# NEW PERSPECTIVES ON PLANT POPULATION AND ROW SPACING OF RAINFED MAIZE

by

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# Declaration

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This dissertation includes three original papers published in peer-reviewed journals and two unpublished publications. The development and writing of the papers (published and unpublished) were the principal responsibility of myself and, for each of the cases where this is not the case, a declaration is included in the dissertation indicating the nature and extent of the contributions of co-authors.

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# Abstract

Recent maize grain yield increases are attributed to genetic advances and changes in soil and crop management practices, including no-tillage (NT) and additional conservation agriculture (CA) practices. Management practices such as plant population and row spacing should be adapted for NT and other CA practices to optimise maize grain yield and promote sustainable production. However, there is a lack of information reporting on the influence of environmental and management factors and its relationship with plant density and maize grain yield. This study was initiated to generate novel perspectives on the complex concept of interplant competition of rainfed maize under various soil and crop management practices and climate conditions. The study entailed five research themes. The first research theme consisted of a critical review of the current soil and crop management practices followed in rainfed maize production regions of South Africa. Sustainable and alternative agronomic management approaches were highlighted. Alternative agronomic management practices, such as NT, crop intensification and diversification, crop residue retention, and livestock integration may provide pathways to increase the sustainability of these rainfed maize systems. Improved soil water content may support higher plant populations. The second research theme entailed consolidation of global published data from rainfed maize plant population field trials to investigate the effects on yield and to determine the influence of rainfall, soil tillage and nitrogen on the relationship between plant population and yield. Data was extracted from 64 peer-reviewed articles. Maize grain yield responded positively to increased plant population in high rainfall environments, while yields in rainfall limited environments were highly variable. The optimal plant population under NT was lower than under conventional tillage. However, at a given plant population, maize grain yield under NT outperformed the yield obtained under conventional tillage. As a third research theme, the effects of plant population and row spacing on soil water, soil temperature and maize grain yield under CA in a sub-tropical environment, were evaluated over three seasons. Although maize grain yield was not affected by plant population in the season with the highest early-season rainfall, maize grain yield increased with increasing plant population in the average rainfall and drier seasons. The fourth and fifth research themes involved a two-year trial in a semi-arid environment. In this trial, the effects of plant population and row spacing on the aboveground growth, water use efficiency and root morphology were evaluated under NT. A row spacing of 0.76 m was advantageous in the drier season. Plant populations of 20 000 to 50 000 plants ha$^{-1}$ out-yielded plant populations more than 25 000 plants ha$^{-1}$ at 0.52 m row spacing. Rainfall affected maize root growth while plant population had a small effect on maize root morphology. Optimising maize grain yield using plant population and row spacing requires a flexible systems-based (i.e., CA) approach. Conservation agriculture should incorporate management practices (such as plant population and row spacing) tailored for specific context.

**Keywords**: Conservation agriculture, corn, regenerative agriculture, soil tillage, *Zea mays* L.

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# List of abbreviations

| | |
|---|---|
| ANOVA | Analysis of variance |
| CA | Conservation agriculture |
| Ca | Calcium |
| Cl | Chloride |
| Crop ET | Crop evapotranspiration |
| CT | Conventional tillage |
| CV | Coefficient of variance |
| DAE | Days after emergence |
| FWC | Field water capacity |
| GDD | Cumulative growing degree days |
| GRM | General regression model |
| h | Hour |
| ha | Hectare |
| i.e. | id est (that is) |
| IPAR | Intercepted photosynthetically active radiation |
| K | Potassium |
| KCl | Potassium chloride |
| LAI | Leaf area index |
| LSD | Fisher's least significant differences |
| Mg | Magnesium |
| N | Nitrogen |
| Na | Sodium |
| NT | No-tillage |
| P | Phosphorus |
| *P* | Probability value |
| pH | The negative logarithm to the base ten of the hydrogen ion activity in the solution |
| PPAW | Percent plant available water |
| PP | Plant population |
| PWP | Permanent wilting point |

| | |
|---|---|
| REML | Restricted maximum likelihood |
| $RLD_v$ | Volumetric root length density |
| *r* | Pearson's correlation coefficient |
| RS | Row spacing |
| RT | Reduced tillage |
| R2-R3 | Kernel development growth stage |
| R3-R4 | Kernel filling growth stage |
| R5-R6 | Physiological maturity growth stage |
| S | Season |
| SD | Soil depth |
| VE | Seedling emergence growth stage |
| VT | Tasseling growth stage |
| V6 | Sixth-leaf collar |
| V14 | Fourteenth-leaf collar growth stage |
| $WUE_b$ | Water use efficiency for biomass production |
| $WUE_g$ | Water use efficiency for grain production |

# CHAPTER 1

# Introduction

## 1.1 Rationale

Maize (*Zea mays* L.) is the most important grain crop in South Africa and represents 52.69% of the gross value of field crops annually (DAFF, 2019). Maize produced in South Africa is primarily used to meet the high local food demand and livestock feed needs. The average food supply quantity of maize and its products for South Africa was 287.59 g capita $d^{-1}$ for the period 2000 to 2013 (FAO, 2019), highlighting the key role of maize in the daily diet of South Africa's population. Approximately 91% of South Africa's maize is produced under rainfed conditions, despite South Africa being a water scarce country with a mean annual rainfall of 450 mm (Schulze, 2016). As a result, producers continuously need to strategically (through land-use decisions) or tactically (through agronomic decisions) adapt the management practices to mitigate crop failure risks and achieve economic maize grain yields in the event of low rainfall seasons.

