EFFECTS OF MAIZE AND LEGUME INTERCROPPING SYSTEM ON SOIL NITROGEN DYNAMICS AND CROP GROWTH

by

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DECLARATION

I declare that the mini-dissertation hereby submitted to the University of Limpopo, for the degree of Master of Science in Soil science has not been submitted previously by me or for a degree at this or any other university; that it is my work in design and in execution, and that all materials contained herein has been duly acknowledged.

Surname, Initials (tittle)	Date

DEDICATION

This work is dedicated to my parents (Mabothe and Hunadi Mmotong) and my siblings (Morongoa, Lebala and Letago Mmotong) for their support throughout the study.

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I would like to thank God for the wisdom and strength provided for the duration of the study. I would also like to show my appreciation for the following:

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ABSTRACT

Nitrogen is an essential mineral nutrient that can hinder crop production if not managed properly. Improved agricultural management practices such as cover cropping, crop rotations or intercropping influence nitrogen availability and supply. Hence this study was aimed at investigating how intercropping cereal with legume influences (i) soil nitrogen dynamics and (ii) selected growth and yield parameters. A field experiment was carried out at the University of Limpopo experimental farm (Syferkuil) integrating maize (*Zea mays*) with chickpea (*Cicer arietinum*) and mungbean (*Vigna radiata*) under two different moisture regimes (irrigated and rainfed). The experimental site was a split plot design replicated three times. The treatments were as follows: Sole maize- SM, Sole chickpea- SC, Sole mungbean- SMB, Maize/chickpea intercropping- MC, Maize/mungbean intercropping– MMB under rainfed and irrigated moisture regimes. Soil fertility variables i.e., bulk density, aggregate stability, pH, phosphorus and organic carbon; and nitrogen fractions: biological nitrogen fixation (BNF), mineralisation, uptake, residual and leaching were measured using standard procedures. Data analyses was done using the GenStat 20th Edition software. The study showed insignificant interaction effect between cropping system and irrigation regime did not have a significant effect on soil conditions bulk density, aggregate stability, pH, organic carbon ($p>0.05$). Nitrogen mineralisation was higher in the intercrops in comparison to the sole grown crops. Biological nitrogen fixation (BNF) was higher in the irrigated plot compared to the rainfed plot. Chickpea generally fixed a greater amount of nitrogen compared to mungbean. Chickpea showed greater nitrogen fixation in the intercropped stand while mungbean had a higher BNF in the sole stand. The uptake of nitrogen was greater in the irrigated compared to the rainfed plot. Sole maize had the highest nitrogen uptake, followed by the intercropped stands and then the sole legume stands. Residual nitrogen was greater in the rainfed plot compared to the irrigated plot. Intercropping both legume crops resulted in higher residual nitrogen compared to the sole stands. Mineral nitrogen leached beyond the active root zone was greater in the irrigated plot. The intercropped stands recorded lower mineral nitrogen leached in comparison to the sole stands. Data collected to observe growth and yield parameters were chlorophyll content, leaf area plant height and plant biomass. The results depicted a positive response to intercropping through the chlorophyll content and leaf area. Plant biomass was higher in in the sole stands for all associated crops. In conclusion, cereal/legume intercropping can be a sustainable approach to maximizing nitrogen use efficiency while minimizing potential losses.

Keywords: Intercropping, legumes, soil fertility, nitrogen dynamics, water regime, crop growth

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background

Soil nitrogen (N) is important in facilitating the growth and development of crops (Ladha *et al*., 2022). It is involved in multiple critical processes therefore can have major limiting capabilities if not managed properly. Nitrogen as a nutrient requires proper management to help avoid detrimental effects on plant growth (Anas *et al.,* 2020). Sustainability is an important factor related to the management of nitrogen in agricultural soils to ensure adequate availability of soil resources for future generations. Nitrogen availability is influenced by cycling, which entails various dynamics, some of which may be integral for the growing process such as mineralization (ammonification and nitrification). Nitrogen dynamics describes the fractions of nitrogen within the soil that are dominant contributors to nitrogen supply. These are influenced by the existing soil conditions (e.g., soil moisture content, microbial activity and diversity) (Zou *et al*., 2018). It is important to observe these nitrogen dynamics in the soil to be able to evaluate its effectiveness in supplying nitrogen to growing crops. These dynamics are also greatly influenced by different agronomic practices such as intercropping, crop rotations, cover crops. These affect the nutrient level in the soil and the overall nitrogen supply for crop acquisition and general development (Zou *et al.,* 2018).

Legume based agronomic practices are becoming popular because of their ability to increase N supply in a sustainable manner. This is due to the capabilities of legume crops to biologically fix nitrogen (Jensen *et al*., 2010) and meet their N needs during the growing period. These agronomic practices alter resource acquisition and partitioning by improving the functional biodiversity in the soil. Cereal/legume intercropping is the most common planting combination and is widely adopted by farmers for its multiple advantages to crop production (Lai *et al*., 2022). The benefits of the cropping system include maintaining soil fertility, regulating the usage of water and the disturbance of pests and diseases (Rapholo, 2020).

The intercropping of cereals with legumes has proven to be an efficient approach to satisfying the nitrogen requirements of growing crops while reducing the amount of synthetic fertilizers used at farm level (Jensen *et al*., 2012). According to Lian *et al*.

(2019), the cereal and legume combination improves the conversion of soil N by enhancing microbial activity and soil N contents. The diversification of crops in intercropping alters the soil environment by changing the physicochemical properties of the soil and ultimately influences nitrogen dynamics in the soil (Lalati *et al*., 2014). This is caused by the interspecific interactions between the roots of the intercropped crops. Synchronizing nitrogen supply with nitrogen crop demand requires crucial attention as it is a major step in establishing nitrogen use efficiency and minimizing nitrogen loss in intercropping (Nyawade *et al*., 2020).

1.2 Problem statement

Poor management of nitrogen which is evident through nitrogen deficiencies and toxicities is a major challenge for achieving satisfactory amounts of soil productivity and fertility (Hengl *et al*., 2015). One of the major factors contributing towards low soil fertility and degradation is the loss of nutrients in arable land as a result of unsuitable soil management practices (Meena *et al*., 2017). The loss of nutrients from an agroecosystem has both economic and environmental implications that threaten the sustainability of agronomic practices. The measures of correctly applying nitrogen to the soil are dependent on various factors such as soil properties, climate and crop uptake, which pose difficulties in establishing appropriate rates of applying nitrogen fertilizer (Tremblay *et al*., 2012). Evaluating the relationship between intercropping and nitrogen dynamics requires an understanding of the influence of intercropping on organic matter pools and nitrogen availability. Unfortunately, there is little knowledge on how these nitrogen fractions are influenced by different cropping systems, more especially by different legume crops in different crop combinations, and climatic conditions.

Growing cereals with legumes simultaneously reduce the requirements for synthetic nitrogen fertilizer (Jensen *et al*., 2020), mainly because legumes obtain atmospheric N through biological nitrogen fixation (BNF). Farmers tend to apply inorganic nitrogen fertilizer heavily (Muthoni *et al.,* 2013), as a way of compensating for nitrogen losses. However, although this option has proven to result in considerable crop growth and development, it has potential detrimental environmental implications (Ahmed *et al*., 2017). Excessive buildup of nitrogen in the soil profile can cause high nitrate leaching with drainage water and potential leaching of nitrogen to the surrounding, resulting in the contamination of underground water sources. Therefore, there is a need to implement nitrogen management strategies that observe the fate of nitrogen, especially in intercropping systems, to ameliorate challenges associated with N deficiencies and toxicities. This will help alleviate farmers from the high costs that are associated with inorganic nitrogen input.

1.3 Rationale of study

The management of nitrogen in soils needs to be prioritized to help answer questions related to nitrogen use efficiency in different agronomic practices and eliminate major nitrogen losses to the soil and overall environment (Sainju *et al*., 2019). A better understanding of nitrogen management will promote the use of the nutrient from different reserves in a sustainable manner (Chen *et al*., 2014). The intercropping of cereal crops with legumes has proven to be an efficient way of maintain soil fertility and ensuring crop productivity through improving the nutrient status and microbial activity. Cereal/ legume intercropping is a sustainable way of ensuring productivity and profitability in crop production. Understanding how the different nitrogen dynamics are influenced by the intercropping practice is an efficient way of evaluating the nitrogen use efficiency that is associated with the intercropping practice (Prasad and Hochmuth, 2014). Information on the different nitrogen dynamics will provide understanding on different nitrogen inputs and outputs and how to manage available nitrogen. The information obtained from the interpretation of a nutrient dynamics will show the points of excess or deficit nitrogen application in the farming systems (Nyawade *et al*., 2020). This will help individuals understand different nitrogen pathways and how to maximize the efficient use of nitrogen. The study will help farmers, scientists and agricultural advisors understand how they can use intercropping to manage nitrogen dynamics and simultaneously ensure soil productivity. The information will also help farmers interpret observed deficiencies and toxicities in intercropping (Ti *et al.*, 2012). The observation of nitrogen dynamics is essential in establishing a synchronization between nitrogen supplied and the amount of nitrogen that is efficiently used for the development of the crops (Nyawade *et al*., 2020).

1.4 Purpose of the study

1.4.1 Aim

Establishing nitrogen dynamics for rainfed and irrigated maize/legume intercropping systems.

1.4.2 Objectives

i. To determine the effects of maize/legume intercropping on nitrogen dynamics under rainfed and irrigated maize/legume intercropping system.
ii. To determine the response of selected plant growth and yield parameters under rainfed and irrigated maize/legume intercropping system.

1.4.3 Hypotheses

i. Maize/legume intercropping will not affect the nitrogen dynamics under rainfed and irrigated maize/legume intercropping system.
iii. The response of the selected plant growth and yield parameters will not differ under rainfed and irrigated maize/legume intercropping system.

1.5 Reliability, validity, and objectivity

Analysis of variance (ANOVA) was performed to derive statistical level of significance and ensure reliability. The samples were replicated during sampling and analysis for both objectives to achieve validity. The discussion of the results was based on factual and verifiable evidence to obtain objectivity.

1.6 Bias

All treatments were replicated to minimize bias and reduce experimental error for both objectives.

1.7 Scientific significance of the study

The study was conducted to investigate the nitrogen use efficiency associated with the maize-legume intercropping systems by observing different nitrogen dynamics in rainfed and irrigated water regimes. Observing different nitrogen transformations is an ideal way of evaluating the influence of the intercropping practice on soil fertility and crop productivity. This will provide a significant contribution to agricultural means of increasing food production and ensuring food security for the increasing population by providing practical ways of sustainably managing nitrogen in the soil.

1.8 Structure of the mini dissertation

This mini dissertation consists of five chapters, structured as follows: Chapter 1 details the research problem. Chapter 2 presents the literature review which shows the work done and work not done in relation to the research problem. Chapter 3 and 4 details the work done, and the analyses methods used in achieving the objectives of the study. Chapter 5 is a summary of all the research findings and their significance, the conclusion that can be made from results of the study, and recommendations for future research. Harvard referencing style was followed in the mini-dissertation, author-alphabet in-text and reference list as approved by the University of Limpopo Senate.

CHAPTER 2

LITERATURE REVIEW

2.1 Intercropping and its significance in agricultural systems

Intercropping is a cropping practice where crops are grown together on the same land (Rapholo, 2020). The growing interest in the practice results from its benefits, such as increasing soil quality, improved productivity and pest management. The practice is also preferable amongst farmers because the associated crops mostly have different pathways of obtaining nutrients (Crusciol *et al*., 2020).

2.2 Crop description and utilization: maize, chickpea and mungbean

2.2.1 Maize

Maize (*Zea mays L*.) is a common cereal crop that belongs to the grass family. It is an essential staple crop for households in Africa (Scott and Emery, 2016). Maize crop belongs to the grass family, therefore it has significant nitrogen requirements to achieve optimum yield (Makgoga, 2013). Maize is commonly produced by most resource-constrained farmers in southern Africa, with climatic conditions ranging from semi-arid to high rainfall areas (Nndwambi, 2015). According to Nkuna (2019), moisture stress and low soil fertility status are the major abiotic factors that limit the production of maize. The production of maize grain has been approximated to reach 8.0 million tons annually on land measuring 3.1 million ha in South Africa. High maize production can be achieved with specific climatic requirements such as a temperature of 16 to 18 ºC for proper germination. Maize requires average temperatures of 19 and 32 °C throughout the growing period. The growing period should include 120 to 140 days without frost. Soil conditions such as good internal drainage, sufficient effective rooting zone and soil moisture are ideal for achieving desirable yield (Du Plessis, 2003).

2.2.2 Chickpea

Chickpea (*Cicer arietinum L*.) is an essential legume crop that follows dry bean and field pea in global production (FAOSTAT, 2018). The continent of Africa contributes less than 4 % to production at a global level (Monyo and Laxmipathi, 2014). Chickpeas significantly contribute to soil fertility by fixing up to 140 kg/ha of atmospheric nitrogen

(Flowers, 2010). It also enhances soil health and fertility by adding residual nitrogen and a significant amount of organic matter (Rasool *et al*., 2015). Chickpea requires a temperature of 5 to 15 °C for the process of germination, for the flowering and pod formation process, temperatures should not exceed 29 °C. The crop is fairly drought tolerant; this is attributed to its deep taproot system, which allows the crop to draw water from deep soil layers. In relation to soil type chickpea requires a soil that is sandy loam textured soil, with a pH ranging from 6 to 7 and a soil with good internal water storage. The production of chickpea in South Africa has the potential to be affected by environmental factors (e.g., soil type, rainfall) and various agronomic practices (Makonya, 2020).

2.2.3 Mungbean

Mungbean (*Vigna radiate*) production in South Africa is widely done for consumption purposes, with Mpumalanga and Limpopo being the main production areas. Mungbean can be harvested as a leafy green or a pulse (Wilbur, 2023). Mungbean requires 90–120 days to reach maturity, depending on the variety that is planted. Optimum mungbean growth requires temperatures of 27 to 30 °C. Mungbeans perform well when planted in fertile soils, with a sandy loam textures with good internal drainage. The preferable soil pH should range between 6.3 and 7.2. Mungbeans have shown the most growth in slightly acid soils.

2.3 Effects of intercropping on soil properties and soil fertility

The incorporation of legume in cropping systems improves the fertility of the soil by positively facilitating different facets of soil fertility e.g., SOC and humus content, nutrient availability (Stagnari *et al*., 2017). It encourages good aggregation and aeration thus promoting greater crop development. Biological nitrogen fixation (BNF) positively influences nutrient availability in the soil and stimulates plant nutrient uptake (Kebede, 2021). Legumes provide N-rich components (e.g., leaves, pods) that can be incorporated into the soil to increase nutrient supply.

Intercropping cereals with leguminous cops have been recognized as a sustainable pathway of ensuring soil fertility. This practice is a feasible alternative technique to improving soil health sustainably. This type of crop diversification significantly influences nutrient availability in the soil. Cereal crops remove large amounts of nitrogen from the soil during their growing season, whilst legume crops obtain most of their nitrogen through biological nitrogen fixation (Lai *et al*., 2022). Intercropping introduces root induced biochemical changes to the soil environment that alter the physical, chemical and biological soil properties (Betencourt *et al*., 2012).

2.3.1 Soil physical properties

Smallholder farmers have shown great interest in cereal and legume intercropping as the ability of legumes to adjust to degeneration of the soil or decline in soil health is proven (Layek *et al*., 2018). Intercropping has shown great water use efficiency as a result of increased leaf area and foliage cover in some cases. Cowpea showed covering abilities in a study involving maize and cowpea, the cowpea showed great potential in decreasing soil disintegration. The incorporation of legumes increases soil organic matter content (SOM), this enhances aggregate stability, increases the water retention, soil aeration and cultivation efficacy. The SOM content is a good component for reducing further soil disintegration by stabilizing soil aggregates (Yavad, 2017).

Ganeshamurthy *et al*. (2006) reported a lower hydraulic conductivity and bulk density in a field experiment that incorporated mungbean, rice and wheat-mungbean cropping sequences. The findings contradicted the one observed by Oelbermann *et al.* (2015) of an increasing bulk density trend by 9 to 20% and 15 to 31% at 20 cm soil depth intervals in a maize and soybean intercropping combination. The bulk density trend can be associated with the difference in root systems and the overall rooting depth. A study including sorghum and cowpea intercropping resulted in a pattern where surface runoff decreased by 20 to 30% in comparison to growing sorghum individually and decreased by 45 to 55% in comparison to cowpea grown solely. The study further showed a 50% reduction in soil loss when intercropping sorghum with cowpea compared to growing the associated crops solely (Zougmore *et al*., 2000).

