. The role of women in sheep and goats production in sub-Saharan Africa*. International journal of scientific research in education*, 3: 177-187.

Ignjatovic, S., Vucetic, J., Lugic, Z., Dinic, B. 2001. Effect of growth stage on macro and trace elements content in red and white clover. *Journal of Scientific Agricultural Research,* 62: 309-316.

IPCC. 2013. Annex I: Atlas of global and regional climate projections. In G. J. van Oldenborgh, J. Collins, J. Arblaster, J. Christensen, J. Marotzke, S. B. Power, M.

Rummukainen, and T. Zhou (Eds.), Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY: Cambridge University Press.

IPCC. 2014. Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. 2018. Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Izaurralde, R.C., Thomson, A.M., Morgan, J.A., Fay, P.A., Polley, H.W., Hatfield, J.L., 2011. Climate impacts on agriculture: implications for forage and rangeland production. *Agronomy Journal,* 103: 371-381.

Jayne, T.S., Chamberlin, J., Traub, L., Sitko, N., Muyanga, M., Yeboah, F., Nkonde, C., Anseeuw, W., Chapoto, A., Kachule, R. 2015. "Africa's Changing Farmland Ownership: The Rise of the Emergent Investor Farmer," 2015 Conference, 9-14, August 2015. Milan, Italy. International Association of Agricultural Economists.

Jera, R and Ajayi, O.C. 2008. Logistic modelling of smallholder livestock farmers' adoption of tree-based fodder technology in Zimbabwe. *Agrekon*, 47: 379-392.

Jiang, X., Wright, A.L., Wang, J. and Li, Z. 2011. Long-term tillage effects on the distribution patterns of microbial biomass and activities within soil aggregates. *Catena*, 87: 276-280.

Jing, P., Wang, D., Zhu, C. and Chen, J. 2016. Plant physiological, morphological and yield-related responses to night temperature changes across different species and plant functional types. *Frontiers in Plant Science,* 8: 1147.

Jirim, H., Dan, K., Kimia, K., Sorgum, K., Kepadatan, P., Dan, P., Menyemai, T., Mahmood,) A, Ullah, H., Shahzad, A. N., Ali, H., Ahmad, S., Zia-Ul-Haq, M., Honermeier, B., and Hasanuzzaman, M. 2013. Dry matter yield and chemical composition of sorghum cultivars with varying planting density and sowing date. *Sains Malaysiana*, 42: 529-538.

Jolliffe, I.T. and Cadima, J. 2016. Principal component analysis: a review and recent developments. *Philosophical Transactions of the Royal Society A,* 374: 20150202. https://dx.doi.org/10.1098/rsta.2015.0202

Jung, J.S., Kim, Y.J., Kim, W.H., Lee, S.H., Park, H.S., Choi, K.C., Lee, K.W., Hwang, T.-Y. and Choi, G.J. 2016. Effect of nitrogen fertilization levels and its split application of nitrogen on growth characters and productivity in sorghum × sudangrass hybrids [Sorghum bicolor (L.) Moench]. *Journal of the Korean Society of Grassland and Forage Science*, 36: 215–222. https://doi.org/10.5333/KGFS.2016.36.3.215

Kabir, M.S., Radović M.M. and Radulović, D. 2019. The Determinants of Income of Rural Women in Bangladesh. *Sustainability, 11*: 5842. https://doi.org/10.3390/su11205842

Kaiser, H.F. 1974. An index of factorial simplicity. *Psychometrika,* 39: 31-36.

Karaan, M. and Vink, N. 2014. Agriculture and rural development policies in the post-apartheid era. In Bhorat H, Hirsch A., Kanbur R and Mncube M (Eds.). The Oxford companion to the economics of South Africa. Oxford: Oxford University Press.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K. Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M. and Smith, C.J. 2003. An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy*, 18: 267-288. http://dx.doi.org/10.1016/S1161-0301(02)00108-9

Kebede, G. 2018. Morpho-agronomic performance of vetch species and their accessions grown under nitosol and vertisol conditions in the central highlands of Ethiopia. *Agriculture and Food Security,* 7: 90. https://doi.org/10.1186/s40066-018-0243-8

Kephe, P.N., Ayisi, K.K. and Petja, B.M. 2020. A decision support system for institutional support to farmers in the face of climate change challenges in Limpopo province. *Heliyon*, 6: e04989. https://doi.org/10.1016/J.HELIYON.2020.E04989

Khapayi, M. and Celliers, P.R. 2016. Factors limiting and preventing emerging farmers to progress to commercial agricultural farming in the King William's town area of the Eastern Cape province, South Africa. *South African Journal of Agricultural Extension*, 44: 25-41. https://doi.org/10.17159/2413-3221/2016/v44n1a374

Kholova, J., Tharanya, M., Sivasakthi, K., Srikanth, M., Rekha, B., Hammer, G.L., McLean, G., Deshpande, S., Hash, C.T., Craufurd, P. and Vadez, V. 2014. Modelling the effect of plantwater use traits on yield and stay-green expression in sorghum. *Functional Plant Biology*, 41: 1019. https://doi.org/10.1071/FP13355.

Kidake, B.K., Manyeki, J.K., Kubasu, D. and Mnene, W.N. 2016. Promotion of range pasture and fodder production among the pastoral and agro-pastoral communities in Kenyan rangelands: Experiences and lessons learnt. *Livestock Research for Rural Development*, 28: 151. http://www.lrrd.org/lrrd28/8/kida28151.html

Kom, L. 2016. Sheep flock structure, dynamics, management practices, and wool production under bush encroached and non-encroached areas of the Eastern Cape Province, South Africa. Published master’s thesis. Fort Hare University, South Africa.

Korres, N.E., Norsworthy, J.K. and Tehranchian, P. 2016. Cultivars to face climate change effects on crops and weeds: a review. *Agronomy for Sustainable Development*, 36: 12. https://doi.org/10.1007/s13593-016-0350-5

Kosgey, I.S., Rowlands, G.J., van Arendonk, J.A.M. and Baker, R.L. 2008. Small ruminant production in smallholder and pastoral/extensive farming systems in Kenya. *Small Ruminant Research*, 77: 11-24.

Kulkarni, K.P., Tayade, R., Asekova, S., Song, J. T., Shannon, J.G. and Lee, J.D. 2018. Harnessing the potential of forage legumes, alfalfa, soybean, and cowpea for sustainable agriculture and global food security. *Frontiers in Plant Science*, 9: 1314. https://doi.org/10.3389/fpls.2018.01314

Kumari, V.V., Roy, A., Vijayan, R., Banerjee, P., Verma, V.C., Nalia, A., Pramanik, M., Mukherjee, B., Ghosh, A., Reja, M.H., Chandran, M.A.S., Nath. R., Skalicky, M., Brestic, M. and Hossain, A. 2021. Drought and heat stress in cool-season food legumes in sub-tropical regions: consequences, adaptation, and mitigation strategies. *Plants*, 10: 1038. https://doi.org/10.3390/plants10061038

Lamega, S.A., Komainda, M., Hoffmann, M.P., Ayisi, K.K., Odhiambo, J.J.O. and Isselstein, J. 2021. "It depends on the rain: Smallholder farmers’ perceptions on the seasonality of feed gaps and how it affects livestock in semi-arid and arid regions in Southern Africa" *Climate risk management,* 34: 1-27. https://doi.org/10.1016/j.crm.2021.100362

Lamei, J., Alizadeh K., Jaime, A., da Silva, T. and Taghaddosi, M. 2012. Vicia panonica: a suitable cover crop for winter fallow in cold regions of Iran. *Plant Stress,* 6: 73-76.