Plant population and row spacing are principal agronomic management practices influencing maize growth, development and grain yield (Amelong et al., 2017; Cheng et al., 2015; DeBruin et al., 2017). Compared to other species in the *Poaceae* family, maize is the most sensitive species to changes in plant density (Almeida and Sangoi, 1996). Both plant population and row spacing directly influence the rate and efficiency of soil resource and rainfall use (Haarhoff and Swanepoel, 2018). In high rainfall environments, a higher plant population and narrow row spacing are needed to fully utilise the available soil water, and interplant competition for soil resources and sunlight increases. In contrast, in drier environments, lower plant populations and wider row spacing is normally followed due to limited soil water. As a result, interplant competition for sunlight is not a critical aspect in low rainfall environments, and the greatest interplant competition occurs belowground between maize roots. Water is the most limiting factor for maize grain production in low rainfall environments and consequently affects soil nutrient uptake by maize roots. Improved crop performance has been linked to improved root system growth (Lynch, 2007). However, achieving this requires an understanding regarding the limiting factors for optimal root system functioning as influenced by climate factors and agronomic management practices. Addressing the limitations experienced by maize root systems in a farming system context may lead to improved maize growth by increasing the efficiency of use of limited soil resources.

Interactions of maize plant density outcomes with soil and other crop management practices have been noted in the USA, China and Argentina (Edmeades and Tollenaar, 1990; Eyherabide et al., 1994; Qin et al., 2016). For example, no-tillage (NT) was introduced to combat severe soil erosion and degradation in cropping systems, with high levels of adoption in the major maize production regions worldwide (Derpsch et al., 2010). Compared to soil under conventional tillage (CT), soil under NT is characterised, *inter alia*, by a higher water content, increased soil microbial activity and organic carbon content (Peiretti and Dumanski, 2014). In turn, this enable soil to sustain more plants per unit area and consequently affect the optimal plant population for maximum maize grain yields (Haarhoff and Swanepoel, 2018). To improve the efficacy of NT, it has often been applied within the context of conservation agriculture (CA). Conservation agriculture was developed as systems-based approach to enhance crop productivity, while the soil resource base is preserved. Conservation agriculture consists of three main principles, i.e. minimum- or no-tillage, a permanent organic soil cover and a diverse crop rotation sequence of three or more crop species (Palm et al., 2014). No-tillage is the central principle of CA providing various economic and environmental benefits (Hobbs et al., 2008) if practiced in association with the additional CA principles.

Despite global acknowledgement of the importance of stand densities in achieving optimal maize grain yields (Assefa et al., 2016; Gamdin et al., 2016), interplant competition for soil resources at different levels of maize density stands are not well understood, and in particular so for South African rainfed maize production systems. Present guidelines for rainfed maize plant population and row spacing are based on field trials managed under CT. Conventional tillage is still used as the primary tillage practice across the major maize production regions of South Africa. The adoption of NT as a sole practice or in the context of CA in South African rainfed maize production systems has been increasing recently to address decades of soil erosion and degradation (Findlater et al., 2019). The need for investigating rainfed maize plant population and row spacing under newly introduced soil and crop management practices in South African rainfed maize production regions exist. The information generated will provide an understanding of the limiting factors for optimal rainfed maize grain production across a variety of soil and climate conditions globally.

## 1.2 Research themes

This study was initiated to generate novel perspectives on the complex concept of interplant competition of rainfed maize under various soil and crop management practices and climate conditions. The information generated is of an applied nature and provide a new understanding regarding rainfed maize production which finally leads to more optimal production. To achieve this, five research themes were investigated:

1. A review of the effects of current agronomic management practices followed in the rainfed maize production systems of South Africa on the soil-plant environment. Sustainable and alternative agronomic management approaches were highlighted. Future research options were explored, expanding our knowledge of proposed approaches in local soil and climate conditions.

2. A global systematic review of published data reporting on the effects of plant population on rainfed maize grain yield under different climate and agronomic conditions, and the influence of mean annual rainfall, soil tillage and nitrogen application on the relationship between plant population and maize grain yield.

3. The effects of varying plant population and row spacing configurations on rainfed maize grain yield, soil temperature and soil water content under CA in a subtropical environment.

4. The effects of plant population and row spacing on aboveground rainfed maize growth, grain yield, water use efficiency and soil β-glucosidase activity under NT in a semi-arid environment.

5. The response of rainfed maize root morphology to varying levels of plant population under NT in a semi-arid environment.

## 1.3 Outline of dissertation

The main findings are presented in a chapter specific manner and were summarised within the following chapters:

Chapter 2 provides a comprehensive review on the effects of current agronomic management practices followed in the South African rainfed maize production systems. This chapter intended to critically review literature of both local and global origin, which reported on the effects of a wide range of agronomic management practices on the soil-plant environment, with emphasis on rainfed maize production systems. Sustainable and alternative agronomic management approaches for each distinct South African rainfed maize production region were subsequently highlighted. Future research options were explored, expanding knowledge of proposed approaches in local soil and climate conditions. This chapter has been published as a Review and Interpretation article in Crop Science with co-authors TN Kotzé (Department of Agronomy, Stellenbosch University) and PA Swanepoel (Department of Agronomy, Stellenbosch University) which could be cited as: Haarhoff, S.J., T.N. Kotzé and P.A. Swanepoel. 2020. A prospectus for sustainability of rainfed maize production systems in South Africa. Crop Science. *In Press*. (DOI: 10.1002/csc2.20103).

Chapter 3 aimed to consolidate global findings of published data from field trials reporting on the effects of plant population on maize grain yield under rainfed conditions. The influence of mean annual rainfall, soil tillage and applied nitrogen on the relationship between plant population and maize grain yield was also investigated. A systematic literature search was conducted using a keyword search and an eligibility criteria to collate peer-reviewed, published articles. Data was extracted from 64 articles representing 13 countries and 127 trial locations. This chapter has been published as a Scientific Perspectives research article in Crop Science with co-author PA Swanepoel which could be cited as: Haarhoff, S.J., and P.A. Swanepoel. 2018. Plant population and maize grain yield: A global systematic review of rainfed trials. Crop Science 58:1819-1829.