2.3.2 Soil chemical properties

Greater levels of soil organic related to intercropping cereal and legume crops contribute to the soil nutrient build (Lakey *et al*., 2018). Singh *et al*. (2009), stated that legumes possess the net effect to depress the soil pH. Chickpea showed the greatest decline in soil pH, pea along with pigeon pea followed chickpea respectively. These findings did not support the ones reported by Oelbermann *et al.* (2015), where soil pH was not significantly affected in a study intercropping maize with soybean. The extent of change in pH in cereal and legume intercropping depends on the legume specie grown and the existing soil conditions.

Cereal/legume intercropping significantly affected the level organic carbon (Ayele, 2020). In a study intercropping maize with cowpea SOC increased from 0.86 to 1.21 as a result of intercropping. The findings agree with the findings by Ofori *et al*. (2014), where a 0.37-0.82 % increase in organic carbon was observed when maize was grown intercropped with cowpea. Dang *et al*. (2020), observed a similar pattern from an intercropping study that included proso millet and mungbean, which resulted in increased mineral nitrogen amounts. The nitrogen accretion is highly accredited to microbial diversity and community and the N contents from the crop residues of the associated crops. According to Li *et al*. (2016), abundance of microbial species at the study site was altered by belowground interactions when maize/peanut were intercropped.

Changes in phosphorus availability have also been reported as a result of below-ground root interactions in cereal/legume intercropping systems (Lalati *et al*., 2016). According to Stangnari *et al*. (2017), intercropping increased rhizosphere phosphorus availability compared to sole cropping. In a study intercropping maize with cowpea, phosphorus increased in the rhizosphere of the intercrops. This increase might result from different mechanisms such as organic acid exudation occurring from the roots of the legume crops that can lower the soil pH and solubilize phosphorus or through the of different phosphatase enzymes that will facilitate the decomposition of organic material that contains phosphorus (Kebede, 2021).

2.3.4 Soil biological properties

Microorganisms in the soil are essential components as they facilitate different biochemical processes that take place in the soil ecosystem, e.g., nutrient cycling and suppressing specific soil borne pathogens (Zhang *et al*., 2018). Cereal/legume intercropping alters the structure of soil microbes and the abundance of various microbial species (Meena *et al*., 2014). Intercropping creates strong interspecific interactions amongst the roots of the associated crops, this can improve the activity of microbes and encourage the decomposition of humus and organic material transformation (Lai *et al*., 2022). According to Lian *et al*. (2019), intercropping sugarcane/soybean increased microbial diversity. Cereal and legume intercropping increases microbial activity through niche complementarity. Complementary effects means spatial ecological niches are separated from temporal to promote methodical use of available resources by the coexisting species. Pang *et al*. (2022), observed a 9.28% increase in the richness of rhizosphere bacteria in sugarcane-peanut intercropping compared with sugarcane monoculture. Intercropping sugarcane with soybean resulted in a 111.5%, 43.6% and 57.3% increase in fungi, bacteria, and actinomycetes, respectively, compared to monoculture (Li *et al*., 2013)

Biological nitrogen fixation occurs legume interacts with rhizobia (Lai *et al*., 2022). The legume can fix atmospheric N from 75 to 150 kg/ha and even reach 300 kg/ha per year in favourable conditions. The diversity of the planting pattern increases soil enzyme activity. Enzyme activity and soil physicochemical properties are closely related (Lai *et al.,* 2020). According to Yao *et al*. (2006), monoculture results in significant reduction and harm to soil enzyme activity. The study revealed an increase in urease and sucrose activity when intercropping peanut with atractylodes.

2.4 Agronomic benefits of intercropping

Cereal and legume intercropping is a more sustainable practice in terms of improving soil health and producing desirable crop yields compared to mono cropping (Himmelstein *et al*., 2017). Latati *et al*. (2014), observed greater maize grain and biomass yield when intercropped with cowpea. A similar trend was observed when durum wheat was intercropped with faba bean. The positive response of yield parameters was accredited to the increased rhizosphere phosphorus availability for the cereal crops (Betencourt *et al*., 2012). Legumes have a higher adaptability to various cropping practices and offer the opportunity to sustain an increase in biomass for the intercrops. Latati *et al*. (2016) observed an increase in above ground biomass in a maize and cowpea crop mixture in comparison to the individual sole counterparts. Wang *et al*., (2012) demonstrated a similar pattern in a field study with maize grown intercropped with faba bean, there was a high above ground biomass as a result of intercropping the two crops in comparison to growing them separately. Contrastingly, Latati *et al*. (2013) observed a decline of 58% in cowpea grain yield when intercropped with maize.

There are evident contradictions regarding the effects of cereal and legume intercropping on crop growth dynamics. Whilst most studies have recorded increased crop yields and positive growth parameters as a result of intercropping, some studies have reported the opposite or no significant changes. This can be because of various factors such as seeding rate, different growth cycles or competitive interactions taking place between the crops. A study conducted by Khalid *et al*. (2021), showed that sole mungbean recorded the highest crop growth rate and also the lowest crop growth rate when intercropped with barley and pear millet. According to Dordas *et al*. (2012), the plant height of sole oat and barley did not significantly change in comparison to when intercropped with pea.

2.5 The effect of cereal/legume intercropping on nitrogen dynamics.

2.5.1 Biological nitrogen fixation

The complementarity between the crops in intercropping offers a range of advantages which include protecting the soil from various environmental factors and the efficient use of available environmental resources (Bantie, 2014). According to Bedoussac *et al* (2015), the cereal/legume intercropping combination decreases the need for nitrogen inputs due to the biologically fixed nitrogen done by the legume crops. Legumes fix varying amounts of atmospheric nitrogen depending on different factors such as the type of legume, nutrient status or competition amongst the crops (Mhango, 2011). Katamaya *et al*. (1995), found that reported pigeon pea derived greater amounts of nitrogen from the atmosphere under cereal/pigeon pea intercrops compared to pigeon pea/groundnut or pigeon pea/cowpea intercrops. A similar trend was found by Ismail *et al*. (2012), where biological nitrogen fixation increase was recorded when intercropping wheat with chickpea. The increased BNF legumes intercropped with cereal crops is caused by the increased competition between the associated crops, where the cereal crop commonly derives a much larger proportion of mineral nitrogen.

As a result of this interaction, the legume crop compensates for the lower nitrogen share by subsequently fixing atmospheric nitrogen (Rodriquez *et al*., 2020). In cereal and legume intercropping, the cereal crops are more competitive and efficient at using soil N than legumes and this may encourage the associated legume to fix increased amounts of nitrogen. These findings align with the observations made by Betencourt *et al.* (2012), where the nitrogen fixation of chickpea doubled when grown together with durum compared to when grown separately. The competitive ability of the intercropped cereal crop influences the nitrogen that is fixed by the legume integrated into the intercropping system. The nitrogen that is fixed by the grown legume has limited benefits to the associated cereal crop. Combining legumes with non-legumes is important in efficiently using the nitrogen being fixed by the legume crops grown currently, however this system is also important in the residual build-up of nutrients in the soil and can be used by the subsequent crop grown in the same location.

2.5.2 Nitrogen uptake

Nitrogen utilization in intercropping is influenced by the interspecific interaction of the crops. Nitrogen uptake in when different crops are grown simultaneously can vary spatially and temporally. Spatial nitrogen uptake can be observed when there is an increase in the root mass of either one of the associated crops, whilst temporal advantages in nutrient acquisition are observed when the associated crops differ in the periods of peak nutrient demands. The inclusion of legumes within intercropping improves the uptake of nitrogen by crops by improving the inherent nitrogen content (Fan *et al*., 2020). According to Fan *et al*. (2020), intercropping maize and soybean showed a high nitrogen utilization efficiency compared sole crops. Nitrogen nutrient utilization efficiency increased by 9.9% in maize soybean intercropping. Similarly, Yong *et al.* (2021) observed an increase of 24.3 and 25.1 % in nitrogen uptake by maize and soybean respectively when intercropping maize with soybean. Due to the difference in rooting and uptake patterns in cereal and legume intercropping, nutrients are used more effeciently.

Chen *et al*. (2018), recorded greater plant nitrogen uptake as a result of an increase in organisms responsible for cycling nitrogen and existing beneficial bacteria found in the rhizosphere a result of cereal/legume intercropping. The same trend was observed in a field study with wheat durum and chickpea, where 22% increase in nitrogen uptake was recorded in a study intercropping chickpea with durum wheat in low phosphorus soils and increased by 19 % in soils with high phosphorus content. Soil phosphorus content facilitates the acquisition of N by influencing root development. Controversially, the findings of Li *et al*. (2006) depicted that the integrating barley with pea did not significantly increase nitrogen uptake, this can be associated with the lower contribution of legume. Commonly, the cereal will acquire more soil N compared to the other intercrop, as a result the grain legume will compensate for this by fixation of atmospheric nitrogen (Rodriquez *et al*., 2020). The increase in nitrogen uptake in cereals is encouraged by the greater demand for N.

2.5.3 Nitrogen mineralization

The net nitrogen mineralization is important in crop production as it influences nutrient availability for crop growth. The cereal and legume intercropping system is linked to increased residues. Omokanye *et al*. (2011), found that incorporating legumes in crop diversification can increase nitrate content through the mineralization of the legume residues. Legume intercropping increases dry matter, this encourages nitrogen mineralization and ultimately increases the soil nitrogen content available that can be used by the associated crops through uptake (Nyawade *et al*., 2020). The mineralization of nitrogen increased when maize was intercropped with soybean and was higher relative to the subsequent sole crops (Regehr *et al*., 2015). The increase mineralization was due to residues from the intercropped species which, vary in their ratios in contrast to the sole stands. According to Regehr *et al*. (2015), information detailing the underlying process of mineralization and how it influences nitrogen availability when different intercrop mixtures over a short-term period is limited. Understanding the dynamic of the mineralization process provides an indication on the amount of nitrogen that is available for plant uptake.

2.5.4 Nitrogen leaching

Intercropping has shown great potential in reducing in situ nitrate leaching (Manevski *et al*., 2015). Intercropping maize using rate of nitrogen fertilizer that can be applied to sole maize reduces nitrogen leaching without significantly decreasing production. The study showed that intercropping maize lowered nitrogen leaching by 15–37 % lower than maize grown as a monocrop. The results were in line with the study conducted by which showed the legume intercropping reduced nitrate leaching by 10-16% when compared with the sole crops. The findings concurred with observations done by Pappa *et al*. (2011) where intercropping spring barley and pea in reduced nitrate leaching and N_2O emissions compared to when barley was grown solely. The reduced leaching rate in intercrops results from the different rooting and uptake patterns, where the crop with a higher effective rooting zone can act as a catch crop and recover nutrients from the lower depth.

2.6 Work not done on the research problem.

There is no substantial literature that can be accurately used to synchronize nitrogen supply with the nitrogen demand in nitrogen based intercropping systems (Nyawade, 2020). Cereal and legume intercropping is mostly known for its benefits in biological nitrogen fixation but there is a lack of existing literature observing the soil nitrogen fractions that facilitate nutrient availability and the general growing process of the associated crops. There is limited information and inclusivity on nitrogen management in the cereal/ legume intercropping system especially focusing on less popular legume crops (chickpea and mungbean) in South Africa. Efforts to minimize external inorganic inputs for sustainable cropping system requires an understanding of the nutrient dynamics within the soil as they are influenced by the interspecific interactions in the rhizosphere. Therefore, it is important to observe the fate of nitrogen under these specific rhizosphere conditions to avoid possible negative environmental and economic implications. This study aims to highlight and resolve these information gaps by providing information on the mechanisms influencing the nitrogen availability in cereal and legume intercropping.

CHAPTER 3

EFFECTS OF MAIZE/LEGUME INTERCROPPING SYSTEM ON SOIL NITROGEN DYNAMICS.

3.1 INTRODUCTION

Nitrogen in the soil is an important nutrient that facilitates crop growth and development (Bhardwaj *et al*., 2021). Nitrogen has major limiting capabilities to the growing process of crops, if not managed properly (Louarn *et al*., 2021). Nitrogen in the soil is subjected to various transformation processes that determine its availability and effective use by growing plants. It is very important to quantify the specific fractions of nitrogen that are dominant contributors to nitrogen supply in a particular system (Luce *et al*., 2011). Nitrogen responds differently in different agricultural management practices as they influence soil organic nitrogen (SON) pool, microbial activity, and soil aggregation. The observation of the nitrogen supply in a specific system is important in identifying the manner in which nitrogen is used within the system (Yong *et al*., 2018). Therefore, understanding nitrogen availability during the growing season is important for improving fertiliser use efficiency. Amongst the different intercropping combinations, cereal and legume intercropping is mainly preferred because the associated crops obtain nitrogen through different pathways and have different nitrogen use abilities (Dang *et al*., 2020). The difference in the resource niche for the associated crops makes the practice more sustainable and effective for smallholder farmers. This chapter investigates different soil nitrogen dynamics in a cereal and legume intercropping system conducted under two irrigation regimes (irrigated and rainfed conditions).

3.2 Materials and methods

3.2.1 Study site description

The study was conducted at the University of Limpopo’s Experimental farm (UL farm) (23°50’42.86” S; 29°42’44.3” E). The farm is located in Syferkuil in the Polokwane municipality, Capricorn district, South Africa (Figure 3.1). The study site experiences semi-arid climate with a range of 405 to 500 mm in mean annual precipitations. The average summer day temperatures at UL farm vary from 28 to 30°C (Nndwambi, 2015). The experimental site is dominated by Hutton soil forms and the soils are moderately shallow to deep sandy loam (Soil Classification Working Group, 2018).

The study was carried out during the 2021/2022 growing season from early February until June.

3.2.2 Treatments and research design

Field experiment layout

The trial was laid out in a 2 x 5 split plot design, arranged in a randomized complete block design (RCBD), and replicated three times. The main plots were two watering regimes (rainfed and irrigated plots). The subplots were the different cropping systems: sole maize (SM), sole chickpea (SC), sole mungbean (SMB), maize/chickpea row intercropping (MC), and maize/mungbean row intercropping (MMB).

Soil sampling for physicochemical and biological properties.

Prior to field establishment, soil samples were randomly collected from the main plots for physicochemical analyses at the study site before planting. Post-trial, soil samples were collected from each sub-plot at a depth of 0-30 cm. To quantify the amount of nitrogen below the active root zone, additional samples were collected from the 0-60 and 60-90 cm soil depth. Each sample was a composite sample of three replicates. The samples were transported in a cooler box with ice and stored in a refrigerator at 4 °C before laboratory analyses.