Lamidi, A.A. and Ologbose, F.I. 2014. Dry season feeds and feeding: a threat to sustainable ruminant animal production in Nigeria. *Journal of Agriculture and Social Research*, 14: 17-30. https://doi.org/10.2989/10220119.2013.779596

Larbi, A., Hassan, S., Kattash, G., El-Moneim, A.M.A., Jammal, B., Nabil, H. and Nakkul, H. 2011. Annual feed legume yield and quality in dryland environments in north-west Syria: 1. Herbage yield and quality. *Animal Feed Science and Technology*, 160: 81-89. https://doi.org/10.1016/j.anifeedsci.2010.07.003

Lawson, T., Caemmerer, S.V. and Baroli, I. 2010. Photosynthesis and stomatal behaviour. *Progress in Botany*, 72: 265-304.

Legese, G., Haile, A., Duncan, A.J., Dessie, T., Gizaw, S. and Rischkowsky, B. 2014. Sheep and goat value chains in Ethiopia: A synthesis of opportunities and constraints. International Center for Agricultural Research in the Dry Areas and International Livestock Research Institute Project Report. Nairobi, Kenya.

Leitão, S.T., Alves, M.L., Pereira, P., Zerrouk, A., Godinho, B., Barradas, A., Vaz Patto, M.C. 2021. Towards a trait-based approach to potentiate yield under drought in legume-rich annual forage mixtures. *Plants*, 10: 1763. https://doi.org/10.3390/plants10091763

Lemma, M., Negesse, T. and Nurfeta, A. 2016. Assessment of feed resource availability and quality in Kedida Gamela district, Southern Ethiopia. *International Journal of Environment Agriculture and Biotechnology*, 1: 31-39.

Li, J., Liu, K., Zhang, J., Huang, L., Coulter, J.A., Woodburn, T., Li, L. and Gan, Y. 2018. Soil–plant indices help explain legume response to crop rotation in a semiarid environment. *Frontiers in Plant Science*, 9: 1488. https://doi.org/10.3389/fpls.2018.01488

Linstädter, A., Schellberg, J., Brüser, K., García, C. A. M., Oomen, R. J., Du Preez, C. C., Ruppert, J. C.,Ewert, F. 2014.. Are there consistent grazing indicators in drylands? Testing plant functional types of various complexity in South Africa's grassland and savanna biomes. *PLoS ONE*, 9: e104672. https://doi.org/10.1371/journal.pone.0104672

Lonati, M., Moot, D.J., Aceto, P., Cavallero, A. and Lucas, R.J. 2009. Thermal time requirements for germination, emergence and seedling development of adventive legume and grass species. *New Zealand Journal of Agricultural Research*, 52: 17-29. https://doi.org/10.1080/00288230909510485

Long, S.P., Zhu, X.G., Naidu, S.L. and Ort. D.R. 2006. Can improvement in photosynthesis increase crop yields? *Plant, Cell and Environment,* 29: 315-330.

Lukuyu, B., Franzel, S., Ongadi, P.M. and Duncan, A.J. 2011. Livestock feed resources: Current production and management practices in central and northern rift valley provinces of Kenya. *Livestock Research for Rural Development*, 23: 1-17.

Lukuyu, B., Maina, K., Namutebi, P., Allen, M., Nanyenya, W., Faitwa, W. and Chrisbonus, O. 2021. An assessment of livestock production systems and local feed resources, used to inform feed utilization and livestock production in the Mbarara District of Uganda. International Livestock Research Institute. Nairobi, Kenya

Lupwayi, N.Z., Kennedy, A.C. and Chirwa, R.M. 2011. Grain legume impacts on soil biological processes in sub-Saharan Africa. *African Journal of Plant Science*, 5: 1-7.

Lüscher, A., Mueller-Harvey, I., Soussana, J.F., Rees, R. and Peyraud, J.L. 2014. Potential of legume-based grassland–livestock systems in Europe: a review. *Grass and Forage Science*, 69: 206-228.

Mahama, G.Y., Vara Prasad, P.V., Mengel, D.B. and Tesso, T.T. 2014. Influence of nitrogen fertilizer on growth and yield of grain sorghum hybrids and inbred lines. *Agronomy Journal*, 106: 1623-1630. https://doi.org/10.2134/agronj14.0092

Mahar, P.A., Soomro, A.A., Solangi, M.H., Chandio, M.A., Malik, M.A. and Shar, Z.A. 2017. Effect of different sowing dates on growth and yield of berseem (Trifolium alexandrinum). *National Journal of Advanced Research,* 3: 36-43.

Mahlobo, B.T. 2016. Multi–criteria livestock assessment for sustainability of smallholder farms in Kwa-Zulu Natal. Published master's thesis. Stellenbosch University Western Cape, South Africa. https://scholar.sun.ac.za

Makkar, H. P. S. 2018. Review: Feed demand landscape and implications of food-not feed strategy for food security and climate change. *Animal*, 12: 1744-1754. https://doi.org/10.1017/S175173111700324X

Makkar, H. P. S. and Ankers, P. 2014. Towards sustainable animal diets: a survey based study. *Animal Feed Science and Technology*, 198: 309-322. http://www.journals.elsevier.com/animal-feed-science-and-technology

Maluleke, W., Mokwena, R.J. and Olofinbiyi, S.A. 2019. An evaluative study on criminalistics: stock theft scenes. *International Journal of Management and Business Studies*, 11: 101-138.

Mapiliyao, L., Pepe, D., Chiruka, R., Marume, U. and Muchenje, V. 2012. Production practices and constraints to sheep productivity in two ecologically different and resource-poor communal farming systems of South Africa. *Scientific Research and Essays*, 7: 3209-3217. https://doi.org/10.5897/sre12.140

Mapiye, C., Foti, R., Chikumba, N., Poshiwa, X., Mwale, M., Chivuraise, C., Mupangwa, J.F. 2006. Constraints to adoption of forage and browse legumes by smallholder dairy farmers in Zimbabwe. *Livestock Research for Rural Development,* 18: 1-12. http://www.lrrd.org/lrrd18/12/mapi18175.htm

Maponya, P. and Mpandeli, S. 2012. Climate change and agricultural production in South Africa: Impacts and adaptation options. *The Journal of Agricultural Science*, 4: 48-60.

Marandure, T., Dzama, K., Bennett, J., Makombe, G., Chikwanha, O., Mapiye, C., 2020b. Farmer challenge-derived indicators for assessing sustainability of low-input ruminant production systems in sub-Saharan Africa. *Environmental and Sustainability Indicators*, 8: 100060. https://doi.org/10.1016/j.indic.2020.100060

Martiniello, P. and Teixeira da Silva, J. 2011. Physiological and bioagronomical aspect involved in growth and yield components of cultivated forage species in Mediterranean environments. *European Journal of Plant Science and Biotechnology*, 5: 64-98.

McCartney, D. and Fraser. J. 2010. The potential role of annual forage legumes in Canada: A review. *Canadian Journal of Plant Science*, 90: 403-420.

Meissner, H., Scholtz, M.M.and Palmer, A.R. 2013. Sustainability of the South African livestock sector towards 2050 – Part 1: Worth and impact of the sector. *South African Journal of Animal Science,* 43: 283-297.

Mengistu, A., Kebede, G., Assefa, G. and Feyissa, F. 2017. Descriptions and characteristics of cultivated forage crops growing under different Agro-Ecological Zones in Ethiopia. *International Journal of Agriculture and Biosciences*, 6: 238-247.