Chapter 4 evaluated the response of rainfed maize grain yield, soil temperature and plant available water to varying plant population and row spacing configurations under CA in a subtropical environment. This was done by conducting a three-year field trial near Reitz in the eastern Free State, South Africa. This chapter has been published as an original research article in Agronomy Journal with co-author PA Swanepoel which could be cited as: Haarhoff, S.J., and P.A. Swanepoel. 2020. Narrow rows and high maize plant population improve water use and grain yield under Conservation Agriculture. Agronomy Journal. *In Press*.

Chapter 5 reports on the findings of a rigorously managed two-year field trial conducted near Ottosdal, North West Province of South Africa, a region with erratic rainfall patterns and characterised by a semi-arid climate regime. In this study, the aboveground plant architecture and biomass production, grain yield, yield components, grain quality, water use efficiency, and soil β-glucosidase activity were evaluated in response to various plant population and row spacing configurations under no-tillage. This chapter has been submitted as an original research article for publication in Field Crops Research with co-authors TN Kotzé and PA Swanepoel which could be cited as: Haarhoff, S.J., T.N. Kotzé and P.A. Swanepoel. 2020. Benefits of increased maize plant population and wider rows under no-tillage is season-specific. Field Crops Research. *Under review*.

Chapter 6 provide information on the effect of plant population on rainfed maize root morphology under no-tillage in a semi-arid environment. Maize root data was collected from the same two-year trial mentioned in Chapter 5. This chapter has been submitted as an original research article for publication in Field Crops Research with co-authors E Lötze (Department of Horticultural Science, Stellenbosch University) and PA Swanepoel which could be cited as: Haarhoff, S.J., E. Lötze and P.A. Swanepoel. 2020. Rainfed maize root morphology response to plant population under no-tillage. Field Crops Research. *Under review*.

Chapter 7 provides the dissertation conclusion and includes a synthesis of the empirical findings, discussion on the theoretical implication of the study, recommendations for future research and limitations of the study.

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# CHAPTER 2

# A prospectus for sustainability of rainfed maize production systems in South Africa

**Abstract**

The rainfed maize (*Zea mays* L.) production systems of South Africa require an integrated approach to use the limited soil available water more efficiently, and to increase system productivity and sustainability. The soils across the major maize production regions are highly susceptible to wind and water erosion. Rigorous soil tillage, maize monoculture, and fallow periods are common, which depletes the soil from organic matter and nutrients. Despite the pressing need for transforming the highly degraded rainfed maize production systems, adoption of more sustainable management approaches has been limited, likely due to a shortage of local scientific field trials to evaluate current and alternative maize agronomic management practices. Erratic inter-seasonal rainfall patterns cause high variability in maize grain yields. Major challenges associated with no-tillage are poor crop establishment, subsoil compaction, and high maize grain yield variability. The use of fallow in the maize-fallow production system leads to excessive runoff and soil erosion losses despite increased maize grain yields. Crop intensification and alternative crops are needed to increase rainfall water use efficiency and lower fallow frequency. The use of cover and forage crops may provide the opportunity to diversify and intensify maize production systems. Cover crop biomass could be beneficial in mixed rainfed crop-livestock systems by addressing livestock feed needs in either winter or summer. Research is drastically required to improve the understanding of current South African rainfed maize production systems and to facilitate the development of fitting sustainable agronomic management practices.

**Keywords:** Soil fertility, grain production, livestock production, conservation agriculture

## 2.1 Introduction

South African maize (*Zea mays* L.) production systems are managed with unsustainable practices. Soils are degraded through rigorous soil tillage, maize monoculture, and fallow periods. Soil organic matter and nutrients are depleted and there are significant soil losses through wind and water erosion (Le Roux et al., 2008; Mills and Fey, 2003). Although more sustainable practices have been proposed (Kassam et al., 2016; Smith et al., 2017; Swanepoel et al., 2017), adoption of management practices that limit degradation has been slow (Findlater et al., 2019).

Maize is the most widely produced crop in South Africa (FAO, 2018). During the 2016-2017 production season, approximately 16.7 million tons of maize grain was produced from 2.6 million ha (FAO, 2018). The food supply quantity (maize and its products) for South Africa ranges from 250 - 300 g capita$^{-1}$ d$^{-1}$ (FAO, 2018), illustrating the significant role of maize in the daily diet of South Africans. In addition, 40% of maize is used as livestock feed, constituting approximately 4.5 million tons annually (AFMA, 2017).

Soil management in grain production systems in Australia, North America, and South America changed dramatically during the 1900s in response to severe soil degradation (Derpsch et al., 2010; Kassam et al., 2015). By the year 2007, it was estimated that 41% of South Africa's cultivated areas were highly degraded (Bai and Dent, 2007). Despite significant soil losses as a result of degrading management practices, maize grain yields increased (Figure 2.2). Modern drought-tolerant and genetically modified maize hybrids enabled producers to attain profitable yields, which likely softened the effects of soil degradation. Therefore, although maize grain yields increased in recent decades, there exists uncertainty regarding the sustainability of this increasing trend, while high volumes of soil are lost and degraded. The vulnerability of the rainfed maize production systems is further hampered by erratic rainfall patterns and frequent drought periods. The effects of current agronomic management practices followed in the South African rainfed production systems was reviewed. Sustainable and alternative agronomic management approaches are subsequently highlighted. Future research options are explored, expanding knowledge of proposed approaches in local soil and climate conditions.