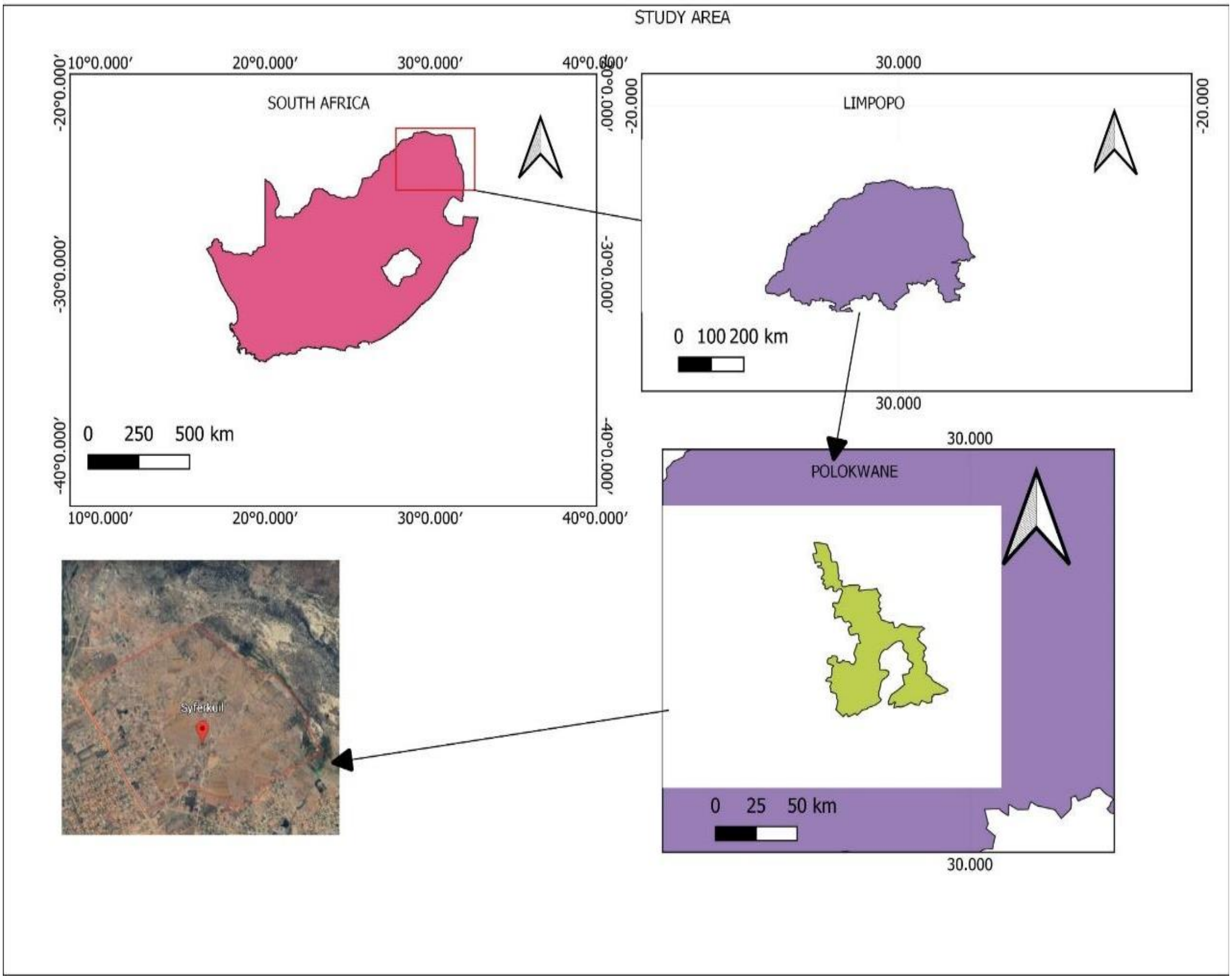

Figure 3.1: Map of the study area.

Study practices

A fallowed plot at the study was divided into two main plots, one with 15 subplots. Mechanised tillage was performed for the purpose of seedbed preparation. A cooler box with ice was used to transport soil samples for biological analyses. The demarcation and measurements of the plots was done using a measuring tape and T-markers. For planting, a total of 3 seeds were placed at a depth of 5 cm. The inter and intra row spacing were 90 cm and 10 cm, respectively in the sole maize stands. For the sole legumes the inter and intra row spacing was 40 cm and 30 cm, respectively. In intercropped plots, maize inter- and intra-row spacing was used as a reference and the legume crops were planted in-between the maize crops (Figure 3.2). The seedlings were thinned at 14 days after emergence. Weeding was performed by hand hoeing. The irrigation was scheduled accounting for soil moisture content. This was done using the sprinkler irrigation system on a weekly basis. The fertilizer was applied based on soil analysis results, the nitrogen in the soil before planting was used as a reference. A side dressing of 50 kg/ ha limestone ammonium nitrate (LAN) was done 14 days after emergence following laboratory analyses.

Figure 3.2: Field layout of treatments.

3.2.3 Data collection

Physicochemical properties

Particle size distribution from soil samples was determined using the hydrometer method (Bouyoncos, 1962). Bulk density samples were collected using 21 cm^3 cylinder core, oven dried at 105 °C for 24 hours and determined using the cylindrical core method (Campbell and Henshall, 1991). Soil aggregate stability was determined by separating air-dried soil aggregates through wet sieving of three sieve sizes using a method by Elliot (1986). Soil pH was determined in a 1:2.5 solution ratio in both deionised water and 1M KCl suspension using a glass electrode (Reeuwijk, 2002). The electrode method with a glass EC meter was used to determine electrical (Rhoades, 1982). Soil organic carbon (SOC) was determined using the Walkely Black method. Phosphorus (P) was determined through the Olsen extraction method (Olsen, 1982). Phosphorus uptake was calculated as the product between the biomass weight and nutrient concentration in each plant part (roots and the shoots).

Nitrogen fractions

Residual nitrogen and the amount of N leached were determined using Colorimetric method through liquid converted samples and absorbances read using T60 UV spectrophotometer at a wavelength of 655 nm and 419 nm respectively (Bremmer and Mulvaney, 1982). Biological nitrogen fixation (BNF) was quantified using the traditional N difference method (Eq.1) (Karpenstein-Machan and Stuelpnagel, 2000).

$$N_{fix\ (legume)} = [N_{leg} - N_{ref}] + [soilN_{leg} - soilN_{ref}] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where Nleg, Nref, referred to aboveground N concentration of the legume and the reference plant while soilNleg, and soilNref referred to the mineral soil N of the legume and the reference plant in the cropping system.

Nitrogen uptake was determined at the maturation stage. The samples were partitioned into shoots and roots. Nitrogen uptake was obtained as the product between the biomass weight and nutrient concentration in each plant part (Eq. 2).

$$[\text{Nutrient concentration} \times \text{biomass}/100] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Soil mineral nitrogen found below the active rootzone was considered leached. The amount of leached N was determined using the colorimetric method. The method proposed by Stanford and smith (1972) was used to determine the Potentially Mineralisable Nitrogen (PMN) through incubation of samples for a period of 7 days.

3.2.4 Statistical analyses

The pre-trial, soil physicochemical data was summarized using descriptive statistics, while all post-trial data was subjected to split plot analysis of variance (ANOVA) using the GenStat 20th Edition software. Mean separation for significant soil and plant variables was determined using the Waller Duncan's Multiple Range Test at a probability level of 5% confidence interval. Pearson's correlation was performed to assess the relationship between nitrogen dynamics and soil fertility variables.

3.3 Results

3.3.1 Selected soil properties prior to trial establishment.

Soil analysis prior to planting at the study site showed the following characteristics. The bulk density = 0.83 g/cm^3, Aggregate stability = 0.23, Soil pH= 8.54 (H_2O) and 7.56 (KCl), EC= 224 µS/cm, Soil organic C =0.72 %, NO_3^- =0.72 mg/kg, NH_4^+ = 0.12

mg/kg, Olsen P = 22.4 mg/l. The textural class of the soil can be classified as loam (Brady. 1974). These findings suggest that the experimental area was slightly alkaline with a low bulk density, Aggregate stability (AS), Organic carbon, mineral nitrogen content, PMN and adequate available phosphorus (Table 3.1).

Table 3.1: Selected soil properties at Syferkuil prior to trial establishment

Soil properties	Mean	Min	Max	SD
% clay	26.27	20.24	32.4	5.83
% silt	32.73	33.36	29.1	3.83
% sand	40.60	38.4	43.43	2.12
BD (g/cm^3)	0.83	0.81	0.83	6.51
AS (MWD)	0.23	0.17	0.33	0.04
pH (water)	8.54	7.71	8.85	0.27
pH (KCl)	7.56	7.01	7.87	0.29
EC µS/cm	244.22	101.40	497.00	102.43
OC %	0.72	0.04	2.27	0.66
Nitrate (mg/kg)	0.72	0.60	0.78	0.04
Ammonium (mg/kg)	0.12	0.01	0.03	5.62
Phosphorus (mg/l)	22.01	22.0	22.4	0.07
PMN µg N/g	0.12	0.02	0.09	0.17

BD-bulk density, MWD-mean weight diameter (aggregate stability), pH- potential hydrogen, EC-electrical conductivity, OC-organic carbon, P-phosphorus, PMN-potentially mineralisable nitrogen.

3.3.2 Interactive effects of water regimes and cropping systems on selected soil physical properties.

Bulk density and aggregate stability

The interaction between water regime and cropping system did not have a significant effect (p>0.05) on the bulk density. Water regime and cropping system did not have a significant effect (p>0.05) on bulk density. Bulk density ranged from 0.71 to 0.76 and 0.70 to 0.77 g/cm^3 in the irrigated and rainfed plots respectively (Table 3.2). The highest bulk density values were recorded in the sole mung bean stands for both the irrigated and the rainfed plots (Table 3.2). The interaction between water regime and cropping system had a significant effect ($p<0.05$) on the aggregate stability of the soil. The water regime did not have a significant effect ($p>0.05$). However, the cropping system had a significant effect ($p<0.05$) on the aggregate stability. Intercropping increased the aggregate stability of the soil in both the irrigated and the rainfed plot. Aggregate stability ranged from 0.11 to 0.15 in both irrigated and rainfed plots (Table 3.2)

Table 3.2: Interactive effects of water regime and cropping system on bulk density and aggregate stability.

Cropping system	Bulk density (g/cm^3)		Aggregate stability (MWD)	
	Irrigated	Rainfed	Irrigated	Rainfed
SM	0.71^{a}	0.70^{a}	0.14^{c}	0.11^{ab}
SC	0.71^{a}	0.73^{a}	0.11^{ab}	0.12^{ab}
SMB	0.76^{a}	0.77^{a}	0.12^{ab}	0.11^{a}
MC	0.72^{a}	0.71^{a}	0.14^{c}	0.13^{bc}
MMB	0.71^{a}	0.72^{a}	0.15^{c}	0.15^{c}
P values				
WR	0.83		0.053	
CS	0.087		<0.01	
WR×CS	0.978		0.046	
CV (%)	4.99		7.91	

SM=Sole maize, SC-Sole chickpea, SMB-Sole mungbean, MC-Maize intercropped with chickpea, MMB-Maize intercropped with mungbean. WR= water regime, CS= cropping system. Values followed by different letters within a column indicate significant differences at $p< 0.05$ according to the Duncan's multiple range test.

3.3.3 Interactive effects of water regime and cropping system on selected soil fertility variables.

Soil pH

The interaction between water regime and cropping system did not have a significant effect on the pH (H_2O) and pH (KCl). The cropping system did not have a significant effect ($p>0.05$) on pH (H_2O) and pH (KCl) whilst water regime did not have a significant effect ($p>0.05$) on the pH (H_2O) and pH (KCl). Both pH (H_2O) and pH (KCl) were generally higher in the rainfed plot relative to the irrigated plot (Table 3.3). In the irrigated plot. The highest pH (H_2O) and pH (KCl) were recorded in the maize intercropped with chickpea stand. On the contrary in the rainfed plot the highest pH (H_2O) and pH (KCl) were observed in the sole chickpea stands. The pH (H_2O) ranged from 8.39 to 8.99 in the irrigated plot and 8.95 to 9.16 in the rainfed plot. The pH (KCl) ranged from 7.87 to 8.03 in the irrigated plot and 7.76 to 7.93 in the rainfed plot (Table 3.3).

Table 3.3: The interactive effects of water regime and cropping system on soil pH in H_2O and KCl.

	Soil pH			
Cropping system	pH (H_2O)		pH (KCl)	
	Irrigated	Rainfed	Irrigated	Rainfed
SM	8.48^{ab}	9.06^{bc}	7.87^{a}	7.78^{a}
SC	8.95^{abc}	9.16^{c}	7.86^{a}	7.93^{a}
SMB	8.39^{a}	9.05^{bc}	7.93^{a}	7.93^{a}
MC	8.99^{abc}	9.03^{abc}	8.03^{a}	7.85^{a}
MMB	8.86^{abc}	8.95^{abc}	7.90^{a}	7.76^{a}
P values				
WR	0.094		0.28	
CS	0.37		0.52	
WR×CS	0.40		0.59	
CV (%)	3.97		1.86	

SM=Sole maize, SC-Sole chickpea, SMB-Sole mungbean, MC-Maize intercropped with chickpea, MMB-Maize intercropped with mungbean. WR= water regime, CS= cropping system. Values followed by different letters within a column indicate significant differences at $p<0.05$ according to the Duncan's multiple range test.

Electrical conductivity (EC)

The interaction between water regime and cropping system showed an insignificant effect ($P>0.05$) on the EC. Water regime did not have a significant effect on the EC similarly as the cropping system ($p>0.05$). Intercropping maize and chickpea resulted in a higher electrical conductivity in the irrigated plot and in the rainfed plot. The highest

EC was recorded in the sole maize stand (Table 3.4). The lowest EC was recorded in the sole mungbean and sole chickpea for the irrigated and the rainfed plot respectively.

Table 3.4: The interactive effects of water regime and cropping system on electrical conductivity (EC).

	EC (µS/cm)	
Cropping system	Irrigated	Rainfed
SM	263.3^{a}	278.3^{a}
SC	229.5^{a}	191.2^{a}
SMB	200.6^{a}	275.4^{a}
MC	283.4^{a}	219.4^{a}
MMB	214.0^{a}	217.7^{a}
P values		
WR	0.87	
CS	0.78	
WR×CS	0.51	
CV (%)	37.60	

SM=Sole maize, SC-Sole chickpea, SMB-Sole mungbean, MC-Maize intercropped with chickpea, MMB-Maize intercropped with mungbean. WR= water regime, CS= cropping system. Values followed by different letters within a column indicate significant differences at $p<0.05$ according to the Duncan's multiple range test.

Organic carbon (OC)

The interaction between water regime and cropping system resulted in a significant effect ($p<0.05$) on OC. The water regime had a significant effect ($p<0.05$) on OC, however, cropping system did not have a significant effect ($p>0.05$) on the OC. Intercropping maize with mungbean resulted in a significantly higher, with the highest OC being recorded in the irrigated MMB plot. Organic carbon was lower in sole mungbean and sole chickpea in the irrigated and the rainfed plot respectively. Organic carbon ranged from 1.68 to 3.64 % in the irrigated plot and 0.30 to 1.58 % in the rainfed plot (Table 3.5).

Table 3.5: The interactive effects of water regime and cropping system on the organic carbon (OC).

	Organic carbon (%)	
Cropping system	Irrigated	Rainfed
SM	1.69^{abc}	0.45^{ac}
SC	1.68^{abc}	0.58^{abc}
SMB	1.77^{bc}	0.30^{a}
MC	2.12^{c}	1.48^{abc}
MMB	3.64^{d}	1.58^{ab}
P values		
WR	0.044	
CS	0.071	
WR×CS	0.028	
CV (%)	46.61	

SM=Sole maize, SC-Sole chickpea, SMB-Sole mungbean, MC-Maize intercropped with chickpea, MMB-Maize intercropped with mungbean. WR= water regime, CS= cropping system. Values followed by different letters within a column indicate significant differences at $p<0.05$ according to the Duncan's multiple range test.

Phosphorus and phosphorus uptake

The interaction between water regime and cropping system had a significant effect ($p<0.05$) on the phosphorus content (Table 3.6). The factors also had a significant ($p<0.05$) effect individually on the phosphorus content in the soil. The highest phosphorus content was recorded in the sole maize stand of the irrigated plot. Intercropping maize with chickpea resulted in a significantly higher phosphorus content in the rainfed plot. Phosphorus content in the soil ranged from 11.50 to 26.20 mg/l in the irrigated plot and from 20.00 to 22.40 mg/l in the rainfed plot.

The interaction between water regime and cropping system showed a significant effect ($p<0.05$) on phosphorus uptake. Water regime had a significant effect ($p<0.05$) on phosphorus uptake. Similarly cropping system showed a significant effect on phosphorus uptake. Phosphorus uptake ranged from 18.4 to 674.1 kg/ha in the irrigated plot and from 18.0- 489.6 kg/ha in the rainfed plot (Table 3.6). Maize and chickpea intercropping resulted a higher phosphorus uptake in both the irrigated and rainfed plot.

Table 3.6: Interactive effects of water regime and cropping system on phosphorus and phosphorus uptake.