Mndela, M., Madakadze, I.C., Nherera-Chokuda, F.V, Dube, S., Ramoelo, A., Mangwane, M. and Tjelele, J.T. 2022. Short-term responses of herbaceous vegetation to bush clearing in semi-arid rangelands of South Africa. *Pastoralism: Research, Policy and Practice*, 12: 17. https://doi.org/10.1186/s13570-022-00235-7

Molotsi, A., Dube, B., Oosting, S., Marandure, T., Mapiye, C., Cloete, S. and Dzama, K. 2017. Genetic traits of relevance to sustainability of smallholder sheep farming systems in South Africa. *Sustainability*, *9:* 1225. https://doi.org/10.3390/su9081225

Molotsi, A. H., Oosting, S., Cloete, S. W. P. and Dzama, K. 2019. Factors influencing off-take rates of smallholder sheep farming systems in the Western Cape Provinve of South Africa. *South African Journal of Agricultural Extension*, 47: 83-91. https://doi.org/10.17159/2413-3221/2019/v47n3a517

Molotsi, A.H., Dube, B., Willem, S. and Cloete, P. 2020. The current status of indigenous ovine genetic resources in Southern Africa and future sustainable utilisation to improve livelihoods. *Diversity*, 12: 14. https://doi.org/10.3390/d12010014

Montgomery, D.C., Peck, E.A. and Vining, G.G. 2012. Introduction to Linear Regression Analysis, 5th ed.; John Wiley & Sons: Hoboken, NJ, USA.

Moore, C.E., Meacham-Hensold, K., Lemonnier, P., Slattery, R. A., Benjamin, C., Bernacchi, C. J., Lawson, T. and Cavanagh, A. P. 2021. The effect of increasing temperature on crop photosynthesis: From enzymes to ecosystems. *Journal of Experimental Botany*, 72: 2822-2844. https://doi.org/10.1093/jxb/erab090

Mpanza, T.D.E., Hassen, A. and Akanmu, A.M. 2020. Evaluation of Stylosanthes scabra accessions as forage source for ruminants: Growth performance, nutritive value and in vitro ruminal fermentation. *Animals,* 10: 1-15. https://doi.org/10.3390/ani10111939

Mthi, S., Skenjana, A. and Fayemi, P.O. 2017. Characteristics of small-scale sheep production systems in some communal areas of the Eastern Cape Province, South Africa. *International Journal of. Livestock Production*, 8: 199-206.

Mthi, S. and Nyangiwe, N. 2018. Farmers' perception on sheep production constraints in the communal grazing areas of the Eastern Cape Province, South Africa*. International Journal of. Livestock Production*, 9: 334-339.

Mudzengi, C.P., Dahwa, E., Kapembeza, C.S. 2020. 'Livestock feeds and feeding in semi-Arid areas of Southern Africa', in M. Abubakar (ed.), Livestock Health and Farming, IntechOpen, London. 10.5772/intechopen.90109

Munyai, F.R. 2012. An evaluation of socio-economic and biophysical aspects of small-scale livestock systems based on a case study from Limpopo province: Muduluni village. PhD thesis. University of the Free State, Bloemfontein.

Mupangwa, W. and Thierfelder, C. 2014. Intensification of conservation agriculture systems for increased livestock feed and maize production in Zimbabwe. *International Journal of Agricultural Sustainability*, 12: 425-439. https://doi.org/10.1080/14735903.2013.859836

Musafiri, C.M., Kiboi, N.M., Macharia, J., Ng'etich, O.K., Kosgei, D.K., Mulianga, B., Okoti M. and Ngetich, F.K. 2022. Adoption of climate-smart agricultural practices among smallholder farmers in Western Kenya: do socioeconomic, institutional, and biophysical factors matter? *Heliyon,* 8: e08677 https://doi.org/10.1016/j.heliyon.2021.e08677

Mwangi, D.M. and Wambugu, C. 2003. Adoption of forage legumes: The case of Desmodium intortum and Calliandra calothyrsus in central Kenya. *Tropical Grasslands*, 37: 227-238.

Mwangi, M. and Kariuki, S. 2015. Factors determining the adoption of new agricultural technology by smallholder farmers in developing countries. *Journal of Economics and Sustainable Development*, 6: 208-216.

Mwendia, S.W., Maass, B.L., Njenga, D.G., Nyakundi, F.N. and Notenbaert, A.M. 2017. Evaluating oat cultivars for dairy forage production in the central Kenyan highlands. *African Journal of Range and Forage Science*, 34: 145-155. https://doi:10.2989/10220119.2017.1358214

Nadeem, M., Li, J., Wang, M., Shah, L., Lu, S., Wang, X. and Ma, C. 2018. Unraveling field crops sensitivity to heat stress mechanisms, approaches, and future prospects. *Agronomy*, 8: 128. https://doi.org/10.3390/agronomy8070128

Nakamanee, G., Srisomporn, W., Phengsavanh, P., Samson, J. and Stür, W. 2008. Sale of fresh forage − a new cash crop for smallholder farmers in Yasothon, Thailand. *Tropical Grasslands*, 42: 65-74. http://goo.gl/HwgCQ4

Nave, R.L.G., Sulc R.M. and Barker, D.J. 2013. Relationships of forage nutritive value to cool-season grass canopy characteristics. *Crop Science*, 53:341-348.

NDA. 2006. Livestock Development Policy. Pretoria. https://www.nda.agric.za/docs/GenPub/DevStrat2007.pdf; accessed 29 June 2020.

Ndah, H.T., Schuler, J., Nkwain, V.N., Nzogela, B., Mangesho, W.E., Mollel, R., Loina, R. and Paul, B.K. 2017. Factors affecting the adoption of forage technologies in smallholder dairy production systems in Lushoto, Tanzania.

Ng'ang'a, S.K., Jalang'o, D.A. and Girvetz, E.H. 2020. Adoption of technologies that enhance soil carbon sequestration in East Africa. What influence farmers' decision? *International Soil and Water Conservation Research*, 8: 90-101. https://doi.org/10.1016/J.ISWCR.2019.11.001

Ngwira, A. 2003. Forage demand and constraints to adoption of forage technologies by livestock keepers in Malawi. *Tropical Grasslands,* 37: 274-278.

Nkamleu, G.B. and Manyong, V.M. 2005. Factors affecting the adoption of agroforestry practices by farmers in Cameroon. *Small-scale Forestry,* 4: 135-148. https://doi.org/10.1007/s11842-005-0009-6

Nkonki-Mandleni, B., Leni, Ogunkoya, F.T. and Omotayo, A.O. 2019. Socioeconomic factors influencing livestock production among smallholder farmers in the Free State province of South Africa. *International journal of entrepreneurship*, 23: 1-17.

Nori, H., Moot, D.J. and Black, A.D. 2014. Thermal time requirements for germination of four annual clover species. *New Zealand Journal of Agricultural Research*, 57:1, 30-37.

NRC*,* National Research Council. 1981. Effect of Environment on Nutrient Requirements of Domestic Animals. Subcommittee on Environmental Stress, National Research Council (NRC). Washington, DC, National Academy Press.

NRC, National Research Council. 2016. Nutrient Requirements of Sheep (6th Ed.). National Academy Press. Washington, DC.

Nyam, N., Matthews, Y. and Bahta, T. 2020. Improving livelihoods of smallholder farmers through region-specific strategies: a case study of South African sheep production. *Agrekon*, 59: 1-15.