## 2.2 Rainfed maize production regions and climate conditions of South Africa

The area used for rainfed maize production is divided into three distinct regions based on climate and soil type, namely, the (i) Western region (35% total production), (ii) Eastern region (45%), and (iii) KwaZulu-Natal region (10%) (Figure 2.1). The Western and Eastern regions form part of the South African inland plateau with an altitude of 1 500 - 1 800 m. The difference in climate between production regions are mainly due to the influence of oceans surrounding South Africa. South Africa is located between the cold Atlantic Ocean to the west and the warm Indian Ocean the east, with the latter ocean inducing a warm and humid climate in the KwaZulu-Natal region. The Atlantic Ocean induce a drier climate in the west. As a result, there is a strong rainfall gradient from east to west, with annual rainfall gradually decreasing westward. Across the Western and Eastern regions, summer rains are caused by the southward flow of hot and humid air from the tropics resulting in high-intensity thunderstorms. The Western region is classified as cold semi-arid (BSk) according to the Köppen-Geiger climate classification system (Kottek et al., 2006) with a mean annual rainfall ranging from 400 mm in the most western areas to 550 mm in the northeastern areas. Approximately 90% of the rainfall occurs between October and April with high inter-annual variability. Prolonged dry spells during the rainy season is a common phenomenon (Zuma-Netshiukhwi et al., 2013). Intermittent wet seasons occur between extremely dry and normal rainfall years in the Western region. The Eastern and KwaZulu-Natal regions receive 600 - 700 and 700 - 900 mm of rainfall per annum, respectively, with humid subtropical (Cwa) and subtropical highland (Cwb) climate zones found in both regions (Kottek et al., 2006). The east-west rainfall gradient is accompanied by an intense, increasing east-to-west gradient in potential evaporation. For example, Class A pan evaporation in the KwaZulu-Natal and Eastern regions ranges from 1 500 - 2 000 mm annually, increasing to more than 2 500 mm per year in the Western region. Growing degree days for the period October to March gradually decreases from approximately 2 011 to 1 872 moving from the Western to the KwaZulu-Natal regions (Walker and Schulze, 2008). Frost risk is an additional major factor influencing agronomic decisions made in the rainfed maize production regions. In the Western region, the frost-free period is approximately 7 - 9 months, with a more limited 7 - 8 months in the Eastern and KwaZulu-Natal regions.

Variability in rainfall patterns between growing seasons extensively affects maize grain yields in the Western and Eastern regions, whereas temperature variability is more critical in the

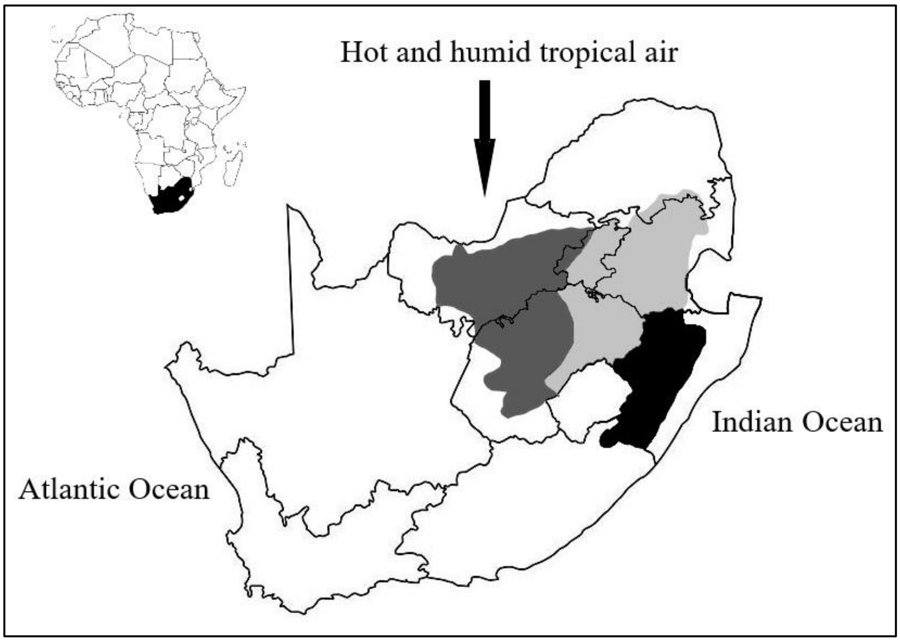


**Figure 2.1:** Three distinct rainfed maize production regions in South Africa, namely Western (dark grey), Eastern (grey) and KwaZulu-Natal (black) region. The summer rainfall pattern across the three rainfed maize production regions is induced by the southward movement of hot and humid tropical air from the equator, with the warm Indian Ocean further inducing rainfall across the KwaZulu-Natal region.

KwaZulu-Natal region (Ray et al., 2015; Walker and Schulze, 2008). Ray et al. (2015) reported that maize grain yield variability was explained by extreme rainfall inconsistency related to the El Niño Southern Oscillation in the Western and Eastern production regions. The interseasonal rainfall variability explained more than 60% of maize grain yield variability in the Western region. This statement is supported using data collected by the South African Department of Agriculture, Forestry and Fisheries in 36, 43, and 14 districts from the Western, Eastern, and KwaZulu-Natal regions, respectively (Table 2.1; Figure 2.2) (R. Beukes, personal communication, 2019). Data show high interannual maize grain yield variability during the 1980-1981 to 1999-2000 periods, especially in the Western and Eastern regions, with lower variability in the KwaZulu-Natal region. High variability in maize grain yields is not solely experienced in the South African semi-arid region, but also in a global context (Haarhoff and Swanepoel, 2018). The lower variability in maize grain yield during the 2000/01 to 2017/18 period in all three production regions is attributed to improved crop breeding (Gouse et al., 2005) where plants became more drought and disease tolerant. Also, the release of effective herbicides may have also contributed towards the decreased yield variability.

Rainfed maize grain is produced on deep sandy Oxisols of aeolian origin with a clay content of between 5 and 20% in the Western region (Bennie and Botha, 1986). Plinthic variants of Ultisols and Alfisols are also found in this region. During the wet summer months, a perched water table is present in and above the plinthic B horizon, serving as a reservoir for maize during the growing season. Soil types found in the Eastern and KwaZulu-Natal regions have textures of loamy sands, clay loams, and clay and are classified as Oxisols, Vertisols, Ultisols, and Mollisols (Fey, 2010; Turner, 2000). The interlinked combinations of rainfall amount, evaporation losses, soil types, and frost risk ultimately determine the spatial distribution of agronomic management practices followed in the rainfed maize production regions. The interplay between climate factors and current agronomic management practices in each maize production region is discussed in more detail in the following sections of this review, with emphasis placed on the reasoning behind these practices and the consequent effects on the soil-crop environment.