Cropping system	Phosphorus (mg/l)		Phosphorus uptake (kg/ha)	
	Irrigated	Rainfed	Irrigated	Rainfed
SM	26.20^{f}	20.00^{c}	652.6^{h}	368.4^{d}
SC	20.60^{c}	20.60^{c}	117.3^{c}	104.8^{b}
SMB	11.50^{a}	20.40^{e}	18.4^{a}	18.0^{a}
MC	23.70^{e}	22.40^{d}	674.1^{i}	489.6^{f}
MMB	13.90^{b}	21.80^{d}	554.0^{g}	387.1^{e}
P values				
WR	<0.001		<0.001	
CS	<0.001		<0.001	
WR×CS	<0.001		<0.001	
CV (%)	2.53		1.43	

SM=Sole maize, SC-Sole chickpea, SMB-Sole mungbean, MC-Maize intercropped with chickpea, MMB-Maize intercropped with mungbean. WR= water regime, CS= cropping system. Values followed by different letters within a column indicate significant differences at $p < 0.05$ according to the Duncan's multiple range test.

3.3.4 Interactive effects of water regime and cropping system on selected soil nitrogen dynamics.

Potentially mineralisable nitrogen (PMN)

The interaction between water regime and cropping system did not show a significant effect ($p>0.05$) on the PMN. Individually the factors water regime and cropping system had a significant effect ($P<0.05$) on the PMN. Potentially mineralisable nitrogen was generally higher in the irrigated plot compared to the rainfed plot (appendix 3.8). Potentially mineralisable nitrogen ranged from 0.12 to 0.27 µg N/g in the irrigated plot and from 0.10 to 1.3 µg N/g in the rainfed plot. The PMN in the study was higher in the intercropped stands compared to the sole stands for both the legumes. The lowest PMN was recorded in the rainfed sole maize stand (Figure 3.2).

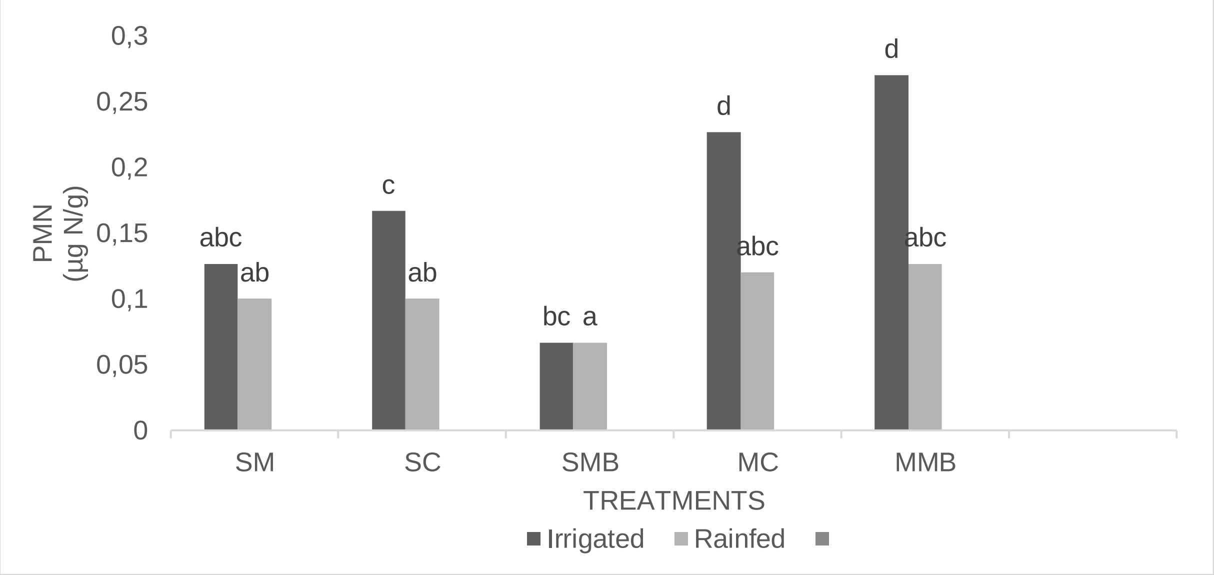

Figure 3.3: Effects of water regime and cropping system on potential mineralisable nitrogen.

Biological nitrogen fixation (BNF)

The interaction between water regime and cropping system had a significant effect ($p<0.05$) on the BNF (Figure 3.4). Individually, both factors were significant on BNF. Chickpea fixed a significantly higher amount of nitrogen from the atmosphere compared to mungbean. Intercropping insignificantly increased the amount of nitrogen fixed in the irrigated plot for both chickpea and mungbean. In the rainfed plot.

Intercropping significantly increased the amount of nitrogen fixed by chickpea and insignificantly decreased the amount of nitrogen fixed by mungbean.

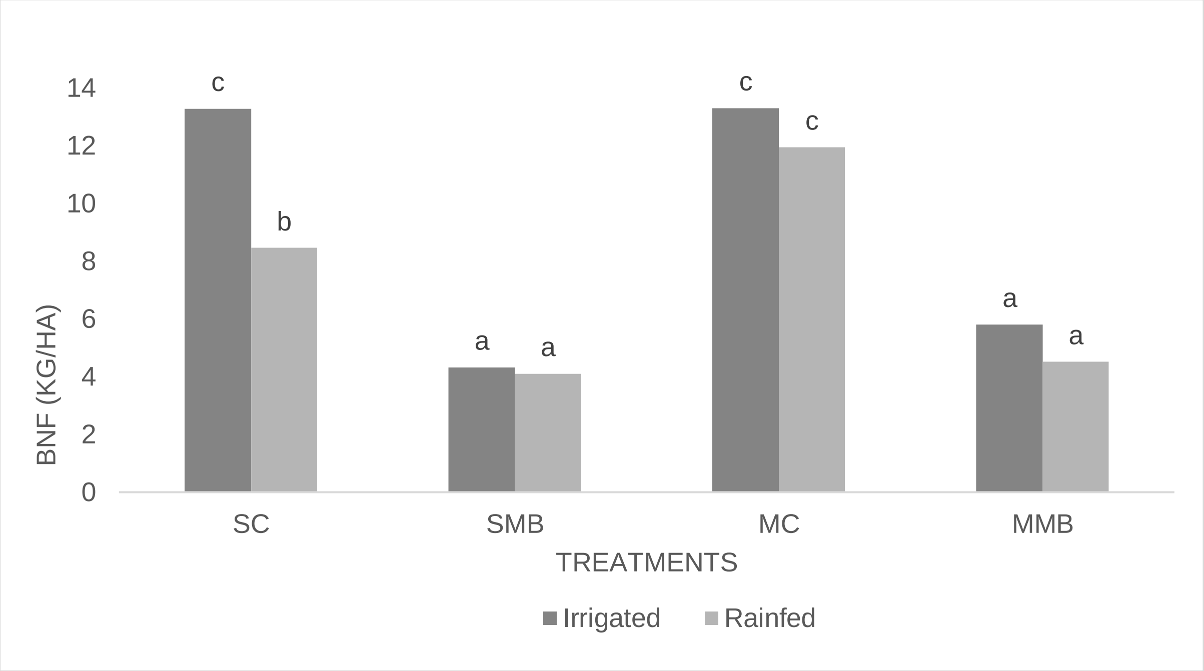

Figure 3.4: Interactive effects of water regime and cropping system on BNF.

Nitrogen uptake

The interaction between water regime and cropping system had a significant effect ($p<0.05$) on the nitrogen uptake. Water regime and cropping system individually had a significant effect ($p<0.05$) on the nitrogen uptake (appendix 3.10). Nitrogen uptake ranged from 1.23 to 74.33 kg/ha in the irrigated plot and from 1.54 to 53-80 kg/ha in the rainfed plot. The uptake of nitrogen from the soil was higher in the sole maize stand for the irrigated plot and maize intercropped with chickpea in the rainfed plot. Nitrogen uptake was significantly lower in the pure stands of two legumes in both the irrigated and the rainfed plot (Figure 3.5).

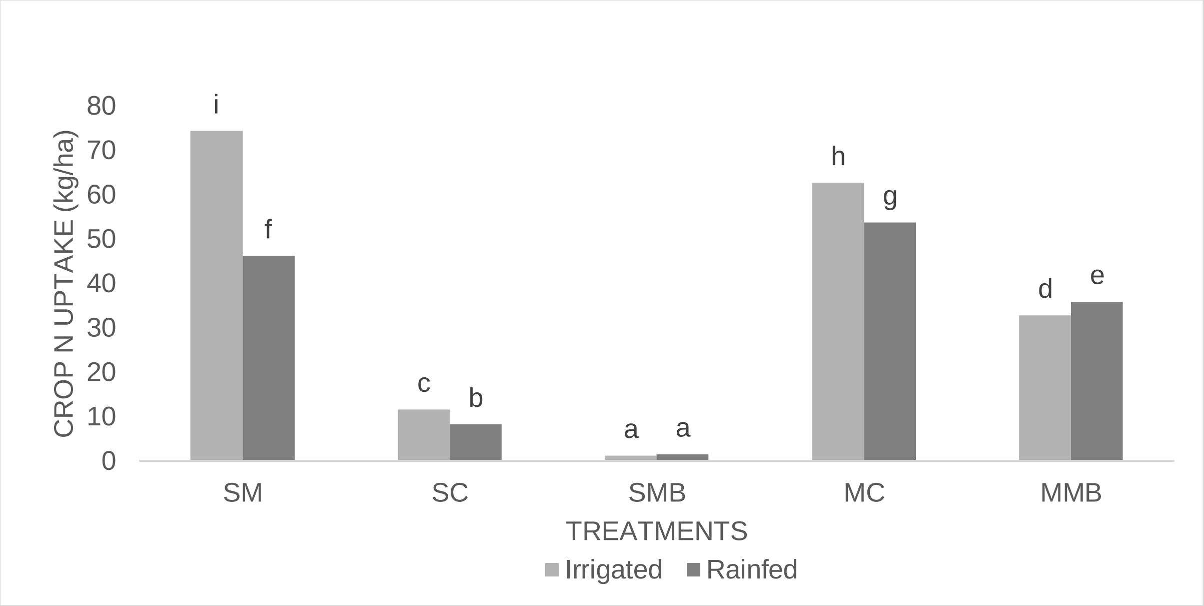

Figure 3.5: Interactive effects of water regime and cropping system on nitrogen uptake.

Residual nitrogen

The interaction between water regime and cropping system did not have a significant effect (p>0.05) on the residual nitrogen in the soil. Water regime did not have a significant effect (p>0.05) on the residual nitrogen similar to cropping system (appendix 3.11). Residual nitrogen ranged from 0.76 to 1.34 mg/kg in the irrigated plot and from 0.10 to 1.66 mg/kg in the rainfed plot. Residual nitrogen was higher in the intercropped stands under both irrigation regimes compared to the sole stands (figure 3.5).

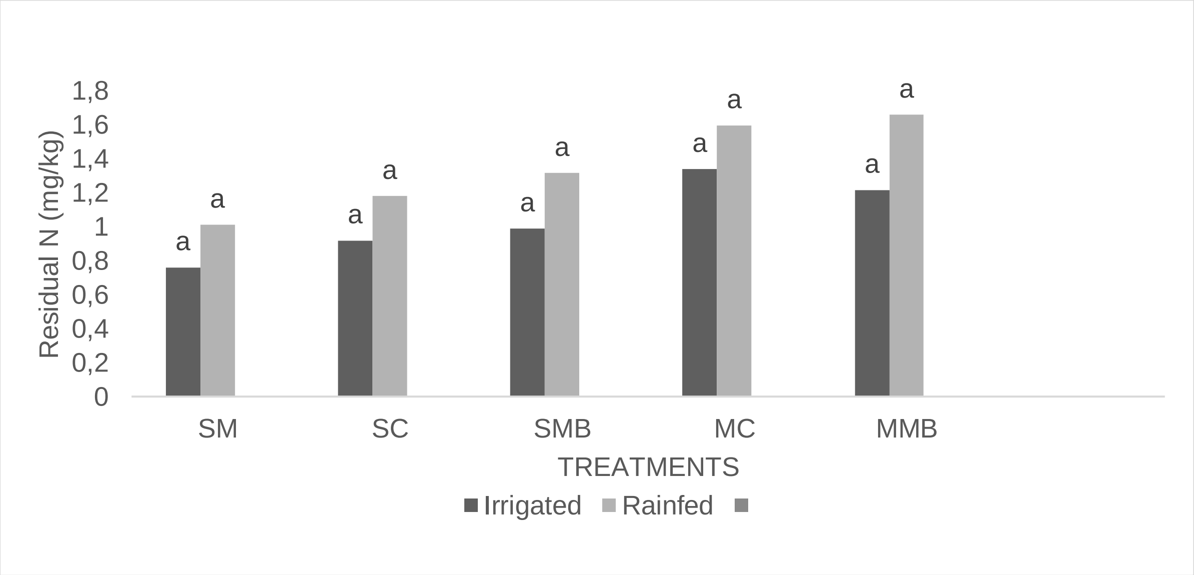

Figure 3.6: Effects of water regime (a) and cropping system (b) on residual nitrogen.

Nitrogen leaching

The interaction between the cropping system and the water regime showed significant effect (p<0.05) on the leaching of nitrogen. Water regime did not have a significant effect on leaching similar to cropping system (p>0.05) (appendix 3.12). The amount of nitrogen leached below the active root zone was higher in the irrigated plot compared to the rainfed plot for all the treatments. The amount of leached nitrogen ranged from 0.84 to 2.76 in the irrigated plot and from 0.48 to 0.93 in the rainfed plot. The highest amount of leached nitrogen was recorded in the irrigated sole maize stand (Figure 3.6).

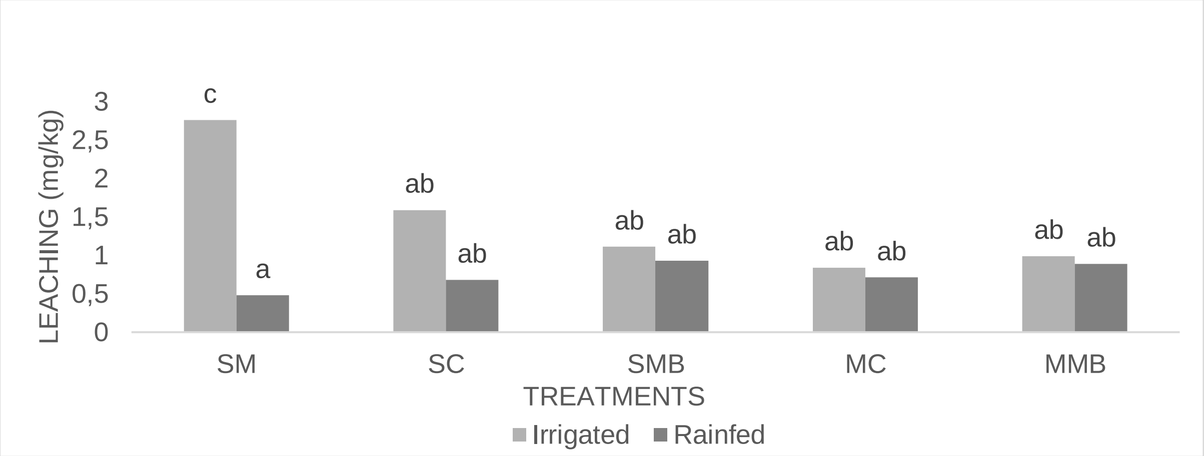

Figure 3.7: Interactive effects of water regime and cropping system on nitrogen leaching.

Correlation between nitrogen dynamics and the selected soil fertility variables.

The Pearson correlation showed the relationship between the nitrogen dynamics and the soil fertility variables. Residual nitrogen did not show a significant correlation (p>0.05) with the soil fertility variables. There was an insignificant, negative relationship between bulk density and residual nitrogen, PMN and nitrogen uptake. Aggregate stability showed a significant, positive relationship with PMN and nitrogen uptake. Organic carbon and PMN depicted a moderate positive correlation (0.60). Potentially mineralisable nitrogen showed a positive moderate correlation (0.44) with aggregate stability and phosphorus uptake (0.48). Nitrogen uptake also showed a positive moderate correlation with aggregate stability (0.51) and phosphorus content (0.48). Phosphorus uptake showed a moderate and strong relationship with PMN and nitrogen uptake respectively (0.48). Nitrogen uptake correlated strongly with phosphorus uptake (0.94). Biological nitrogen fixation (BNF) and nitrogen leaching did not show a significant correlation (-0.15).