Nyam, Y.S., Bahta, Y.T., Oduniyi, O.S. and Matthews, N. 2022. Smallholder sheep farmers' perception of production constraints and competitiveness strategies in South Africa. *Scientific African,* 16. https://doi.org/10.1016/j.sciaf.2022.e01192

Ojeda, J.J., Pembleton, K.G., Caviglia, O.P., Islam, M.R., Agnusdei, M.G. and Garcia, S.C. 2018. Modelling forage yield and water productivity of continuous crop sequences in the Argentinian Pampas. *European Journal of Agronomy*, 92: 84-96. https://doi.org/10.1016/j.eja.2017.10.004

Olugbemi, O. and Ababyomi, Y. A. 2016. Effects of nitrogen application on growth and ethanol yield of sweet sorghum [Sorghum bicolor (L.) Moench] Varieties. https://doi.org/10.1155/2016/8329754

Oluwatayo, I.B. and Oluwatayo, T.B. 2012. Small ruminants as a source of financial security: A case study of women in rural Southwest Nigeria.1-6. http://www.imtfi.uci.edu/files/blog_working_papers/2012-2_oluwatayo.pdf

Omotayo, A.O. 2018. Climate change and food insecurity dynamics in the rural Limpopo province of South Africa. *Journal of Economics and Behavioural Studies*, 10: 22-32.

Oo Soe, P. and Koichi Usami. 2020. "Farmers' perception of good agricultural practices in rice production in Myanmar: a case study of Myaungmya district, Ayeyarwady region" *Agriculture,* 10: 249. https://doi.org/10.3390/agriculture10070249

Palmer, A.R. and Bennett, J.E. 2013. Degradation of communal rangelands in South Africa: towards an improved understanding to inform policy. *African Journal of Range and Forage Science,* 30: 57-63. https://doi.org/10.2989/10220119.2013.779596

Parwada, C., Gadzirayi, C.T., Muriritirwa, W.T., Mwenye, D. 2010. Adoption of agro-forestry technologies among smallholder farmers: A case of Zimbabwe. *Journal of Development and Agricultural Economics*, 2: 351-358.

Paul, B.K., Groot, J.C.J., Maass, B.L., Notenbaert, A.M.O., Herrero, M. and Tittonell, P.A., 2020. Improved feeding and forages at a crossroads: farming systems approaches for sustainable livestock development in East Africa. *Outlook on Agriculture*, 4:13-20. https://doi.org/10.1177/0030727020906170

Pembleton, K.G., Rawnsley, R.P., Jacobs, J.L., Mickan, F.J., O'brien, G.N., Cullen, B. R. and Ramilan, T. 2013. Evaluating the accuracy of the Agricultural Production Systems Simulator (APSIM) simulating growth, development, and herbage nutritive characteristics of forage crops grown in the south-eastern dairy regions of Australia. *Crop and Pasture Science,* 64: 47-64.

Pembleton, K., Cullen, B., Rawnsley, R., Harrison, M. and Ramilan, T. 2016. Modelling the resilience of forage crop production to future climate change in the dairy regions of Southeastern Australia using APSIM. *The Journal of Agricultural Science*, 154: 1131-1152. https://doi:10.1017/S0021859615001185

Peoples, M., Brockwell, J., Herridge, D., Rochester, I., Alves, B., Urquiaga, S. 2009. The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis,* 48:1-17. https://doi:10.1007/BF03179980

Pereira-Crespo, S., Valladares, J., Flores, G., Fernández-Lorenzo, B., Resch, C., Piñeiro, J., Díaz, N., González-Arráez, A., Bande-Castro, M.J. and Rodriguez-Diz. X. 2012. Prediction of the nutritive value of annual forage clovers and serradella by near infrared spectroscopy (NIRS). *Options Méditerranéennes*, 102: 241-244.

Perera, R. S., Cullen, B. R. and Eckard, R. J., 2019. Growth and physiological responses of temperate pasture species to consecutive heat and drought stresses. *Plants* 8: 227. https://doi.org/10.3390/plants8070227

Phelan, P., Moloney, A.P., McGeough, E.J., Humphreys, J., Bertilsson, J., O'Riordan, E.G. and O'Kiely, P., 2015. Forage legumes for grazing and conserving in ruminant production systems. *Critical Reviews in Plant Sciences*, 34: 281-326. https://doi:10.1080/07352689.2014.898455

Phohlo, M.P., Swanepoel, P.A. and Hinck, S. 2022. Excessive nitrogen fertilization is a limitation to herbage yield and nitrogen use efficiency of dairy pastures in South Africa. *Sustainability*, 14: 4322. https://doi.org/10.3390/su14074322

Pissinati, A., Moreira, A. and Santoro, P.H. 2016. Biomass yield and nutrients concentration in shoot dry weight of winter cover crops for no-tillage system. *Communications in Soil Science and Plant Analysis*, *47*: 2292-2305.

Pizarro, E. and Sauma G. 2007. A novel approach for seed forage production by small farmers in South America: SEFO story. In: Hare MD; Wongpichet K, eds. Forages: A pathway to prosperity for smallholder farmers. Proceedings of an International Forage Symposium, 5-7 March, 2007. Faculty of Agriculture, Ubon Ratchathani University, Ubon Ratchathani, Thailand.

Polley, H.W., Briske, D.D., Morgan, J.A., Wolter, K., Bailey, D.W. and Brown, J.R., 2013. Climate change and North American rangelands: trends, projections, and implications. *Rangeland Ecology and Management*, *66*: 493-511.

Pommeresche, R. and Hansen, S. 2017. Examining root nodule activity on legumes (FertilCrop: Technical note). Research Institute of Organic Agriculture FiBL, and Norwegian Centre for Organic Agriculture.

Prikner, P., Lachnit, F. and Dvorak, F. 2004. A new soil core sampler for determination bulk density in soil profile. *Plant Soil & environment. 50*: 250-256.

Rauff, K.O. and Bello, R. 2015. A review of crop growth simulation models as tools for agricultural meteorology. *Agricultural Sciences*, *6*: 1098.

Rayment, G.E. and Higginson, F.R., 1992. *Australian laboratory handbook of soil and water chemical methods*. Inkata Press Pty Ltd.

Raza, A., Razzaq, A., Mehmood, S.S., Zou, X., Zhang, X., Lv, Y. and Xu, J., 2019. Impact of climate change on crops adaptation and strategies to tackle its outcome: A review. *Plants*, *8*: 34.

Renta, I., Digiantonio, G., Kelley, E., Matlock, G., Bayler, E., Davis, S. and Wielgus, J. 2021. NOAA Science Report. NOAA Science Council Science Council. Maryland, USA. https://doi:10.25923/pxeq-6g91

Ripple, W.J., Smith, P., Haberl, H., Montzka, S.A., McAlpine, C. and Boucher, D.H. 2014. Ruminants, climate change and climate policy. *Nature climate change*, *4*: 2-5. https://doi.org/10.1038/nclimate2081

Rojas-Downing, M.M., Nejadhashemi, A.P., Harrigan, T. and Woznicki, S.A. 2017. Climate change and livestock: Impacts, adaptation, and mitigation. *Climate Risk Management*, 16:145-163. https://doi.org/10.1016/j.crm.2017.02.001

Rotz, C. A. & Muck, R. E. 1994. Changes in forage quality during harvest and storage in Forage quality, evaluation, and utilization. (ed. Fahey, G. C.). 828-868. Soil Science Society of America, Madison.

Rust, J.M. and Rust, T. 2013. Climate change and livestock production: A review with emphasis on Africa. *South African Journal of Animal Science*, *43*: 255-267.