**Table 2.1:** The coefficient of variance (CV) of maize grain yield for periods 1980/81 to 1999/00 and 2000/01 to 2017/18 in the Western, Eastern and KwaZulu-Natal regions. Source: South African Department of Agriculture, Forestry and Fisheries (R. Beukes, personal communication, 2019).

| Production region | CV (%) | |
|---|---|---|
| | **1980/81 to 1999/00** | **2000/01 to 2017/18** |
| Western | 39.94 | 25.79 |
| Eastern | 29.14 | 20.48 |
| KwaZulu-Natal | 24.92 | 13.76 |

## 2.3 Rainfed maize production regions in South Africa

A single production system of continuous maize is principally followed across the three rainfed maize production regions, taking advantage of the high sunlight intensity and available soil water with the onset of the rainy season (Figure 2.3a). After harvest in winter, a 3-5- month fallow period is allowed before the next maize planting. Maize may be replaced with sorghum [*Sorghum bicolor* (L.) Moench], soybean [*Glycine max* (L.) Merr.], sunflower (*Helianthus annuus* L.), and groundnut (*Arachis hypogaea* L.). Sorghum and sunflower are more common

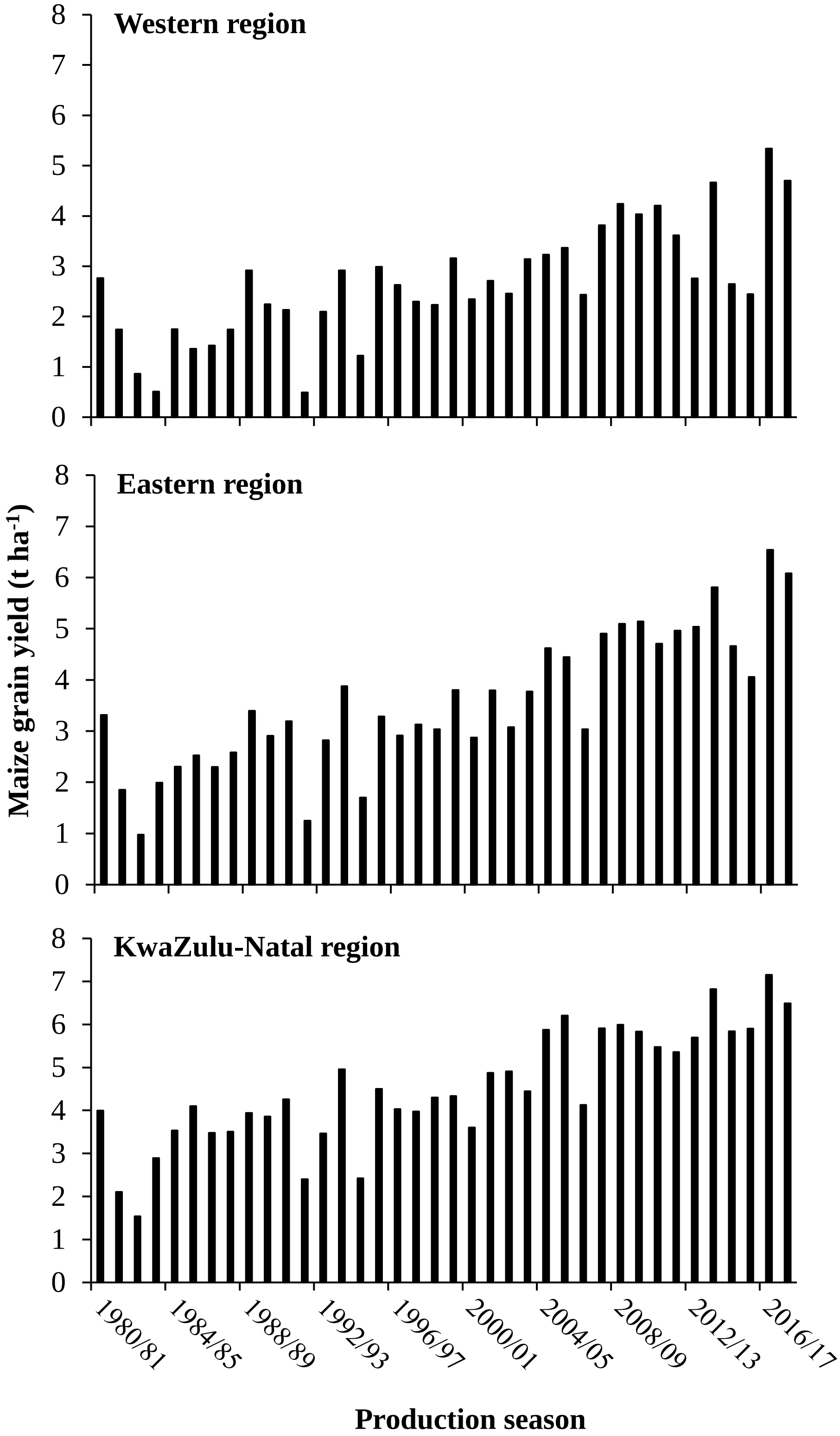


**Figure 2.2:** Long-term maize grain yields achieved in the Western (36 districts), Eastern (46 districts) and KwaZulu-Natal (14 districts) regions for production seasons 1980/81 to 2017/18. Source: South African Department of Agriculture, Forestry and Fisheries (R. Beukes, personal communication, 2019).

in the Western region due to the increased tolerance for drier growing conditions. When maize is planted at optimal timing, maturity is achieved before potential frost in late autumn. Since sunflower requires fewer days to reach maturity, it replaces maize in years with late rainfall arrival to reduce potential frost risk and crop failure in the Western and Eastern regions.