Table 3.7: Relations between soil nitrogen dynamics and soil fertility variables as affected by water regime and intercropping

Nitrogen dynamics	Bulk density	Aggregate stability	pH (H_2O)	pH (KCl)	EC	OC	Phosphorus	P uptake
Bulk density	1.00							
Aggregate stability	-0.10	1.00						
pH (H_2O)	0.05	-0.04	1.00					
pH (KCl)	0.03	0.15	0.35	1.00				
EC	0.12	0.11	0.01	-0.02	1.00			
OC	-0.11	0.36	-0.23	-0.06	-0.08	1.00		
Phosphorus	-0.10	-0.01	0.22	-0.03	0.21	**-0.40**	1.00	
P Uptake	-0.35	**0.68**	-0.04	-0.00	0.11	0.34	0.32	1.00
PMN	-0.33	**0.44**	-0.17	0.10	0.03	**0.60**	-0.34	**0.48**
BNF	-0.35	-0.14	0.29	0.14	0.00	0.04	-0.01	**0.46**
N Uptake	-0.36	**0.51**	-0.05	-0.06	0.14	0.12	0.02	**0.48**
Residual N	-0.28	0.16	-0.02	-0.15	-0.19	-0.18	0.10	0.07
Leaching	-0.06	0.16	-0.25	0.10	0.15	0.03	0.25	0.20

3.4 Discussion

3.4.1 Pre-existing soil conditions at the study site

Initial soil analyses showed that the experimental area had a low mineral nitrogen and organic carbon content. Crop production in such areas requires management practices that improve soil fertility and minimize soil degradation. The loam textured soil with slight alkaline pH is suitable for the solubility and availability of major essential nutrients such as nitrogen and phosphorus. The pre-existing soil conditions at the experimental site render the location suitable for the practice of cereal and legume intercropping, as the practice has proven to improve soil nutrient status, organic matter decomposition and soil aggregation (Dugassa, 2023).

3.4.2 The effects of maize/legume intercropping on soil physicochemical properties: Bulk density, aggregate stability, soil pH, electrical conductivity, organic carbon, phosphorus and phosphorus uptake.

Literature has reported contrasting views to the observed bulk density trend by reporting a lower bulk density due to the incorporation of legume residues and increased decomposition as a result of integrating legumes into the intercropping system (Layek *et al*., 2018). Ganeshamurthy *et al*. (2006), observed a decline in bulk density as a consequence of incorporating mungbean in a rice-wheat-mungbean intercropping mixture. Contrary to findings Begam *et al*. (2020), an increase in bulk density when intercropping maize with soybean was. The higher bulk density trend can be linked to the reduced residue supply in the sole mungbean stand which influences organic matter content and ultimately the bulk density of the soil.

Intercropping resulted in an insignificant increase in aggregate stability in both legume crops for both main plots, which can be credited to addition of organic matter from the incorporation of legumes. According to Layek *et al*. (2018), incorporating legumes in crop diversification enhances SOM which improves soil aggregation. A positive relationship between OC and aggregate stability, r=0.36 was observed. Similarly, Garland *et al*. (2017) reported a 52% increase in the proportion of macro aggregates as a result of incorporating legumes into the intercropping system in comparison to sole crops. The observed soil pH (H_2O) did not show a significant difference amongst the treatments in both plots (Table 3.4). The highest pH (H_2O) was recorded in the maize/chickpea and sole chickpea for the irrigated and rainfed plots respectively, a trend that was similar for the pH (KCl). The findings observed in the irrigated plot are supported by the study conducted by (Hailu and Geremu, 2021). Their study revealed a soil pH increase in a sorghum and cowpea intercropping mixture compared to their sole counterparts. Tang *et al*. (2020) also observed an increase in soil pH when intercropping Cassava and peanut. In the rainfed plot intercropping resulted in lower soil pH. The increase in soil pH can also be associated with substances secreted by the chickpea crop such as malic acid which has shown the ability to increase soil pH. The reason for the decrease in pH as a result of intercropping can be associated with the process of acidification. According to Betencourt *et al*. (2012), the incorporation of legume crops in an intercropping system can trigger acidification as a result of the protons that are released by legume crops during the process of N_2 fixation. A similar trend was observed by Tilahun (2007) who found a lower soil pH after maize/haricot intercropping.

On average the irrigated plot recorded a slightly higher EC compared to the rainfed plot. According to Mirzakhaninafchi *et al*. (2017), sufficient moisture is essential for the movement of ions thus influencing the measured EC. Their study showed a significant positive relationship between soil moisture and electrical conductivity. The range of EC at the study site was classified as non-saline. The observed variations in EC amongst the treatments can be associated with nutrient content. The highest EC was recorded in the maize/chickpea stand in the irrigated plot, coincidentally this stand also had a high nitrogen content. According to Shi *et al*. (2009), nitrate concentration is one of the factors influencing soil EC.

Intercropping both chickpea and mungbean resulted in higher OC in the irrigated plot. Maize intercropped with chickpea in the irrigated plot had the greatest OC. A similar trend was reported by Begam *et al*. (2020), where organic carbon concentration increased from 27 to 37% and 38 to 53% with 20 cm soil depth intervals was recorded in a study intercropping maize and soybean. Legume residues are beneficial to the soil nutrient status because they expand soil organic matter (SOM). Organic carbon increase in intercropping can also be supported by the increase in biological biomass as a result of intercropping. This is also caused by the soil moisture content differences. According to Dugassa (2023), crop diversity increases SOM decomposition. This may be due to the residues having lower C: N ratio and greater litter input.

In the irrigated plot sole maize recorded the highest phosphorus content. Both legumes had a higher phosphorus content in their intercropped stands. Intercropping both legumes led to significantly greater phosphorus content in the rainfed plot. These results are in alignment with the ones observed by Betencourt *et al*. (2012), where an increase in phosphorus content was observed when intercropping durum wheat with chickpea. Similarly, Mugwe *et al*. (2011) reported an increase in phosphorus content when intercropping maize with cowpea. Belowground interactions alter the soil pH as a result of intercropping, this can increase phosphorus availability in the root zone and improve soil available nutrients.

Phosphorus uptake increased significantly in the maize/chickpea stands in both plots. The uptake of phosphorus by crops is mainly facilitated by root induced changes that influence phosphorus availability (Lalati *et al*., 2014). The outcome in this study is supported by the results of Li *et al*. (2016), who also found a 20% increase in total P acquisition when intercropping maize with faba bean when no phosphorus was applied to the soil. According to Li *et al*. (2014), legume crops have the ability to mobilize limited amounts of soluble P to benefit the associate cereal crop, thus increasing the total P uptake.

3.4.3 Effects of maize/legume intercropping on soil nitrogen dynamics: Potential mineralisable nitrogen (PMN), biological nitrogen fixation (BNF), Nitrogen uptake, residual nitrogen and leaching.

Nitrogen mineralisation

The highest nitrogen mineralisation was recorded in the intercropped sub plots for both the irrigated and the rainfed plots. The increase in nitrogen mineralisation can be linked to the increase in nitrogen supply. This can be due to the addition of N-rich residues from the legume crops. Similarly, Regehr *et al*. (2015), recorded a greater nitrogen mineralisation integrating maize with soybean in comparison to when grown solely. The increase in nitrogen mineralisation as a result of intercropping can also be associated with the increase in microbial activity. Intercropping stimulates interspecific interactions which influences the transformation of nitrogen by regulating microbial activity and diversity (Lian *et al*., 2019) which could have been the case in the current study. The different maize and legume ratios involved in intercropping can increase nitrogen content. The combination of these residues results in a complex interaction that facilitates the mineralisation process (Redin *et al*., 2014). Contrary to this Nyawade *et al*. (2020), observed a higher nitrogen mineralisation in sole legume treatments in comparison to the intercrops. Nyawade *et al*. (2020), argued that legumes improve nitrogen mineralisation and supply by providing residues that are high in nitrogen when grown solely. In this study, both legumes recorded a higher nitrogen mineralisation compared to sole maize in the irrigated plot. Contrary to the mineralisation pattern in the rainfed plot where sole maize showed higher nitrogen mineralisation compared to the sole legumes.

These findings can be supported by the increased organic carbon levels in the intercropped stands which suggests a greater organic matter abundance relative to the legume sole stands. A significant, positive correlation is seen between organic carbon and PMN, r=.64, p<0.001 (Table 3.7), which supports the activities from mineralising organisms. Dang *et al*. (2020), observed greater nutrient supply in the intercropped subplots in comparison to the sole crops when intercropping prosso millet with mungbean thus providing sufficient amounts of nutrients essential for bacterial growth. Significantly, the increase in organic compound content below ground can result in an increase in sources of carbon responsible for the growth of microorganism in the rhizosphere. This can facilitate change in the microbial structure in intercropped treatments.

The mineralisation in the rainfed plot was lower relative to the irrigated plot. This trend can be attributed to the moisture stress that inhibits maximum microbial activity from carrying out the mineralisation process. Optimum soil moisture is required for satisfactory microbial population and activity (Lei and Mcdonald, 2019). Mineralisation is a biotic process and requires an environment that encourages microbial population and activity. Soil moisture content controls decomposer activity and therefore facilitate the decomposition of plant residues and the mineralisation pattern (Guntiñas *et al*., 2012).

Biological Nitrogen Fixation

Generally, N_2 fixation was higher in the irrigated plot relative to the rainfed plot. This trend is a consequence of the variation in soil moisture content. According to Mhango (2011), inadequate moisture content can affect the biological nitrogen fixation process. Adequate soil moisture is a necessity for the process of nodulation and growth of the legume crop. Pimratch *et al*. (2008), conducted a study that showed that under drought stress conditions, the N_2 fixation by groundnut was reduced by 44-69%.

Chickpea generally had a higher nitrogen fixation relative to mungbean in both sole and intercropped stands under both irrigation regimes. The difference in fixation amounts between the two crops can be attributed to their differences in fixation abilities. According to Mhango (2011), the type of legume incorporated into the cropping system is one of the major factors that influence the process BNF. Nyawade *et al*. (2020), reported differences between dolichos and lima bean in an intercropping system, this was attributed to the variation in their genetic differences. Another factor influencing this trend could be the differences in N_2 fixing bacterial specie. Rhizobium and Bradyrhizobium are the dominant N_2 fixing bacterial species in chickpea and mungbean respectively, these species differ in their growth rate. This observation can also be linked to the difference in the length of growing period for the legume crop. According to Mhango (2011), growth duration is also a key factor in the process of nitrogen fixation. Mungbean was harvested firstly before chickpea and therefore has less time to fix substantial amount of nitrogen compared to chickpea. The accumulation of biomass by chickpea after mungbean was senesced can be a contributing factor to the difference in fixed N_2 between the legume crops.

N_2 fixation by chickpea was greater when intercropped with maize in contrast to when grown alone. These results agree with the ones by Nyawade *et al.* (2020), who observed a higher N fixation by intercropped legumes. This pattern of fixation was in response to the increase in competition for soil nitrogen. This increases the reliance of the legume crops on symbiotic N fixation. Alonso-Ayuso *et al*. (2014), also reported a similar trend when intercropping barley with vetch. The results of the study showed that the increased competition for soil nitrogen encouraged the vetch crop to depend on N_2 fixation to meet its nitrogen requirements, this resulted in the intercropped vetch accumulating large amounts of nitrogen compared to the sole vetch. Lithourgidis *et al*.

(2011), stated due to the complementarities caused by the interactions between the crop species, BNF is likely to be greater in legume intercrops relative to legumes separately. This is as a result of natural regulation mechanisms such as improved nitrogen capture facilitated by the complementarity in space and time. The observed BNF trend between the irrigated and rainfed plots can also be attributed to the soil pH in the respective plots. The active acidity in the irrigated plot ranged from 8.39-8.88 and 8.95-9.16 in the rainfed plot. According to (Bordeleau and Prévost, 1994), highly alkaline soils can reduce nitrogen fixation. The correlation between these was a positive, insignificant correlation.

Nitrogen uptake

Intercropping maize with the legumes led to significantly greater nitrogen acquisition relative to the sole legumes in both the irrigated and the rainfed plots. The shift in uptake can be attributed to facilitative root interactions between the intercropped crops such as nitrogen transfer. Similarly, Rodriguez *et al.* (2020) reported that the total soil derived nitrogen acquisition (cereal +legume) was significantly higher in intercrops in comparison to the legume crops grown solely. Total soil nitrogen uptake was 25 % higher in cereal and legume intercrops in contrast to the sole legumes. These findings highlight the fact that the intercropping practice facilitates complementary nitrogen use between the cereal and legume crops thus increasing nitrogen acquisition. According to Hauggard-Niesel *et al*. (2009), these results are strongly influenced by the legume crops. The results can be linked to the observed trend of biological nitrogen fixation. Intercropping increases the amount nitrogen derived from symbiotic nitrogen fixation as the dependency of the legume crop for atmospheric nitrogen and increases soil nitrogen uptake.

In the rainfed plot, maize intercropped with chickpea had a significantly higher nitrogen uptake compared to the other treatments. Rodriguez *et al*. (2020), reported a 54- 64% increase in cereal soil nitrogen uptake as a result of intercropping. Cereals acquire 61% more nitrogen from the soil when grown together with legumes compared to when grown separately. These findings can be associated with the increased plant biomass in these plots. Dang *et al*. (2020), found that intercropping proso millet with mungbean resulted in an increased nitrogen accumulation in the intercrops relative to their sole crops. According to Gaba *et al.* (2015), the complementarity between intercrops causes the cereal crop to recover more available soil nitrogen thus improving nitrogen use throughout the season in cereal/legume intercropping. This can also be associated with the change in microbial communities and structure resulting from the intercropping system.

The greater nitrogen uptake in the sole maize stand in contrast to when the crops were intercropped can be related to interspecific competition between the intercropped species for available nitrogen. The competition between the intercropped plant species can constrain nutrient uptake amongst the associated crops. The observed trend is similar to the one observed by Ben-chuan *et al*. (2022), who found a 46.6% nitrogen uptake per plant decrease in the intercrops compared with the corresponding monocultures when intercropping maize and peanut. This observation can further be linked to the decrease in biomass as a result of intercropping which affects the amount of nitrogen acquired by the different crop species. According to Zheng *et al*. (2022), nitrogen uptake increased from 31.7 to 45.4% in a maize and soybean strip intercropping system at the same time 7.4–12.2% increase was observed when maize was grown simultaneously with peanut. The findings can be supported by the high plant biomass in the irrigated sole maize.

The higher soil N acquisition by chickpea compared to mungbean can be related to the improved nitrogen fixation. The mechanism of N fixation directly affects nitrogen uptake (Nyawade *et al*., 2020). The ability of crops to acquire in any system varies depending on the type of specie. Acquisition in the irrigated plot was significantly higher than the one recorded in the rainfed plot. Moisture stress has an influence on the nitrogen uptake through diffusion and root development. According to Chtouki *et al*. (2022), the shortage of water flow through the soil roots has the potential to manifest as reduced nitrogen uptake by the crops.

Residual Nitrogen

Residual nitrogen is inorganic nitrogen that is left in the field after harvesting (Nyawade *et al*., 2020). Sole maize recorded the lowest residual nitrogen in both the irrigated and the rainfed plots. The decrease in residual nitrogen in the sole maize stands can be attributed to low nitrogen supply in the stands. Kebede (2021), stated that cereal crops tend to have a lower residual nitrogen that might benefit the succeeding crop due to their higher C:N ration in their residues compared to the associated legume crops.

The increased residual nitrogen in the intercropped stands can be associated with the increased nitrogen supply from the nitrogen rich legume residues. A portion of the nitrogen fixed through biological nitrogen fixation is left in the soil and can be used by the crops in the following season through the processes of decomposition and mineralisation, resulting in more mineral nitrogen (Thilakarathna *et al*., 2016). Nitrogen that is derived from the rhizo-deposits of legumes contribute 35–44% to the soil residual nitrogen content. These findings are in alignment with the ones observed by Nyawade *et al*. (2020), where a higher residual nitrogen in the lower highland in the sole legume plots relative to the intercropped plots. The observed trend of residual nitrogen at harvest can be supported by the BNF findings of the legume crops. According to Kebede (2021), the improved nitrogen fixation can result in an increase in residual nitrogen. This forms part of the organic matter content and can serve as an inexpensive nutrient for the succeeding crops.