Sajid, S.S. and Hu, G. 2022. Optimizing Crop Planting Schedule Considering Planting Window and Storage Capacity. *Frontiers in Plant Science*, *13*: 762446. https://doi.org/10.3389/fpls.2022.762446

Sakoda, K., Yamori, W., Shimada, T., Sugano, S.S., Hara-Nishimura, I. and Tanaka, Y., 2020. Higher stomatal density improves photosynthetic induction and biomass production in Arabidopsis under fluctuating light. *Frontiers in Plant Science*, *11*: 589603. https://ddoi:10.3389/fpls.2020.589603

Samarappuli, D.P., Johnson, B.L., Kandel, H. and Berti, M.T. 2014. Biomass yield and nitrogen content of annual energy/forage crops preceded by cover crops. *Field Crops Research*, *167*: 31-39. https://doi.org/10.1016/j.fcr.2014.07.005

Sankatane, M. R. 2016. Assessment of the sheep production management systems of small-scale farmers in the Maluti-a-Phofung Local Municipality of the Eastern Free State Published M.Tech master's thesis. Central University of Technology, Free State, South Africa.

Scholtz, M.M., van Ryssen, J.V., Meissner, H.H. and Laker, M.C. 2013. A South African perspective on livestock production in relation to greenhouse gases and water usage. *South African Journal of Animal Science*, *43*: 247-254. https://doi.org/10.1016/j.fcr.2014.07.005

Seo, J.H., Lee, H.J., Hur, I.B., Kim, S.J., Kim, C.K. and Jo, H.S. 2000. Use of hairy vetch green manure as nitrogen fertilizer for corn production. *Korean Journal of Crop Science*, *45*: 294-299.

Serdeczny, O.S., Adams, F., Baarsch, D., Coumou, A., Robinson, B., Hare, M., Schaeffer, M., Perrette, M. and Reinhard, J. 2016. Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Regional Environmental Change*, 5: 119-125. https://doi:10.1007/s10113-015-0910-2

Serote, B., Mokgehle, S., Du Plooy, C., Mpandeli, S., Nhamo, L. and Senyolo, G. 2021. Factors influencing the adoption of climate-smart irrigation technologies for sustainable crop productivity by smallholder farmers in arid areas of South Africa. *Agriculture*, 11: 1222. https://doi.org/10.3390/agriculture11121222

Shamme, K.S., Cherukuri, R.V., Balemi, T. and Hamza, I. 2015. Differential productivity response of rain fed sorghum (Sorghum bicolor L.) genotypes in relation to graded levels of nitrogen in Kellem Wollega zone of Ethiopia, East Africa. *International Journal Life Sciences*, 3: 306-316. www.ijlsci.in

Shang, Z.H., Gibb, M.J., Leiber, F., Ismail, M., Ding, L.M., Guo, X.S. and Long, R.J. 2014. The sustainable development of grassland-livestock systems on the Tibetan plateau: problems, strategies and prospects. *The Rangeland Journal*, *36*: 267-296.

Sharma, L., Priya, M., Bindumadhava, H., Nair, R.M. and Nayyar, H. 2016. Influence of high temperature stress on growth, phenology and yield performance of mungbean under managed growth conditions. *Scientia Horticulturae*, *213*: 379-391.

Simkin, A.J., López-Calcagno, P.E. and Raines, C.A. 2019. Feeding the world: improving photosynthetic efficiency for sustainable crop production. *Journal of Experimental Botany*, *70*: 1119-1140. https://doi:10.1093/jxb/ery445

Singh, B. and Ryan, J., 2015. Managing fertilizers to enhance soil health. *International Fertilizer Industry Association,* Paris, France.

Sinyolo, S. 2019. Technology adoption, gender and household food security among rural households in South Africa. *Technology in Society*, *60:* 101214. https://doi.org/10.1016/j.techsoc.2019.101214

Senyolo, M.P., Long, T.B., Blok, V., Omta, O. and van der Velde, G. 2021. Smallholder adoption of technology: Evidence from the context of climate smart agriculture in South Africa. *Journal of Development and Agricultural Economics*, 13: 156-173. https://doi.org/10.5897/jdae2020.1191

Sita, K., Sehgal, A., Kumar, J., Kumar, S., Singh, S., Siddique, K.H. and Nayyar, H. 2017. Identification of high-temperature tolerant lentil (Lens culinaris Medik.) genotypes through leaf and pollen traits. *Frontiers in Plant Science*, *8*: 744. https://doi.org/10.3389/fpls.2017.00744

Sita, K., Sehgal, A., Nair, R.M., Vara Prasad, P.V., Kumar, S., Gaur, P.M., Farooq, M., Siddique, K.H.M. and Varshney, R.K. 2017. Food legumes and rising temperatures: effects, adaptive functional mechanisms specific to reproductive growth stage and strategies to improve heat tolerance. *Frontiers in Plant Science,* 8: 1658. https://doi.org/10.3389/fpls.2017.01658

Smith, J., Tarawali, S., Grace, D. and Sones, K. 2013a. Feeding the world in 2050: trade-offs, synergies and tough choices for the livestock sector. *Tropical Grasslands Forajes Tropicales*, 1: 125-136.

Soil Classification Working Group. 1991. Soil classification: a taxonomic system for South Africa. Memoirs of the Natural Agricultural Resources of South Africa No. 15. Department of Agricultural Development, Pretoria.

Sotelo, F., Molina, A. and Rojas, K. 2018. Application of the snowball sample in the diagnostic based on factors that affect the productivity of Cherimoya production in MSEs: A case of study of Callahuanca and San Mateo de Otao, Peru. *Advances in Social Sciences Research Journal*, *5*: 54-71.

https://doi.org/10.14738/assrj.58.4948

SPSS Inc., 2019. Statistical package for social sciences. SPSS for windows, version 25.0. Chicago, USA

Stagnari, F., Maggio, A., Galieni, G. and Pisante, M. 2017. Multiple benefits of legumes for agriculture sustainability: an overview. *Chemical and Biological Technologies in Agriculture*, 4:2. https:// doi.org/10.1186/s40538-016-0085-1

Strauss, A.J., and Hardy, M. 2014. An Investigation into the Production Dynamics of Eight Crop Rotation Systems Including Wheat, Canola, Lupins and Pasture Species in the Swartland, Western Cape. Western Cape Government Department of Agriculture.

Stroebel, A., Swanepoel, F.J.C. and Pell, A.N. 2011. Sustainable smallholder livestock systems: A case study of Limpopo Province, South Africa. Livestock Science, 139: 186-190. https://doi.org/10.1016/j.livsci.2011.03.004

Subhan, U.D., Ullah, I. Bashir, A. and Kamran, K. 2015. Influence of sowing dates on fodder yield production of Berseem under the climatic condition of Peshwar Valley. *Food Science and Quality Management,* 36: 88-90.

Tahir, M.B., Wossen, A.M. and Mersso, B.T. 2018. Evaluation of livestock feed balance under mixed crop-livestock production system in the central highlands of Ethiopia. *Agriculture and Food Security*, *7*: 1-17. https://doi.org/10.1186/s40066-018-0170-8

Tarekegn, K. and Ayele, A. 2020. Impact of improved beehives technology adoption on honey production efficiency: empirical evidence from Southern Ethiopia. *Agriculture and Food Security*, 9: 1-13. https://doi.org/10.1186/s40066-020-00258-6

Taye, M., Yilma, M., Mengistu, S., Abiso, T., Bassa, Z., Wolde, S., Haile, A., 2016. Characterization of production system and breeding practices of sheep producers in Doyogena district, Southern Ethiopia. *African Journal of Agricultural Research*, 11: 5192-5201. https://doi.org/10.5897/AJAR2016.11825

Teasdale, J.R., Thomas, E.D., Jorge, A.M., Bellinder, R.R. and Beste, C.E. (2004). Growth and development of hairy vetch cultivars in the northeastern United States as influenced by planting and harvesting. *Agronomy Journal*, 96: 1266-1271.