Late rainfall arrival and unpredictable dry spells during the maize growing season in the Western region resulted in poor crop establishment and yields in the continuous maize production system. Consequently, a maize-fallow production system was introduced, adding a further 11-12 months to the fallow period, where soils are kept bare and weed free using herbicides or soil tillage, allowing the subsequent maize to take advantage of accumulated soil water and reducing the risk of crop failure and poor maize grain yields (Figure 2.3b). The maize-fallow production system is the only fallow system used by producers. Despite producing only one crop in two seasons, the maize-fallow production system increased maize grain yields (Bennie and Hensley, 2001; Bennie et al., 1995; De Bruyn, 1974) and was established as principal practice on the sandy soils in the Western region during the 20th century. The optimal maize planting date range from mid-November to mid-December in the Western region and from mid-October to mid-November in the Eastern and KwaZulu-Natal regions.

## 2.4 Soil management for improved and sustainable rainfed maize production

### *2.4.1 Soil tillage practices*

Conventional tillage (CT) is traditional practice in the continuous maize and maize–fallow production systems. No-tillage (NT) or other forms of reduced tillage (RT) are uncommon, especially in the Western region, where producers commonly believe that soil tillage is the most fitting method to control soil erosion and soil compaction effectively. Weed control in CT systems is performed using multiple passes of chisel and disc ploughs in combination with pre- and post-emergence herbicides. During early maize growth stages, interrow cultivation is performed to eliminate weeds between rows. Soils in the Western region are extremely prone to compaction due to the region’s well-sorted fine-sandy composition (Bennie and Krynauw, 1985). Consequently, in-row deep ripping (500 - 750 mm soil depth) is performed prior to maize planting to alleviate compaction and plough pans caused by machinery wheel pressure and previous tillage operations. Chisel and disc plough are used for seedbed preparation and alleviation of cattle-induced compaction at shallow soil depths.

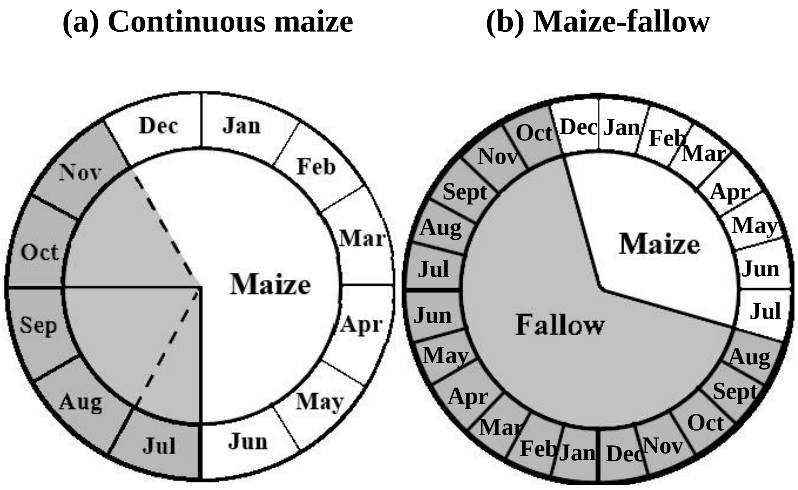


**Figure 2.3:** The (a) continuous maize and (b) maize-fallow production systems followed in the rainfed maize production regions of South Africa presented as one- and two-year cycles with production seasons lasting from September to June in the Eastern and KwaZulu-Natal regions (solid lines) and from November to July in the Western region (dotted lines) in the continuous maize production system.

Mouldboard ploughs are particularly used in the maize-fallow production systems after harvest to create soil surface roughness to counteract wind erosion during the lengthy fallow period (Wiggs and Holmes, 2011). However, effects are short lived, as soil clods break down during rainfall events and dislodged soil particles are transported by water, clogging soil pores, forming a sealed soil surface intensifying water erosion. Secondary uses for mouldboard ploughs include the incorporation of crop residues and soil amendments such as gypsum or limestone, as well as weed control.

Weed control in NT depends entirely on chemical control, alternating herbicides with varying modes of action to lower the potential of herbicide resistance development among weeds. Total area used for rainfed maize production under NT is approximately 75% in KwaZulu-Natal, with less than 30 and 60% in the Western and Eastern regions, respectively (Findlater et al., 2019). No-tillage is practiced in the continuous maize production system, with very little to zero adoption in the maize-fallow production system.

Research has evaluated the response of maize grain yield to various soil tillage practices in all three South African rainfed maize production regions (Table 2.2). At various locations in the KwaZulu-Natal region, the response of maize grain yield to soil tillage practice was mainly influenced by rainfall during the growing season and poor crop establishment. Mallett et al.

(1987) reported maize grain yields of between 5 000 and 9 400 kg ha$^{-1}$ under NT, whereas maize grain yields of 4 200 - 9 300 kg ha$^{-1}$ were achieved under CT. These maize grain yield ranges were fairly similar for NT and CT and were equally inconsistent over the duration of the trial. In years with low rainfall, however, maize grain yields under NT were higher ($P \leq 0.05$) than CT. During the latter four years of the trial, average and above-average rainfall was received, resulting in no maize grain yield differences ($P > 0.05$). Berry et al. (1987) found maize grain yield 13% higher under NT than CT, with maize grain yields of 7 600 and 6 700 kg ha$^{-1}$, respectively. Maize grain yield achieved under RT was approximately 7 000 kg ha$^{-1}$. The reason for the increased maize grain yield the higher soil water content, with more water held at plant available soil water tensions during critical reproductive growth stages. The NT plots had 79% more soil cover by maize residues than the CT plots, which possibly explains the improved soil water content. Although not reported, a present soil cover could have increased the infiltration rate and lowered surface runoff during rainfall events, leading to higher soil water contents. Soil tillage practice had no influence ($P > 0.05$) on mean maize grain yield in research by Lawrance et al. (1999) and Berry and Mallett (1988) on finer textured soils in the KwaZulu-Natal region. However, in three seasons, NT had higher ($P \leq 0.05$) maize grain yields than CT (two of these years had below-average rainfall). In seasons with above-average rainfall, CT had higher ($P \leq 0.05$) maize grain yields than NT (Lawrance et al., 1999). Overall, the mean maize grain yields for NT, RT, and CT were 6 736, 6748, and 6 631 kg ha$^{-1}$, respectively. Despite no significant differences between soil tillage treatments over the 13-year experiment, final plant population was lower ($P \leq 0.05$) in the NT treatment in six trial years. Similarly, Berry and Mallett (1988) reported no difference ($P > 0.05$) in maize grain yield between soil tillage practices, which ranged from 7 500 - 8 200 kg ha$^{-1}$ between trial years, even though the plant population was 19% lower in the NT plots. The lower plant population was attributed to poor planter penetration into the soil due to the presence of a thick crop residue layer, resulting in shallow planting depths. Since 1988, planter equipment has improved significantly, easing the planting action and resulting in greater maize seedling establishment in NT systems. Lang and Mallett (1987) reported a maize grain yield of 11 000, 10 000, and 9 410 kg ha$^{-1}$ for CT, RT, and NT, respectively. Again, plant population was lower ($P \leq 0.05$) in both the NT and RT plots, resulting in higher ($P \leq 0.05$) maize grain yields in the CT treatment.