Leaching

The greater nitrogen leaching in the irrigated plot relative to the rainfed plot is caused by the increased water movement through the soil profile. Nitrate is highly mobile in the profile. Jehan *et al*. (2020), stated that nitrogen leaching increases in the soil profile as water percolation increases. The increased nitrogen leaching in the irrigated plot can be associated with the greater mineralisation in the plot relative to the rainfed plot. An increase in net N mineralisation increases available mineral nitrogen in the profile which can then lead to an increase in nitrogen leaching (Turner *et al*., 2010).

Nitrogen leaching was greater in the sole maize, followed by sole legumes then the intercropped stands. This observation can be explained by the complementary function between the intercrops which facilitates an improved use of the available mineral nitrogen. Intercropping can help decrease the risks associated with nitrate leaching compared crops grown separately due to complementary of mineral nitrogen by the cereal and legume crops in the system (Hauggaard-Nielsen *et al*., 2003). According to Frimpong *et al*. (2012), the competition between the intercrops may cause immediate nitrogen immobilization simultaneously delaying net mineralisation thus reducing potential nitrogen loss from the system.

Jensen *et al*. (2020) showed that specie diversification can be beneficial in lowering nitrogen leaching by 10–16% as opposed to when crops are grown separately.

Nyawade *et al*. (2020), also reported that legume intercrops enhance the recovery of leached nitrogen utilising their extensive root system. In addition to the improved use of nitrogen resources the crop residues of the associated intercrops have a C:N ratio that is less favourable to mineralisation and consequently results in a less risk of nitrogen loss to leaching in comparison to their sole counterparts. Similarly, Mariotti *et al*. (2015) observed lower leaching of nitrogen in the intercropped stands as opposed to when the crops were grown solely in a field study intercropping barley with filed bean. Field bean grown solely had the highest amount of nitrate leaching. The intercropping of spring barley with pea reduced NO_3^- leaching in contrast to barley grown solely (Pappa *et al*., 2011).

3.5 Conclusion

The findings of the study provide insight on the possibility of using cereal and legume intercropping as an integrated nutrient management technique. Overall, intercropping showed a great impact on the soil fertility and the selected nitrogen dynamics. Intercropping proved to have a positive effect on BNF, nitrogen mineralisation, leaching and residual nitrogen. Chickpea fixed a greater amount of atmospheric nitrogen relative to mungbean. Incorporating legumes resulted in greater nitrogen mineralisation, and residual N. The observed synchrony between nitrogen uptake and mineralisation suggest intercropping cereal crops with legumes can be a sustainable way of achieving a higher nitrogen use efficiency. Intercropping showed significant influence on the different nitrogen dynamics, which invalidates our hypothesis.

CHAPTER 4

EFFECTS OF MAIZE/LEGUME INTERCROPPING SYSTEM ON PLANT GROWTH AND YIELD PARAMETERS.

4.1 Introduction

Crop diversification is gaining recognition globally as an approach to sustainably improve and maintain yields amongst farmers (Kammoun *et al.*, 2021). The cereal and legume intercropping species mixture is proving to be a potential lever in improving the efficiency of the system with regards to increasing crop production (Layek *et al.*, 2018). The positive interactions that take place between the plants as a result of mechanisms such as facilitation and complementarity induce a greater acquisition of available resources, therefore resulting in greater yields in contrast to sole cropping (Dordas *et al.*, 2012). The ability of associated species to use nutrients efficiently is essential in ensuring satisfactory levels of yield. Using available resources efficiently is critical as it threatens the soil fertility, stability of crop yields and the sustainability of the intercropping system. The mechanisms associated with intercropping influence the crop growth and development due to the alteration in the soil nutrient status (Matusso *et al.*, 2014).

Cereal and legume intercropping has been suggested as a potential low input agricultural management practice due to its proven ability to facilitate and improve nutrient and water use efficiency. This is achieved through rhizosphere interspecific interactions that also influence microbial activities (Chen *et al.*, 2018). The documented changes in the soil conditions influence crops differently depending on various factors. Therefore, this chapter investigates the effect of maize/legume intercropping on different growth and yield parameters under two different irrigation regimes (irrigated and rainfed) at the Syferkuil experimental farm.

4.2 Materials and methods

4.2.1 Study site description and research design

The study site and research design are similar to the ones outline in the previous chapter (chapter 3), with the exception of the number of treatments as the growth parameters in the intercropped crops are observed separately. The treatments used were as follows: SM-sole maize, SC-sole chickpea, SMB-sole mungbean, MC-maize intercropped with chickpea, C INTER-chickpea intercropped with maize, MMB-maize intercropped with mungbean and MUNG- mungbean intercropped with maize.

4.2.2 Cultural practices

All the cultural practices are similar to the ones mentioned in the previous chapter (chapter 3).

4.2.3 Data collection

Growth parameters

Chlorophyll content was determined on both the legume and maize leaves every two weeks after emergence using a patented chlorophyll concentration meter (MC-100). Plant height was recorded in centimetres (cm) as average height from ground to top of 4 plant using a measuring tape for both maize and legume crops in each subplot. A ruler was used to measure the length and width to obtain the leaf area. The number of seeds were determined as the average of 4 pods on a plant. The data about (chlorophyll content, leaf area and plant height) was recorded during three different growth stages (vegetative, flowering and maturity) at the study site, whilst the aboveground biomass was recorded at maturity.

Yield parameters

Maize and legume biomass was obtained by recording the weight of the above ground plant material. The samples were oven dried, and the net weight was obtained after drying at a temperature 60 °C for a period of 48 hours and expressed per unit area (g/m^2). The roots were separated from the above ground crop. The root biomass was recorded by removing excess soil from the roots and weighing the roots of both crops separately after oven drying. The grain yield could not be determined as a result of cob damage by monkeys.

4.2.4 Statistical analyses

The data were subjected to split plot analysis of variance (ANOVA) using the GenStat 20th Edition software. Mean separation for significant soil and plant variables was determined using the Waller Duncan’s Multiple Range Test at a probability level of 5% confidence interval.

4.3 Results

Chlorophyll content

The interaction between water regime and cropping system did not show a significant effect ($p>0.05$) on the chlorophyll content. Cropping system had a significant effect ($p<0.05$) while the water regime did not have a significant effect ($p>0.05$) on the chlorophyll content during the vegetative stage (appendix 4.1). The cropping system had a significant effect ($p<0.05$) on the chlorophyll content at the flowering phase whilst the water regime did not show a significant effect ($p>0.05$) on the chlorophyll content (appendix 4.2). At maturity the cropping systems showed a significant effect ($p<0.05$) on the chlorophyll content while the water regime did not have a significant effect ($p>0.05$) on the chlorophyll content (appendix 4.3). Chickpea chlorophyll content was higher in the rainfed plot compared to the irrigated plot for both sole and intercropped chickpea. Maize crops had a higher chlorophyll content in the rainfed plot for sole maize and maize intercropped with chickpea. The maize intercropped with mungbean had a higher chlorophyll content in the irrigated plot compared to the rainfed plot. Chickpea intercropped with maize had a higher chlorophyll content compared to sole chickpea in both the irrigated and rainfed plots. The chlorophyll content in mungbean was higher in the rainfed plot compared to the irrigated plot. Sole mungbean had a higher chlorophyll content compared to mungbean intercropped with maize (Figure 4.1).

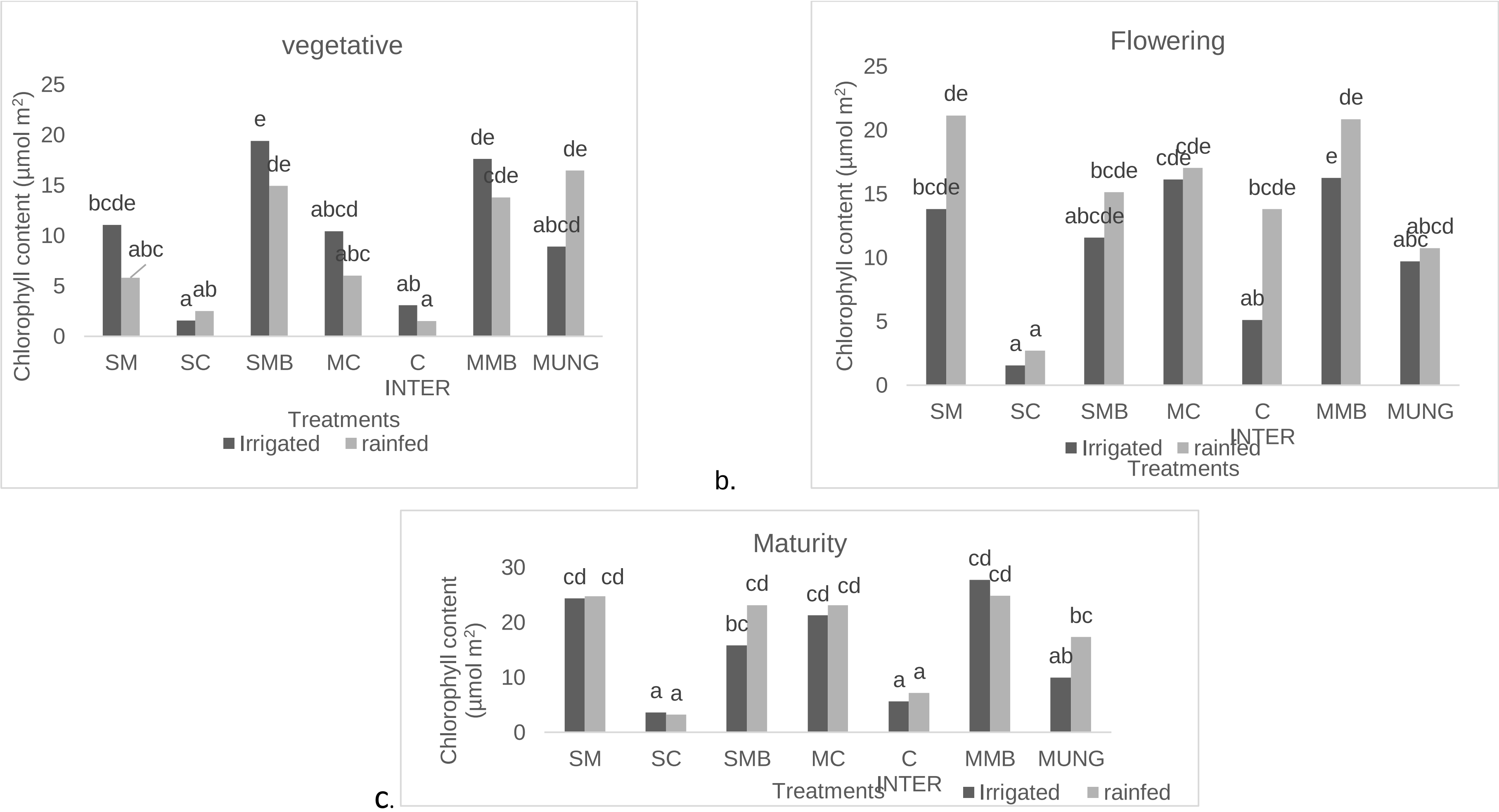

Figure 4.1: Interactive effects of cropping system and water regime on chlorophyll content at different growing stages (a) vegetative, (b) flowering and (c) at maturity.

Leaf area

The interaction between cropping system and water regime showed significant effect ($p<0.05$) on leaf area during the vegetative stage. Cropping system showed a significant effect ($p<0.05$) on the leaf area of the crops during the three growing stages. The average maize leaf area was greater in the irrigated plot in contrast with the rainfed plot for both the sole and intercropped subplots. Sole maize showed the highest leaf area compared to the intercropped maize in the irrigated plot. Maize/mungbean had the highest leaf area in the rainfed plot compared to sole maize. Chickpea had a higher leaf area in the rainfed plot compared to the irrigated plot. Chickpea leaf area was higher for the intercropped subplots compared to the sole grown chickpea. Mungbean leaf area was higher in the rainfed plot for the sole mungbean and higher in the irrigated plot for the intercropped mungbean. Sole mungbean had a lower leaf area compared to the intercropped mungbean in the irrigated plot contrastingly sole mungbean had a higher leaf area in contrast to intercropped mungbean in the rainfed plot (Figure 4.2).

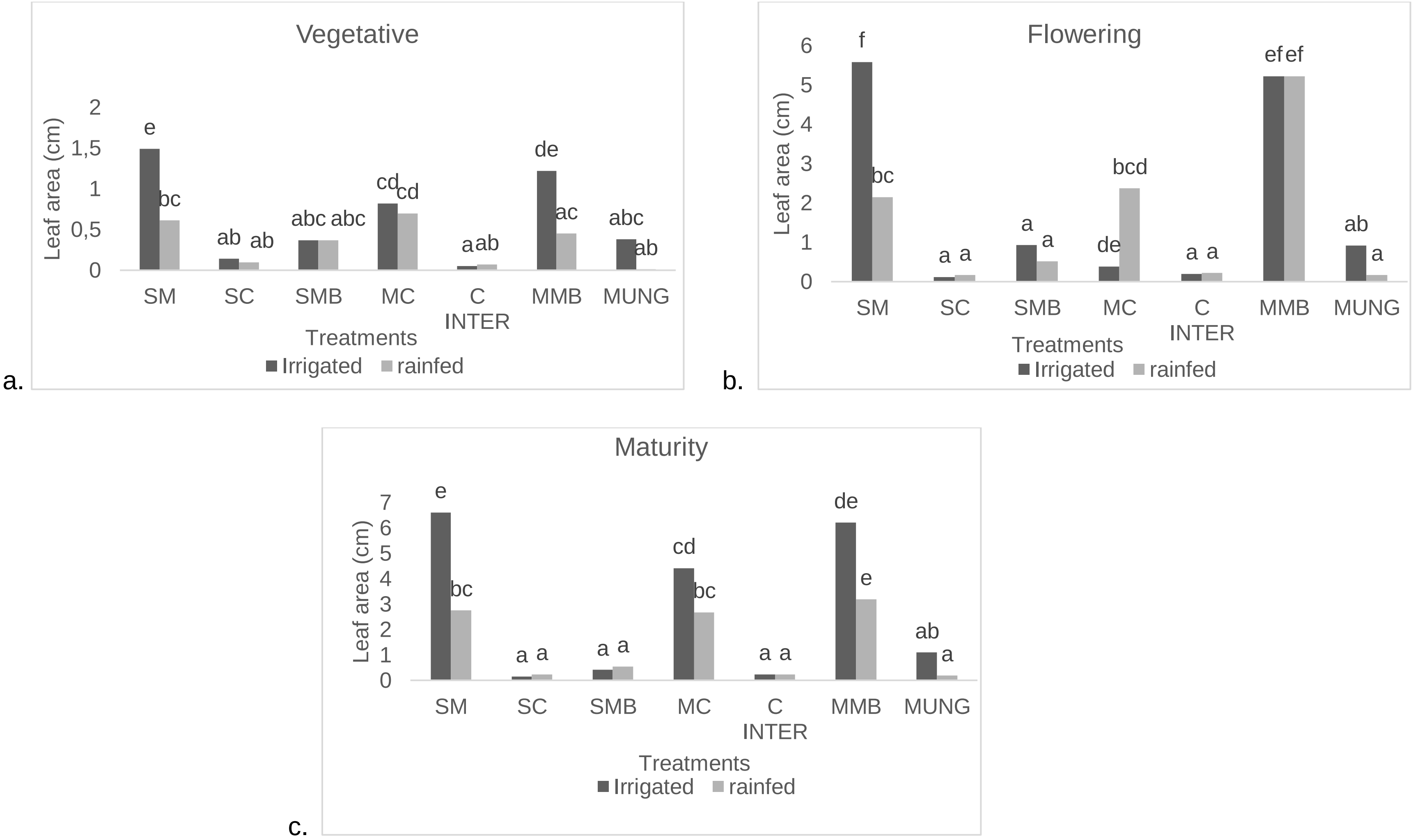

Figure 4.2: Interactive effects of cropping system and water regime on leaf area at different growing stages (a) vegetative, (b) flowering and (c) at maturity.