Thamaga–Chitja, J.M. and Morojele, P. 2014. The context of smallholder farming in South Africa: towards a livelihood asset building framework. *Journal of Human Ecology*, 45: 147-155.

Thornton, P.K., Boone, R.B., Ramirez-Villegas, J. 2015. Climate change impacts on livestock. CCAFS Working Paper no. 120. Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Thornton, P.K. 2010. Livestock production: recent trends, future prospects. Philosophical Transaction: *Biological Sciences*, 365: 2853-2867.

Thornton, P.K., and Herrero. M. 2014. Climate change adaptation in mixed crop–livestock systems in developing countries. *Global Food security,* 3: 99-107.

Tisserand, J.L. and Alibes, X. 1989. Feeds of the Mediterranean area. In: Ruminant Nutrition, recommended allowances and feed tables. (R. Jarrige Ed.). INRA and John Libbey Eurotext. London, Paris.

Tonitto, C. and Ricker-Gilbert, J.E. 2016. Nutrient management in African sorghum cropping systems: applying meta-analysis to assess yield and profitability. *Agronomy for Sustainable Development*, 36: 1-9. https://doi.org/10.1007/s13593-015-0336-8

Toom, M., Talgre, L., Pechter, P., Narits, L., Tamm, S. and Lauringson, E. 2019. The effect of sowing date on cover crop biomass and nitrogen accumulation. *Agronomy Research*, 17: 1779-1787. https://doi.org/10.15159/AR.19.164

Truter, W. and Dannhauser, C.S. 2011. Revitalizing Planted Pastures in South Africa. *Grassroots,* 11: 20-23.

Truter, W., Dannhauser, C., Smith, H., Trytsman, G. 2015. Integrated crop and pasture-based livestock production systems. Conservation agriculture, Part 11. Grain SA. South Africa.

Trytsman, M., Masemula, E.L., Müller, F.L., Calitz, F.J., van Wyk, A.E. 2019. Assessing legumes indigenous to South Africa, Lesotho and Swaziland for their pasture potential. *African Journal of Range and Forage*, 36: 27-40.

Turinawe, A., Mugisha, J., and Kabirizibi, J. 2011. Socio-economic evaluation of improved forage technologies in smallholder dairy cattle farming systems in Uganda. *The Journal of Agricultural Science*, 4: 163-174.

Turpie, J.K. and Akinyemi, B.E. 2018. Chapter 3: The socio-economic impacts of livestock predation and its prevention in South Africa. In: Livestock predation and its management in South Africa: A scientific assessment. Eds: G. Kerley, S. Wilson, D. Balfour. Centre for African Conservation Ecology, Nelson Mandela University, Port Elizabeth.

Underwood, W.J., Blauwieke, I.R., Delano, Gillesby, L., Mischler, S.A. and Schoell, A. 2015. Biology and diseases of ruminants (sheep, goats, and cattle). Laboratory Animal Medicine. 623-94. https://doi.10.1016/B978-0-12-409527-4.00015-8

Underwood, W.J., Blauwiekel, R., Delano, M.L., Gillesby, R., Mischler, S. A., and Schoell, A. 2015. Chapter 15 - Biology and Diseases of Ruminants (sheep, goats, and cattle). In Laboratory Animal Medicine: Third Edition (pp. 623–694). Elsevier Inc. https://doi.org/10.1016/B978-0-12-409527-4.00015-8

United Nations (2020) World Population Projected to Reach 9.8 Billion in 2050, and 11.2 Billion in 2100. https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html

United Nations, Department of Economic and Social Affairs, Population Division (2015). Population 2030: Demographic challenges and opportunities for sustainable development planning (ST/ESA/SER.A/389). https://www.un.org/en/development/desa/population/publications/pdf/trends/Population2030.pdf

Urban, J., Ingwers, M., Mcguire, M.A. and Teskey, R.O. 2017. Stomatal conductance increases with rising temperature. *Plant Signaling and Behavior*, 8: e1356534 https://doi.org/10.1080/15592324.2017.1356534

Van den Berg. J. 2013. Socio-economic factors affecting adoption of improved agricultural practices by small scale farmers in *South Africa. African Journal of Agricultural Research*, 8: 4490-4500. https://10.5897/AJAR12.1025

Van Reeuwijk, L.P. (Ed.) Procedure for Soil Analysis, 6th ed.; International Soil Reference and Information Center (ISRIC)/Food and Agricultural Organization: Wageningen, The Netherlands, 2002: 120

Van Soest, P.J., Robertson, J.B. and Lewis, B.A. 1991. Methods for Dietary Fiber, Neutral Detergent Fiber, and Nonstarch Polysaccharides in Relation to *Animal Nutrition. Journal of Dairy Science*, 74: 3583-3597. http://dx.doi.org/10.3168/jds.S0022-0302(91)78551-2

Vasileva, V. and Athar, M. 2018. Studies on nodulating capacity of some forage legumes grown alone or in mixtures. *Planta Daninha*, 36: e018171642. https://doi.org/10.1590/s0100-83582018360100033

Vetter, S. 2013. Development and sustainable management of rangeland commons- Aligning policy with the realities of South Africa's rural landscape. *African Journal of Range and Forage Science*, 30: 1-9. https://doi.org/10.2989/10220119.2012.750628

Virendra, S.S., Narwal, S. and Sardana, V. 2000. Influence of time of sowing and last cut for fodder and seed yield of Egyptian clover. *Journal of Agricultural Science,* 3: 285-291.

von Caemmerer, S. and Evans, J.R. 2015. Temperature responses of mesophyll conductance differ greatly between species*. Plant, Cell and Environment*, 38: 629-637.

Wang, X., Wang, L. and Shangguan, Z. 2016. Leaf gas exchange and fluorescence of two winter wheat varieties in response to drought stress and nitrogen supply. *Public Library of Science*, 11: 165733.

Wang, L., Hu, W., Zahoor, R., Yang, X., Wang, Y., Zhou, Z. and Meng, Y. 2019. Cool temperature caused by late planting affects seed vigor via altering kernel biomass and antioxidant metabolism in cotton (Gossypium hirsutum L.). *Field Crops Research,* 236:145-154. https://doi.org/10.1016/J.FCR.2019.04.002

Yoon, P.R. and Choi, J.Y. 2020. Effects of shift in growing season due to climate change on rice yield and crop water requirements. *Paddy and Water Environment,* 18: 291-307. https://doi.org/10.1007/s10333-019-00782-7

Zenda, M. and Malan, P. 2021. The sustainability of small-scale sheep farming systems in the Northern Cape (Hantam Karoo), South Africa. *South African Journal of Agricultural Extension*, 49: 105-121. https://doi.org/10.17159/2413-3221/2021/v49n1a10781

Zhang, X., Evans, P.M. and Riffkin, P.A. 2004. Performance of annual pasture legumes in cropping rotations in the cool temperate zone of south eastern Australia. *Australian Journal of Experimental Agriculture,* 44: 863-871.