In the Western region, Bennie et al. (1995) found higher ($P \leq 0.05$) maize grain yields under CT (1 600 kg ha$^{-1}$) in a maize-fallow production system compared with NT (1 200 kg ha$^{-1}$) in a continuous maize production system. Overall, the lowest mean maize grain yield was 1 400 kg ha$^{-1}$ under RT. The higher yield was attributed to the longer fallow period associated with the maize-fallow production system. The authors concluded by stating continuous maize in a NT system is not recommended for the region and sandy soil type. However, new drought-tolerant maize hybrid releases, new planter equipment, and improved weed control strategies (herbicides) have provided novel pathways to increase maize grain yields in NT systems. Furthermore, conclusions and recommendations from previous research evaluating the effects of soil tillage practices on crop growth may have been based only on yields. A farming system analysis that considers the system's economics such as the potential savings in fuel, labour, and effects across the rotation through time is required. The results reported by studies in Table 2.2 indicate that NT, in combination with high crop residue cover, is an alternative soil tillage practice option to CT in the KwaZulu-Natal region. The lack of studies conducted in the Western and Eastern regions generates uncertainty regarding the viability of NT in these regions. A lack of diverse crop rotations and the inclusion of lengthy fallow periods may have influenced the results and are not solely the effects of the soil tillage practices investigated (Bennie et al., 1995). Moreover, achieving target maize plant populations in NT systems was problematic, even in finer textured soils present in the KwaZulu-Natal region. Poor planter performance hindered the accuracy of maize response to various soil tillage practices in these selected studies. Changes in soil structure and high volumes of crop residue are associated with NT, underpinning the need for specialised planter equipment to achieve maximal maize establishment.

Utilisation of maize residues by cattle and rigorous soil disturbance practices limit the availability of material for a permanent soil cover in the continuous maize and maize-fallow production systems. In addition, high temperatures and low rainfall results in rapid breakdown of maize residues. Maize residues are of high value in mixed crop-livestock production systems. After grazing maize residues by cattle, bare fields are mouldboard or chisel ploughed to counter wind erosion, to address concerns of possible soil compaction and to control weeds before the next maize planting. Bare soil surfaces should be avoided to limit the follow-up soil tillage operations. More strategic maize residue utilisation is needed alongside less intensive soil disturbance practices and the intensification of production systems. Production systems can be intensified by increasing crop frequency and crop diversity, which in turn enhance soil resource capture and use (Caviglia and Andrade, 2010). Consequently, fallow periods will be avoided and the productivity per unit area will be increased. Establishment of cover crops in place of the winter fallow period may provide a pathway to increase annual biomass production and increase rainfall use efficiency in the subtropical KwaZulu-Natal region. This approach is less viable in the drier Western and Eastern regions, with very low soil water levels after maize harvest. Alternative approaches, such as the replacement of maize in the continuous maize production system with a high biomass producing cover crop mixture may be needed. More discussion on cover crops can be found later in this review.

Soil management requires an integrated approach (Giller et al., 2015), and care must be given to challenges associated with long-term NT. For example, strategic tillage can be considered to address subsoil compaction under NT (Wortmann et al., 2010). In-row deep ripping improves root growth by alleviation of compacted soil layers and results in higher maize grain yields (Bennie and Botha, 1986). Alternatively, a controlled traffic farming system may be followed. Controlled traffic farming is a system-based approach that restricts all vehicles to permanent traffic lanes, thereby minimising machinery wheel and soil area contact (Chamen, 2015). Benefits associated with controlled traffic farming include a lower tillage need and frequency, more effective weed control, and fewer soil erosion issues.

### *2.4.2 Fallow and rainfall use efficiency*

Research conducted in the rainfed maize production regions have primarily evaluated the rainfall use efficiency in maize-fallow production systems. Bennie et al. (1995) reported maize grain yield increases varying from 26 - 50% in the maize-fallow production systems. Similarly, when the fallow period was increased to 19 months, maize grain yield increased by 26% over four production seasons (De Bruyn, 1974). In an extremely dry year with only 189 mm of rainfall received during the growing season, maize grain yield in the maize-fallow production system was 629 - 789 kg ha$^{-1}$ with total crop failure in the continuous maize production system (Hensley et al., 1999). Increased available soil water at planting after fallow was responsible for the increased maize grain yields in the maize-fallow production system (Bennie and Hensley, 2001) despite reports of pre-plant rainfall storage efficiencies of only 2 - 37% for soils in the Western region (Bennie et al., 1994). The increased maize grain yields achieved in the maize-fallow production systems results in poor rainfall use efficiency. Despite the yield increases reported by abovementioned studies, rainfall use efficiency decreased with increasing production years. For example, the rainfall use efficiency measured over three production seasons were 5.98 and 5.05 kg grain ha$^{-1}$ mm$^{-1}$ for the continuous maize and maize-fallow production systems, respectively (Bennie et al., 1994). Moreover, 3.56 and 2.41 kg grain ha$^{-1}$

mm$^{-1}$ was achieved in the continuous maize and maize-fallow production systems on a medium-textured soil, respectively (De Bruyn, 1974). The decreased rainfall use efficiency is due to high soil water losses by evaporation and runoff. Between 60 and 75% of rainfall can be lost during the fallow period due to evaporation from the soil surface under local semi-arid conditions (Bennie et al., 1994). These low rainfall use efficiency and high evaporation figures confirm the low viability of a fallow period, and focus needs to be shifted towards more intensified production systems whereby crops are grown when soil water is available.