Plant height

The interaction between cropping system and water regime did not show significant effect ($p>0.05$) on plant height. Cropping systems did not have a significant effect ($p>0.05$) on plant height during the vegetative stage however, a significant effect ($p<0.05$) on the plant height was observed during the flowering and maturity stage. During both the flowering and maturity stage, water regime showed a significant effect ($p<0.005$) on the plant height whilst the effect of water regime on plant height at the flowering stage was no significant ($p>0.05$). The average plant height was greater in the irrigated plot during the vegetative and maturity stage in comparison to the rainfed plot. The opposite trend was observed during the flowering stage where the average plant height was greater in the rainfed plot contrasted to the irrigated plot. Maize height was greater in the irrigated plot in comparison to the rainfed plot in both sole and intercropped plots. The highest maize height was observed in the maize/mungbean intercropped plots in both the irrigated and rainfed plots. The height of chickpea was greater in the irrigated plot compared to the rainfed plot for sole chickpea and a contracting trend was observed for the intercropped chickpea. The average mungbean height was higher in the rainfed plot contrasted to the irrigated plot for the sole subplots. Intercropped mungbean was higher in the irrigated plot in comparison to the rainfed plot (Figure 4.3).

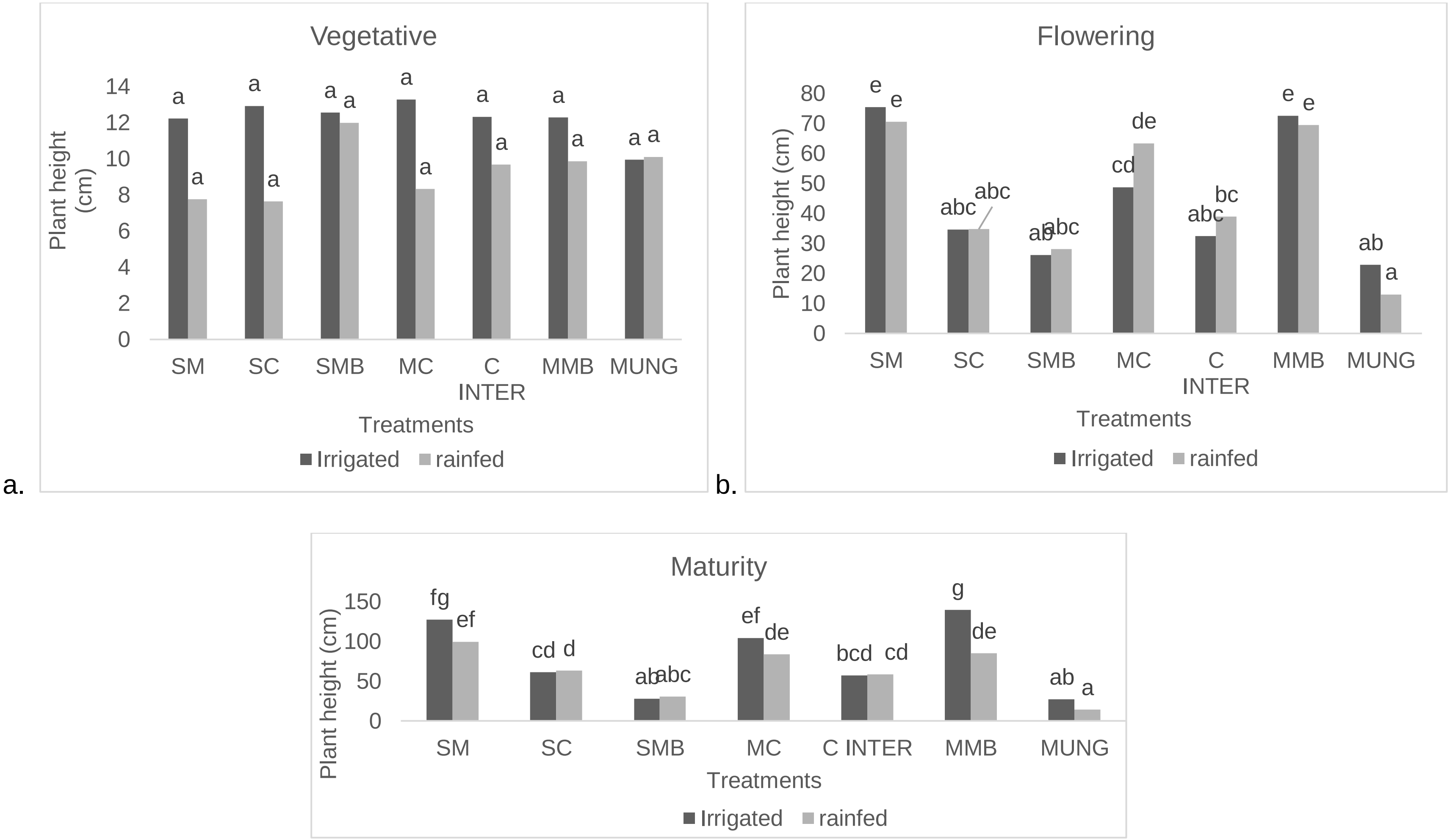

Figure 4.3: Interactive effects of cropping system and water regime on plant height at different growing stages (a) vegetative, (b) flowering and (c) at maturity.

Aboveground biomass

The interaction between regime and cropping system did not have a significant effect on the plant biomass ($p > 0.05$). Cropping system showed a highly significant effect ($p<0.01$) and water regime did not show a significant effect ($p>0.05$) on plant biomass. The plant biomass for the maize crops ranged from 170.97 to 273.29 g/m^2 in the irrigated plot and from 133.22 to 179.67 g/m^2 in the rainfed plot. The highest plant biomass was observed in the sole maize (273.29) sub plot for the irrigated plot and for the rainfed plot it was observed in the maize/chickpea (179.67) sub plot. Chickpea had the highest plant biomass in the irrigated plot for both sole and intercropped subplots (Figure 4.4). The highest plant biomass for mungbean for sole cropping was observed in the rainfed plots and the one for intercropped was observed in the irrigated plots. In totality the irrigated plot had a greater plant biomass compared to the rainfed plot.

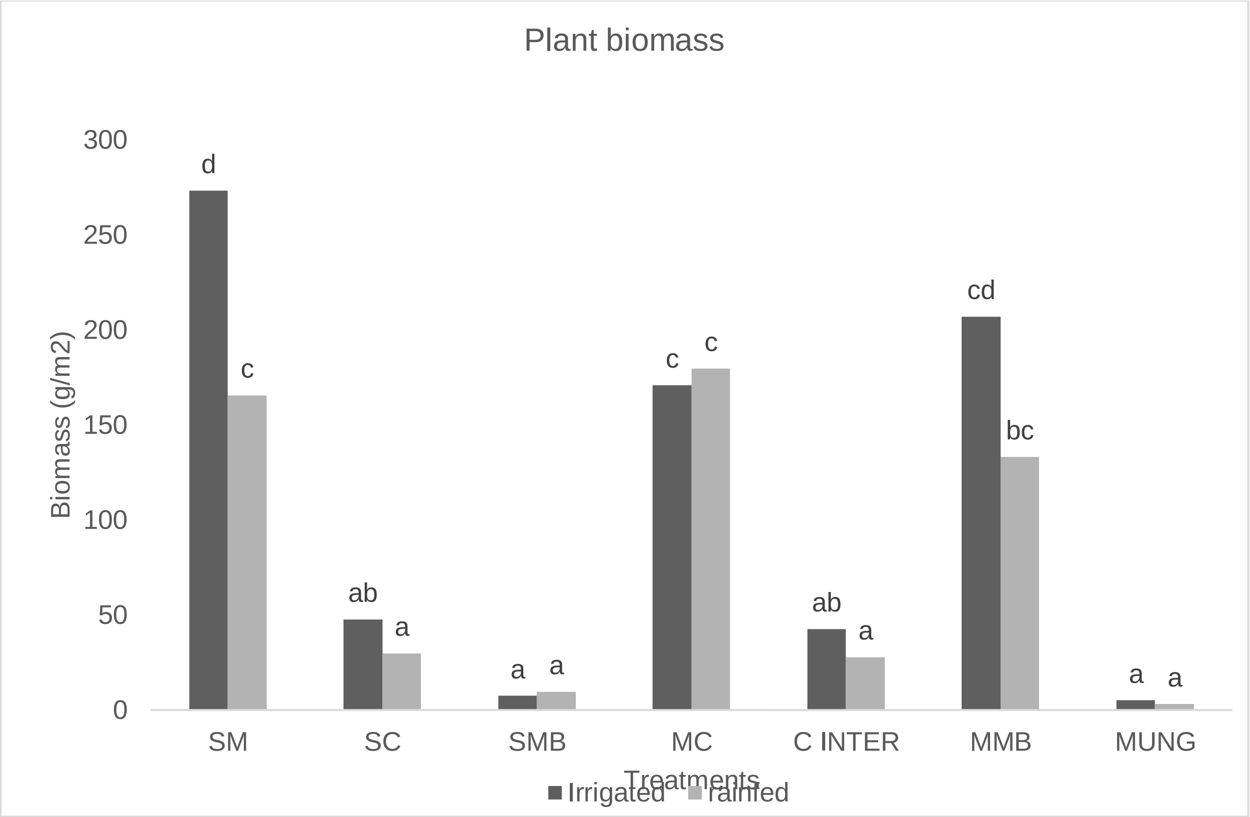

Figure 4.4: Interactive effects of cropping system and water regime on plant biomass.

4.4 Discussion

4.4.1 Interactive effects of cropping system and water regime on growth and yield parameters (Chlorophyll content, leaf area, plant height and plant biomass) of maize, chickpea and mungbean.

Chlorophyll content.

An increasing trend was observed for chlorophyll content during the different growing stages. The increasing chlorophyll content can be attributed to the applied nitrogen fertilizer to the soil. The nutrient levels in the soil have a significant influence on chlorophyll content (Li *et al*., 2018). The results contradict the outcome observed by Pandey *et al*. (2020), who recorded a consistent decrease in chlorophyll content towards maturity in a study intercropping maize with soybean. The results that were recorded for the chickpea align with the study of Pandey *et al*. (2020) where an increase was observed until 80 DAS then the chlorophyll content showed a decreasing trend at and after that stage. The consistent increase in chlorophyll content until maturity can be attributed to nitrogen content and soil moisture. The previous chapter showed that nitrogen content increased from the amount of nitrogen concentration prior to planting until maturity. Similarly, Wang *et al*. (2021) observed an upward trend in chlorophyll content and reached maximum at harvest stage. This was attributed an increase in mineral nitrogen content and soil moisture.

The chlorophyll findings concurred with the findings obtained by Nndwambi (2015), who observed the highest chlorophyll content in the intercropped stand in a study intercropping maize with pigeonpea. On the contrary, Dordas *et al*. (2012), findings recorded a higher chlorophyll content in the monocrop of barley compared to the intercropped stand. The highest chlorophyll reading for chickpea was recorded in the intercropped stand (13.8) during the flowering stage and for mungbean it was recorded in the sole stand (23.14) in the rainfed plot. The high chlorophyll content in the intercropped stand can associated with the nitrogen fixation which increased the mineral nitrogen. An increase in nitrogen fixation results in a higher nitrogen content and ultimately a higher chlorophyll content (Pandey *et al*., 2020). The high chlorophyll content in the sole stand can be caused by the minimal resource competition for nitrogen or soil moisture which are essential components of nitrogen during the growing season.

The low chlorophyll content for both maize and chickpea in the rainfed plot can be explained by the decreased soil moisture content. Drought stress has the ability to decrease chlorophyll which is caused by damage to the chloroplasts (Hailemichael *et al*., 2016). Moisture stress in leaves influences chlorophyll content by promoting the availability of chlorophyll and accelerating chlorosis (Li *et al*., 2018). The low chlorophyll content in the rainfed plot can also be attributed to lower nitrogen mineralisation which influences the quantity of mineral nitrogen. According to Chen *et al*. (2018), the intercropping of maize with peanut resulted in an increase in the affluence of organisms responsible for cycling nitrogen and other organisms that are beneficial in the rhizosphere. This process is largely affected by soil moisture content.

Leaf area

The lower leaf surface area in the rainfed plot can be attributed to the limited soil moisture availability which greatly influences nutrient uptake. There is a direct positive relationship between leaf area and the growing environment. The rainfed plot generally recorded lower nutrient uptake in comparison to the irrigated plot. Leaf area of a crop is influenced by nutrient and water use of the crop (Wang *et al*., 2012). The obtained findings contradict the results of Telkar *et al*. (2017), where higher maize leaf area was reported in the intercropped stands in a study conducted with maize and soybean. Similarly, Bilalis *et al.* (2010) concluded that intercropping with legumes caused increased leaf area than in their respective sole crops.

For the associated legume crops, mungbean had the highest leaf area in the intercropped irrigated plot at harvest. This trend aligns with the outcome of Telkar *et al*. (2017) who observed that the highest leaf area of soybean was found in the intercropped treatments. This is because intercropping has the tendency to efficiently facilitate the use of available resources resulting in the development of the crops accordingly. Contrastingly, Habte *et al*. (2016) reported a higher leaf area when growing sole bean as opposed to intercropping maize with bean. Chickpea recorded the same leaf area in both the sole and intercropped stand. An increase in chickpea leaf area as a result of intercropping was recorded in irrigated plot. This trend can also be related to the observed accumulation of essential nutrients such as nitrogen and phosphorus as a result of intercropping. According to Tian *et al*. (2018), soil nutrients affect the leaf area of the crop.

Plant Height

These results for the plant height trend can be linked to the moisture stress that slowed the growth of the maize crops in the rainfed plot. The two legume crops showed a significantly different influence on the growth of maize. Maize/ mungbean had superior growth compared to maize/chickpea under both irrigation regimes. The results can be attributed to the conducive growing environment that is created by the associated legume crop positively facilitating the growing process of the maize crop. The type of legume that is grown in cereal/legume intercropping plays a significant role in the success of the system in general (Layek *et al*., 2012). Mungbean has a shorter growing season compared to chickpea, therefore has significantly less competition for available resources with the maize crop at critical growing periods.

The results are supported by Telkar *et al*. (2017), where increased plant height when intercropping maize with soybean was recorded in comparison to their respective sole stands. Similarly, Musa *et al*. (2021) recorded a decrease in sorghum plant height because of mono cropping, with the highest plant height recorded when sorghum was grown intercropped with soybean. Intercropping caused an increase in soil mineral nitrogen, as it can be seen by the reported nitrogen mineralisation and residual nitrogen (figure 3.5). The superior maize plant height can be related to this improvement in soil nutrients. According to Amin *et al*. (2011), nitrogen increases the length and number of internodes, promotes the growth of plants and ultimately results in an increase in plant height.

According to Layek *et al*. (2018), combining cereal with legumes in conditions of limited resources can results in intensive competition which will reduce the growth and productivity of the associated legume crop due to their small stature. The tallest mungbean crop was found in the sole stand in the rained plot. The moisture stress did not influence the growth of the legume crops. Legume crops have a greater adaptability to available growing conditions. A similar trend was observed with regards to the growth of chickpea. The tallest chickpea crop was found in the rainfed plot in the sole stand. Intercropping showed a reduction in the growth of the associated legumes which can be attributed to the competitive effects between the crops.

According to Begam *et al*. (2020), the cereal crop is commonly favoured by having increased growth rate in cereal and legume intercropping. This is due to factors such as height advantage and a more extensive rooting system, which are favourable traits for competition with legumes.

Plant biomass

The intercropping yield advantage was observed in the rainfed plot where intercropping resulted in 8.43% increase in maize biomass however, when intercropped with mungbean the biomass of maize decreased by 19.60%. Intercropping does not guarantee increased crop yields because the benefits of intercropping system are largely influenced by different factors such as the choice of the intercropped species involved in the system, time of planting and maturity (Maitra *et al.*, 2020). Maize and mungbean showed positive yield when grown solely. Zhang *et al*. (2022), found that only wheat intercropped soybean increased the total biomass in a study that involved wheat. Corn, soybeans and pea. According to Matusso *et al*. (2014), in conditions where soil moisture is limited, water use efficiency (WUE) tends to be higher in intercrops compared to the sole stands resulting in reduced yield. Compared to chickpea, mungbean has a lower effective rooting depth therefore draws less water to support the growth of the associated maize crop.

The reduced biomass yield in the rainfed plot can be explained by the subjected moisture stress. According to Matusso *et al*. (2014), water availability is a determining factor factors for crop productivity in intercropping systems. Gao *et al*. (2019) also recorded a reduction in maize biomass regardless of nitrogen input when intercropping maize with peanut. The high maize biomass in the sole irrigated stand can be related to the high nitrogen uptake in the stand. According to Anas *et al*. (2020), nitrogen is essential in facilitating the growth and development of crops.