Zhang, X., Davidson, E., Mauzerall, D., Searchinger, T.D., Dumas, P. and Shen, Y. 2015. Managing nitrogen for sustainable development. *Nature,* 528: 51-59 https://doi.org/10.1038/nature15743

Zhang, Z., Whish, J.P.M., Bell, L.W. and Nan, Z. 2017. Forage production, quality and water-use-efficiency of four warm-season annual crops at three sowing times in the Loess Plateau region of China. *European Journal of Agronomy,* 84: 84-94. https://doi.org/10.1016/J.EJA.2016.12.008

Zhao, D., Reddy, K.R., Kakani, V.G. and Reddy, V.R. 2005. Nitrogen deficiency effects on plant growth, leaf photosynthesis and hyperspectral reflectance properties of sorghum. *European Journal of Agronomy*, 22: 391-403. https://doi.org/10.1016/j.eja.2004.06.005

Ziervogel, G., New, M., Garderen, E., Midgley, G., Taylor, A., Hamann, R. and Warburton, M. 2014. Climate change impacts and adaptation in South Africa. *Wiley Interdisciplinary Reviews*, 5: 605-20.

APPENDICES

Appendix 4.1: Analysis of variance (ANOVA) of Leaf gaseous exchange 2018: Ci

Source	DF	SS	Mean Square	F Value	Pr > F
PD	1	53872.2000	53872.2000	40.06	<.0001
CV	9	64382.2625	7153.5847	5.32	<.0001
HS	3	557365.7500	185788.5833	138.14	<.0001
PD*CV	9	14639.7375	1626.6375	1.21	0.2897
PD*HS	3	6544.9000	2181.6333	1.62	0.1849
CV*HS	27	128802.9375	4770.4792	3.55	<.0001
PD*CV*HS	27	75484.1625	2795.7097	2.08	0.0020

Appendix 4.2: Analysis of variance (ANOVA) of Leaf gaseous exchange 2018: E

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PD	1	108.182261	108.182261	99.85	<.0001
CV	9	706.103576	78.455953	72.41	<.0001
HS	3	2729.853214	909.951071	839.86	<.0001
PD*CV	9	11.621814	1.291313	1.19	0.3008
PD*HS	3	8.221784	2.740595	2.53	0.0579
CV*HS	27	360.049849	13.335180	12.31	<.0001
PD*CV*HS	27	24.090441	0.892239	0.82	0.7192

Appendix 4.3: Analysis of variance (ANOVA) of Leaf gaseous exchange 2018: Gs

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PD	1	0.03220031	0.03220031	4.89	0.0279
CV	9	0.08080906	0.00897878	1.36	0.2051
HS	3	2.03053344	0.67684448	102.84	<.0001
PD*CV	9	0.05464656	0.00607184	0.92	0.5061
PD*HS	3	0.17098344	0.05699448	8.66	<.0001
CV*HS	27	0.35494469	0.01314610	2.00	0.0034
PD*CV*HS	27	0.29635719	0.01097619	1.67	0.0240

Appendix 4.4: Analysis of variance (ANOVA) of Leaf gaseous exchange 2018: A

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PD	1	1992.556938	1992.556938	464.02	<.0001
CV	9	1785.175638	198.352849	46.19	<.0001
HS	3	6515.482148	2171.827383	505.77	<.0001
PD*CV	9	147.927465	16.436385	3.83	0.0002
PD*HS	3	608.333958	202.777986	47.22	<.0001
CV*HS	27	989.415773	36.645029	8.53	<.0001
PD*CV*HS	27	661.930326	24.515938	5.71	<.0001

Appendix 4.5: Analysis of variance (ANOVA) of Leaf gaseous exchange 2018: WUEinst

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
PD	1	57.2271695	57.2271695	347.99	<.0001
CV	9	101.6004128	11.2889348	68.65	<.0001
HS	3	66.3214346	22.1071449	134.43	<.0001
PD*CV	9	7.1490228	0.7943359	4.83	<.0001
PD*HS	3	0.5132550	0.1710850	1.04	0.3754
CV*HS	27	27.5309635	1.0196653	6.20	<.0001
PD*CV*HS	27	12.3259088	0.4565151	2.78	<.0001

Appendix 4.6: Analysis of variance (ANOVA) of Leaf gaseous exchange 2018: WUEintr

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
PD	1	6515.95510	6515.95510	28.83	<.0001
CV	9	9353.17575	1039.24175	4.60	<.0001
HS	3	29415.09329	9805.03110	43.39	<.0001
PD*CV	9	6594.69918	732.74435	3.24	0.0010
PD*HS	3	1100.14735	366.71578	1.62	0.1847
CV*HS	27	15277.40559	565.82984	2.50	0.0001
PD*CV*HS	27	23072.27006	854.52852	3.78	<.0001

Appendix 4.7: Analysis of variance (ANOVA) of Leaf gaseous exchange 2019: Ci

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PD	1	45012.258	45012.258	36.70	<.0001
CV	9	94337.915	10481.991	8.55	<.0001
HD	3	1119629.218	373209.739	304.26	<.0001
PD*CV	9	28588.990	3176.554	2.59	0.0073
PD*HD	3	4901.105	1633.702	1.33	0.2646
CV*HD	27	138829.558	5141.835	4.19	<.0001
PD*CV*HD	27	81460.733	3017.064	2.46	0.0002

Appendix 4.8: Analysis of variance (ANOVA) of Leaf gaseous exchange 2019: E

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PD	1	118.840313	118.840313	75.08	<.0001
CV	9	762.375248	84.708361	53.51	<.0001
HD	3	2863.776436	954.592145	603.06	<.0001
PD*CV	9	24.182412	2.686935	1.70	0.0903
PD*HD	3	76.597942	25.532647	16.13	<.0001
CV*HD	27	333.495279	12.351677	7.80	<.0001
PD*CV*HD	27	62.258357	2.305865	1.46	0.0736

Appendix 4.9: Analysis of variance (ANOVA) of Leaf gaseous exchange 2019: Gs

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
PD	1	0.67459236	0.67459236	80.76	<.0001
CV	9	0.47079275	0.05231031	6.26	<.0001
HD	3	2.08154646	0.69384882	83.07	<.0001
PD*CV	9	0.11159807	0.01239979	1.48	0.1542
PD*HD	3	0.01886428	0.00628809	0.75	0.5217
CV*HD	27	0.79388732	0.02940323	3.52	<.0001
PD*CV*HD	27	0.36810701	0.01363359	1.63	0.0293

Appendix 4.10: Analysis of variance (ANOVA) of Leaf gaseous exchange 2019: A

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
PD	1	1231.851510	1231.851510	148.92	<.0001
CV	9	1501.470959	166.830107	20.17	<.0001
HD	3	6595.232453	2198.410818	265.76	<.0001
PD*CV	9	211.107939	23.456438	2.84	0.0034
PD*HD	3	290.547406	96.849135	11.71	<.0001
CV*HD	27	982.919966	36.404443	4.40	<.0001
PD*CV*HD	27	399.289287	14.788492	1.79	0.0121

Appendix 4.11: Analysis of variance (ANOVA) of Leaf gaseous exchange 2019: WUEins

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PD	1	28.19024132	28.19024132	197.00	<.0001
CV	9	66.96719388	7.44079932	52.00	<.0001
HD	3	20.78526388	6.92842129	48.42	<.0001
PD*CV	9	1.65120722	0.18346747	1.28	0.2472
PD*HD	3	2.97503545	0.99167848	6.93	0.0002
CV*HD	27	25.47722265	0.94360084	6.59	<.0001
PD*CV*HD	27	7.67896710	0.28440619	1.99	0.0036