The decrease in yield can be explained by the increased nutrient acquisition competition between the crop species. This happens when the competitive effects in the systems are stronger that the facilitative effects. According to Tian *et al*. (2021), integrating legumes with cereal crops reduced the production of legumes by at least 20% compared to monocropped legumes. The cereal crop in a cereal and legume intercropping system tends to negatively influence the growth of the subsequent legume crop (Tian *et al*., 2021). This trend has been attributed to the height and extensive root system advantage possessed by cereal crops over legume crops. The extensive maize rooting system favours the crop in the competition for available water and the major nutrients. Hence a significantly higher mungbean yield reduction in the rainfed plot. Another reason for the decline in intercropped legume yield could be that maize had a negative shading effect on the subsequent legume crops, minimizing light interception and therefore reducing their growth (Bedoussac *et al.*, 2015).

4.5 Conclusion

In conclusion, the agronomic benefits of intercropping on different growth parameters were observed at the different growing stages. Intercropping increased chlorophyll content and plant height in maize, it also increased leaf area for the legumes and aboveground biomass for maize under rainfed conditions. In terms of yield, maize grown solely under irrigation performed superiorly compared to the other treatments. Irrigation can be recommended for ensuring maximum production. Implementing of the cereal and legume intercropping system requires careful attention to specific components for one to be able to acquire maximum potential when it comes to production. Below ground interaction induce changes that influence N transformations which influence growth and production.

CHAPTER 5

SUMMARY OF FINDINGS, SIGNIFICANCE OF FINDINGS, RECOMMENDATIONS AND CONCLUSIONS

5.1 Summary of findings

The study was investigating the effects of intercropping maize with legumes on nitrogen dynamics. The study also looked at how maize/legume intercropping, and different nitrogen fractions influence selected growth and yield parameters. These two objectives were investigated under two different irrigation regimes, irrigated and rainfed. The results on the nitrogen dynamics showed that incorporating legumes into the system caused nitrogen mineralisation to increase. The difference in soil moisture significantly affected the mineralisation process. Biological nitrogen fixation (BNF) was higher for chickpea in comparison with mungbean. The irrigated plot had a higher BNF compared to the rainfed plot, this increased as a result of intercropping both legume crops. Residual N increased in the rainfed plot compared to the irrigated plot. This was attributed to the high-water percolation in the irrigated plot, hence a higher nitrogen accumulation below the active root zone. Intercropping caused an increase in residual nitrogen in the intercropped stands under both moisture regimes. Nitrogen leached below the active rootzone was higher in the sole stands compared to the intercropped stands.

In relation to the growth parameters, maize recorded the highest chlorophyll content at maturity in the irrigated plot when intercropped with chickpea. Chickpea recorded the highest chlorophyll content during the flowering stage in the rainfed plot when intercropped with maize. Mungbean had the highest chlorophyll content in the rainfed plot at maturity in the sole stand. Sole maize recorded the highest leaf area in the irrigated plot at maturity. Intercropping resulted in an increase in leaf area for both chickpea and mung bean in the irrigated plot at maturity. Intercropping maize with mungbean led to higher plant height at maturity in the irrigated plot. Growing both chickpea and mungbean solely in the rainfed plot resulted in an increase in plant height. Maize plant biomass decreased as a result of intercropping in the irrigated plot while intercropping maize with chickpea increased maize biomass in the rainfed plot. The legumes grown solely yielded a higher plant biomass in both main plots.

5.2 Significance of findings

The findings of this study show that including legumes into the system resulted in improvements in soil fertility, with an increase in soil organic carbon and phosphorus content. The results also outlined an increase in nitrogen mineralisation, BNF, residual nitrogen, improved nitrogen acquisition while simultaneously reducing nitrogen leached below the active rootzone. This profiles maize/legume intercropping as a sustainable and cost-effective practice that can be used to maximize production while reducing the adverse effects of nitrogen on the environment. The results further showed how the different growth parameters are influenced by cropping system, water regime and nitrogen dynamics. It also showed how the different intercropping mechanisms such as facilitation, complementarity, and competition influence growth and yield.

5.3 Conclusion

Intercropping, implemented under irrigation conditions proved to be a more feasible way of efficiently managing available nitrogen by enhancing N cycling and inputs. The findings showed that intercropping is a sustainable practice that can be implemented to reduce the loss of mineral nitrogen. Reducing N outputs in this manner is productive and profitable way of improving nitrogen use efficiency. The advantages of intercropping in terms of efficiently managing and facilitating growth were observed with improvements in chlorophyll content, leaf area, plant height and biomass. Intercropping also proved to facilitate water use efficiency by improving the same parameters even in limited moisture conditions (rainfed).

5.4 Recommendations

Maize/legume intercropping is a cost effective and efficient integrated nitrogen management system that is suitable for the socioeconomic status of smallholder farmers. Intercropping can be a potential technique in ensuring sustainability, profitability, and productivity in crop production. Although the associated legumes in this study did not fix enough nitrogen to meet their nitrogen requirements, for resource-constrained farmers cereal/legume intercropping is an efficient way of ensuring soil fertility. The practice can be implemented with other legume crops such as dry bean or pigeon pea. Irrigation is a secure water regime in terms of securing optimum yields given the unreliable precipitation fluctuations. It is recommended that future studies explore more inputs and output pathways such as nitrogen in irrigation water, volatilisation, and erosion or run off in different climates with different legume crops.

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APPENDICES

Appendices for soil fertility and nitrogen dynamics.

Appendix 3.1: ANOVA table for bulk density.

Source	DF	SS	MS	F	P
Replication	2	0.00921	4.603		
Water regime	1	0.00016	1.633	0.06	0.8318
Error replication*water regime	2	0.00561	2.803		
Cropping system	4	0.01289	3.222	2.46	0.0871
Water regime*cropping system	4	0.00055	1.383	0.11	0.9788
Error replication*water regime*cropping system	16	0.02092	1.307		
Total	29	0.04934			

Appendix 3.2: ANOVA table for aggregate stability

Source	DF	SS	MS	F	P
Replication	2	0.29541	0.14770		
Water regime	1	0.73320	0.73320	9.09	0.0533
Error replication*water regime	2	0.16129	0.08064		
Cropping system	4	0.51419	0.12855	1.13	0.000
Water regime*cropping system	4	0.49101	0.12275	1,08	0,0469
Error replication*water regime*cropping system	16	1,82204	0,11388		
Total	29	4,01714			

Appendix 3.3: ANOVA table for pH (H_2O)

Source	DF	SS	MS	F	P
Replication	2	2,000E-05	1,000E-05		
Water regime	1	4,033E-04	4,033E-04	17,29	0,0946
Error replication*water regime	2	4,667E-05	2,333E-05		
Cropping system	4	6.0533-03	1.513E-04	14.53	0.3779
Water regime*cropping system	4	1.280E-03	3.200E-04	3.07	0.4000
Error replication*water regime*cropping system	16	1.667E-03	1.042E-04		
Total	29	9.470E-03			

Appendix 3.4: ANOVA for soil pH (KCl)

Source	DF	SS	MS	F	P
Replication	2	0.11544	0.05772		
Water regime	1	0.03400	0.03400	2.07	0.2867
Error replication*water regime	2	0.03283	0.01641		
Cropping system	4	0.07257	0.01814	0.84	0.5194
Water regime*cropping system	4	0.06285	0.01571	0.71	0.5857
Error replication*water regime*cropping system	16	0.34527	0.02158		
Total	29	0.66295			

Appendix 3.5: ANOVA for EC

Source	DF	SS	MS	F	P
Replication	2	4842	2420.8		
Water regime	1	718	718.3	0.03	0.8740
Error replication*water regime	2	44502	22250.9		
Cropping system	4	13573	3393.3	0.44	0.7772
Water regime*cropping system	4	26482	6620.4	0.86	0.5083
Error replication*water regime*cropping system	16	123078	7692.4		
Total	29	213195			

Appendix 3.6: ANOVA for OC

Source	DF	SS	MS	F	P
Replication	2	0.4092	0.2046		
Water regime	1	12.4550	12.4550	21.17	0.0441
Error replication*water regime	2	1.1764	0.5882		
Cropping system	4	5.4396	1.3599	2.66	0.0708
Water regime*cropping system	4	7.4054	1.8514	3.63	0.0275
Error replication*water regime*cropping system	16	8.1704	0.5106		
Total	29	35.0560			

Appendix 3.7: ANOVA for phosphorus content

Source	DF	SS	MS	F	P
Replication	2	1.677E-28	8.385E-29		
Water regime	1	53.0670	53.0670	4.141	0.000
Error replication*water regime	2	2.563E-31	1.281E-31		
Cropping system	4	160.782	40.1955	148.87	0.000
Water regime*cropping system	4	350.358	87.5895	324.41	0.000
Error replication*water regime*cropping system	16	4.32000	0.27000		
Total	29	568.527			

Appendix 3.8: ANOVA for phosphorus uptake

Source	DF	SS	MS	F	P
Replication	2	76	38		
Water regime	1	125223	125223	7162.0	0.0001
Error replication*water regime	2	35	17		
Cropping system	4	1559622	389906	16777.87	0.000
Water regime*cropping system	4	87634	21909	942.74	0.000
Error replication*water regime*cropping system	16	372	23		
Total	29	1772962			

Appendix 3.9: ANOVA for residual nitrogen

Source	DF	SS	MS	F	P
Replication	2	1.26341	0.63170		
Water regime	1	0.70736	0.70736	4.49	0.1683
Error replication*water regime	2	0.31523	0.15762		
Cropping system	4	1.50743	0.37686	1.33	0.3025
Water regime*cropping system	4	0.04001	0.0100	0.04	0.9974
Error replication*water regime*cropping system	16	4.54450	0.28403		
Total	29	8.37794			

Appendix 3.10: ANOVA for BNF

Source	DF	SS	MS	F	P
Replication	2	2.649	1.324		
Water regime	1	6.607	6.607	18.47	0.0501
Error replication*water regime	2	0.716	0.358		
Cropping system	4	496.211	124.053	127.54	0.0000
Water regime*cropping system	4	33.386	8.347	8.58	0.0007
Error replication*water regime*cropping system	16	25.562	0.973		
Total	29	555.131			

Appendix 3.11: AVOVA for PMN

Source	DF	SS	MS	F	P
Replication	2	0.02109	0.01054		
Water regime	1	0.05125	0.05125	28.42	0.0334
Error replication*water regime	2	0.00361	0.00180		
Cropping system	4	0.03973	0.00993	3.01	0.0498
Water regime*cropping system	4	0.01641	0.00410	1.24	0.3321
Error replication*water regime*cropping system	16	0.05277	0.00330		
Total	29	0.18487			

Appendix 3.12: ANOVA for nitrogen uptake

Source	DF	SS	MS	F	P
Replication	2	3.7	1.87		
Water regime	1	411.0	411.03	246.71	0.0040
Error replication*water regime	2	3.3	1.67		
Cropping system	4	17476.2	4369.05	5837.63	0.000
Water regime*cropping system	4	926.4	231.60	309.45	0.000
Error replication*water regime*cropping system	16	12.0	0.75		
Total	29	18832.7			

Appendix 3.13: ANOVA for nitrogen leaching

Source	DF	SS	MS	F	P
Replication	2	0.1629	0.08147		
Water regime	1	3.8459	3.84587	20.44	0.0456
Error replication*water regime	2	0.3764	0.18819		
Cropping system	4	2.4836	0.62091	2.19	0.1169
Water regime*cropping system	4	5.2693	1.31731	4.64	0.0112
Error replication*water regime*cropping system	16	4.5439	0.28400		
Total	29	16.6820			

Appendix 4.1: ANOVA table for chlorophyll content during the vegetative stage

Source	DF	SS	MS	F	P
Replication	2	43.20	21.598		
Water regime	1	25.55	25.553	6.28	0.1290
Error replication*water regime	2	8.13	4.066		
Cropping system	6	1302.86	217.144	9.38	0.000
Water regime*cropping system	6	185.37	30.894	1.34	0.2804
Error replication*water regime*cropping system	24	555.35	23.139		
Total	41	2120.46			

Appendix 4.2: ANOVA table for leaf area contend during the vegetative stage

Source	DF	SS	MS	F	P
Replication	2	11617	5808.34		
Water regime	1	7349	7348.74	13.80	0.0654
Error replication*water regime	2	1065	532.67		
Cropping system	6	52359	8726.42	10.57	0.000
Water regime*cropping system	6	13517	2252.83	2.73	0.0364
Error replication*water regime*cropping system	24	19816	825.65		
Total	41	105722			

Appendix 4.3: ANOVA table for leaf area content during the vegetative stage

Source	DF	SS	MS	F	P
Replication	2	22.817	11.4086		
Water regime	1	87.005	87.0048	7.59	0.1103
Error replication*water regime	2	22.918	11.4592		
Cropping system	6	22.829	3.8049	0.44	0.8470
Water regime*cropping system	6	41.346	6.8910	0.79	0.5860
Error replication*water regime*cropping system	24	209.111	8.7130		
Total	41	406.026			

Appendix 4.4: ANOVA table for chlorophyll content during the flowering stage

Source	DF	SS	MS	F	P
Replication	2	3.21	1.603		
Water regime	1	60.93	60.933	0.63	0.5100
Error replication*water regime	2	192.80	96.398		
Cropping system	6	1339.64	223.273	7.19	0.0002
Water regime*cropping system	6	148.26	24.710	0.80	0.5823
Error replication*water regime*cropping system	24	745.01	31.042		
Total	41				

Appendix 4.5: ANOVA table for leaf area during the flowering stage

Source	DF	SS	MS	F	P
Replication	2	49804	24902		
Water regime	1	167492	167492	11.57	0.0766
Error replication*water regime	2	28953	14476		
Cropping system	6	1051537	175256	10.66	0.0000
Water regime*cropping system	6	191547	31924	1.94	0.1148
Error replication*water regime*cropping system	24	394534	16439		
Total	41				

Appendix 4.6: ANOVA table for plant height during the flowering stage

Source	DF	SS	MS	F	P
Replication	2	1824.2	912.08		
Water regime	1	4.6	4.59	0.02	0.9016
Error replication*water regime	2	496.7	234.87		
Cropping system	6	13497.1	2249.52	9.02	0.0000
Water regime*cropping system	6	1472.3	245.38	0.98	0.4575
Error replication*water regime*cropping system	24	5982.9	249.29		
Total	41				

Appendix 4.7: ANOVA table for chlorophyll content at maturity

Source	DF	SS	MS	F	P
Replication	2	56.08	28.040		
Water regime	1	49.79	49.791	1.61	0.3319
Error replication*water regime	2	61.77	30.885		
Cropping system	6	2905.72	484.287	21.16	0.0000
Water regime*cropping system	6	134.52	22.420	0.98	0.4605
Error replication*water regime*cropping system	24	549.39	22.891		
Total	41	3757.28			

Appendix 4.8: ANOVA table for leaf area at maturity

Source	DF	SS	MS	F	P
Replication	2	40008	20004		
Water regime	1	203462	203462	11.74	0.0756
Error replication*water regime	2	34665	17332		
Cropping system	6	1696541	282757	26.22	0.0000
Water regime*cropping system	6	251566	41928	3.89	0.0075
Error replication*water regime*cropping system	24	258821	10784		
Total	41	2485063			

Appendix 4.9: ANOVA table for plant height at maturity

Source	DF	SS	MS	F	P
Replication	2	2130.8	1065.40		
Water regime	1	2616.0	2616.01	8.89	0.0965
Error replication*water regime	2	588.3	294.16		
Cropping system	6	51296.4	8549.40	30.54	0.0000
Water regime*cropping system	6	3926.4	654.40	2.34	0.0641
Error replication*water regime*cropping system	24	6719.2	279.97		
Total	41	67277.1			

Appendix 4.10: ANOVA table for plant biomass content at the maturity stage

Source	DF	SS	MS	F	P
Replication	2	7263	3631.7		
Water regime	1	9003	9003.3	3.10	0.2204
Error replication*water regime	2	5810	2905.1		
Cropping system	4	300174	50029.1	18.73	0.000
Water regime*cropping system	4	17470	2911.6	1.09	0.3966
Error replication*water regime*cropping system	16	64120	2671.7		
Total	29	403841			