Appendix 4.12: Analysis of variance (ANOVA) of Leaf gaseous exchange 2019: WUEintr

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PD	1	28729.63141	28729.63141	124.59	<.0001
CV	9	8409.49016	934.38780	4.05	<.0001
HD	3	8294.66041	2764.88680	11.99	<.0001
PD*CV	9	4608.63128	512.07014	2.22	0.0214
PD*HD	3	2132.42174	710.80725	3.08	0.0281
CV*HD	27	14695.88262	544.29195	2.36	0.0003
PD*CV*HD	27	10455.01097	387.22263	1.68	0.0225

Appendix 4.13: Analysis of variance (ANOVA) of Leaf gaseous exchange 2020: Ci

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PD	1	3504.6281	3504.6281	5.87	0.0161
CV	9	46090.2531	5121.1392	8.58	<.0001
HD	3	890717.0094	296905.6698	497.60	<.0001
PD*CV	9	41513.4031	4612.6003	7.73	<.0001
PD*HD	3	46478.8594	15492.9531	25.97	<.0001
CV*HD	27	172738.5844	6397.7253	10.72	<.0001
PD*CV*HD	27	86919.4844	3219.2402	5.40	<.0001

Appendix 4.14: Analysis of variance (ANOVA) of Leaf gaseous exchange 2020: E

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PD	1	142.553971	142.553971	79.22	<.0001
CV	9	373.419289	41.491032	23.06	<.0001
HD	3	3152.164643	1050.721548	583.93	<.0001
PD*CV	9	41.333469	4.592608	2.55	0.0081
PD*HD	3	6.073809	2.024603	1.13	0.3395
CV*HD	27	326.062405	12.076385	6.71	<.0001
PD*CV*HD	27	107.790362	3.992236	2.22	0.0008

Appendix 4.15: Analysis of variance (ANOVA) of Leaf gaseous exchange 2020: Gs

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
PD	1	0.14065838	0.14065838	30.51	<.0001
CV	9	0.25157240	0.02795249	6.06	<.0001
HD	3	2.21740438	0.73913479	160.33	<.0001
PD*CV	9	0.09616665	0.01068518	2.32	0.0162
PD*HD	3	0.10761963	0.03587321	7.78	<.0001
CV*HD	27	0.41437071	0.01534706	3.33	<.0001
PD*CV*HD	27	0.28220796	0.01045215	2.27	0.0006

Appendix 4.16: Analysis of variance (ANOVA) of Leaf gaseous exchange 2020: A

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
PD	1	404.707553	404.707553	53.26	<.0001
CV	9	2207.484700	245.276078	32.28	<.0001
HD	3	6749.381653	2249.793884	296.09	<.0001
PD*CV	9	194.792524	21.643614	2.85	0.0033
PD*HD	3	71.460341	23.820114	3.13	0.0262
CV*HD	27	857.299695	31.751841	4.18	<.0001
PD*CV*HD	27	423.013351	15.667161	2.06	0.0022

Appendix 4.17: Analysis of variance (ANOVA) of Leaf gaseous exchange 2020: WUEins

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PD	1	134.27442	134.27442	62.14	<.0001
CV	9	842.78409	93.64268	43.33	<.0001
HD	3	12708.24725	4236.08242	1960.23	<.0001
PD*CV	9	23.20812	2.57868	1.19	0.2999
PD*HD	3	101.90798	33.96933	15.72	<.0001
CV*HD	27	1136.47006	42.09148	19.48	<.0001
PD*CV*HD	27	99.12493	3.67129	1.70	0.0201

Appendix 4.18: Analysis of variance (ANOVA) of Leaf gaseous exchange 2020: WUEintr

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PD	1	27011.59910	27011.59910	70.77	<.0001
CV	9	38707.93117	4300.88124	11.27	<.0001
HD	3	7817.54719	2605.84906	6.83	0.0002
PD*CV	9	9711.64158	1079.07129	2.83	0.0035
PD*HD	3	13714.01325	4571.33775	11.98	<.0001
CV*HD	27	24770.27303	917.41752	2.40	0.0002
PD*CV*HD	27	22429.97026	830.73964	2.18	0.0011

Appendix 4.19: Analysis of variance (ANOVA) of Shoot biomass for 2018

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
PD	1	34280763.5	34280763.5	845.82	<.0001
CV	9	422569007.4	46952111.9	1158.46	<.0001
HD	4	913393676.1	228348419.0	5634.09	<.0001
PD*CV	9	7758328.8	862036.5	21.27	<.0001
PD*HD	4	13478930.8	3369732.7	83.14	<.0001
CV*HD	36	130618140.3	3628281.7	89.52	<.0001
PD*CV*HD	36	5883909.4	163441.9	4.03	<.0001

Appendix 4.20: Analysis of variance (ANOVA) of Root biomass for 2018

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
PD	1	1477132.11	1477132.11	859.99	<.0001
CV	9	11092892.65	1232543.63	717.59	<.0001
HD	3	14177368.23	4725789.41	2751.36	<.0001
PD*CV	9	506128.33	56236.48	32.74	<.0001
PD*HD	3	317374.09	105791.36	61.59	<.0001
CV*HD	27	2684120.11	99411.86	57.88	<.0001
PD*CV*HD	27	275147.72	10190.66	5.93	<.0001

Appendix 4.21: Analysis of variance (ANOVA) of Shoot biomass for 2019

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
PD	1	31931784.9	31931784.9	1096.80	<.0001
CV	9	395594122.0	43954902.4	1509.77	<.0001
HD	4	822798238.3	205699559.6	7065.41	<.0001
PD*CV	9	7622005.9	846889.5	29.09	<.0001
PD*HD	4	10791605.7	2697901.4	92.67	<.0001
CV*HD	36	121139347.2	3364981.9	115.58	<.0001
PD*CV*HD	36	4695901.4	130441.7	4.48	<.0001

Appendix 4.22: Analysis of variance (ANOVA) of Root biomass for 2019

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
PD	1	495767.547	495767.547	1088.13	<.0001
CV	9	5827907.807	647545.312	1421.26	<.0001
HD	3	9293525.223	3097841.741	6799.26	<.0001
PD*CV	9	131500.007	14611.112	32.07	<.0001
PD*HD	3	122683.905	40894.635	89.76	<.0001
CV*HD	27	1647350.700	61012.989	133.91	<.0001
PD*CV*HD	27	72449.315	2683.308	5.89	<.0001

Appendix 4.23: Analysis of variance (ANOVA) of Shoot biomass for 2020

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
PD	1	53969079	53969079	1172.24	<.0001
CV	9	626773144	69641460	1512.66	<.0001
HD	4	1144774217	286193554	6216.30	<.0001
PD*CV	9	13253013	1472557	31.98	<.0001
PD*HD	4	15115630	3778908	82.08	<.0001
CV*HD	36	171357115	4759920	103.39	<.0001
PD*CV*HD	36	6963573	193433	4.20	<.0001

Appendix 4.24: Analysis of variance (ANOVA) of Root biomass for 2020

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
PD	1	33377076.3	33377076.3	1295.62	<.0001
CV	9	373775198.6	41530577.6	1612.12	<.0001
HD	3	675544212.1	225181404.0	8741.01	<.0001
PD*CV	9	9318810.5	1035423.4	40.19	<.0001
PD*HD	3	11967427.6	3989142.5	154.85	<.0001
CV*HD	27	118836343.2	4401346.0	170.85	<.0001
PD*CV*HD	27	5589359.7	207013.3	8.04	<.0001