Current adoption of intensified production systems among maize producers is limited by tradition, infrastructure shortages, and a lack of knowledge regarding soil water functioning. Maintaining a soil cover can lead to reduced evaporation from soil (Pittelkow et al., 2015) and can protect the soil surface from direct raindrop impacts, thus lowering the potential for crust formation. Berry and Mallett (1988) found that soils with a soil cover resulted continuously in higher soil water contents compared with bare soils following a winter fallow period. Maize planting following long fallow periods are achievable as soon as early-season rainfall occurs, providing that the top, initially dry soil layer is wetted adequately. As a result, maize crops are established during the optimal planting window from mid-November to mid-December. In addition, a more optimal planting depth is achieved as producers are able to plant immediately after a rainfall event despite only receiving a small amount that wets the top 0-10 cm of the soil profile. Conversely, in a continuous maize production system (where no 15- to 17-month fallow period is practiced) with rigorous soil tillage and no soil cover, maize producers delay planting until adequate rainfall has been received. During the delayed period, the upper 5 cm of the soil profile dries out before planting, and planting depth is consequently deeper to obtain adequate seed germination. Deeper seed placement delays seedling emergence (Alessi and Power, 1971). Moreover, later emerging maize seedlings are confronted with surface crusts, which are common across all rainfed maize production regions. Surface crusts are problematic when formed after planting but before seedling emergence, thereby impeding maize seedling emergence (Parker and Taylor, 1965).

It may be argued that increased maize grain yields in the maize-fallow production system is linked not only to the additional soil water carried over from the previous season, but also to more optimal planting depth, timing of planting, and optimal growing conditions early in the growing season. Alternative production systems need to be recognised in the maize-fallow

**Table 2.2:** Previous research which evaluated the response of maize grain yield to various soil tillage practices in the three distinct South African rainfed maize production regions.

| **Reference** | **Production region** | **Duration of trial (years)** | **Tillage practices and soil cover (%) † ‡** | **Soil texture** | **Production system** | **Maize grain yield responses §** |
|---|---|---|---|---|---|---|
| Mallett et al. (1987) | KwaZulu-Natal | 8 | CT, NT | Clay loam | Continuous maize | First four years NT out yielded CT |
| Lawrance et al. (1999) | KwaZulu-Natal | 13 | CT (3), NT (83), RT (28) | Clay loam | Continuous maize | No differences between tillage practices |
| Bennie et al. (1995) | Western | 3 | CT, NT, RT | Sand | Continuous maize or wheat; Maize-fallow-wheat | CT out yielded NT and RT all years |
| Swanepoel et al. (2018) | Eastern | 6-8 | CT, RT | Sandy loam, clay | Continuous maize | RT out yielded CT in four years, other four years no difference |
| Berry et al. (1987) | KwaZulu-Natal | 1 | CT (4), RT (18), NT (83) | Loam | Continuous maize | NT out yielded CT but not RT |
| Berry and Mallett (1988) | KwaZulu-Natal | 2 | CT (3), RT (28), NT (82) | Clay loam | Continuous maize | No significant differences |
| Lang and Mallett (1987) | KwaZulu-Natal | 1 | CT, RT, NT | Sand | Continuous maize | CT out yielded NT and RT |

† If no value is given the soil cover % was not reported in the paper; CT, conventional tillage; NT, no-tillage; RT, reduced tillage

‡ Reduced tillage defined as shallow chisel and disc tillage

§ Out yielded significantly at $P \leq 0.05$

production systems to improve the use efficiency of available soil water and intensify production systems to improve overall sustainability. A sustainable approach takes all soil and crop management practices of the farming system into account, where the economics of the farming enterprise and long-term environmental sustainability are balanced. Sustainability may be achieved by increasing the resource use efficiency leading to a more intensified production system. To limit fallow in the maize grain production regions, intensified production is needed by increasing crop diversity and frequency (Andrade et al., 2015; 2017). Current crop sequences are based on observations derived decades ago. Recent research evaluating rainfall use efficiency in current South African rainfed maize production regions is extremely limited or at least unpublished. Considering water is the most limiting factor for grain production in the rainfed maize production systems of the Western and Eastern regions, the efficient use of soil water is critical to maximise production per unit soil water available.

### *2.4.3 Runoff losses and soil erosion*

More than 70% of South Africa's land surface is affected by erosion (Hoffman and Todd, 2000), with soil tillage and poor land management as the major causes (Borrelli et al., 2017; Mills and Fey, 2003). Top soils in the Western region are naturally low in organic matter and clay content and highly susceptible to crust forming during rainfall events, leading to increased runoff (Mills and Fey, 2003). At a study site in the Western region, the long-term cumulative runoff was measured from plots of loamy sand soil with a 5% slope under CT in continuous maize and permanent fallow production systems (Du Plessis and Mostert, 1965). Mean annual runoff was 8.5 and 31.9% of the annual rainfall in the continuous maize and permanent fallow plots, respectively. Over 18 years, approximately 2 700 mm of rainfall was lost as runoff (Figure 2.4). The surface roughness caused by soil tillage and the present maize crops lowered runoff losses during the growing seasons. No report is given on the amount of soil cover during the trial years in the continuous maize production system, but presumably it was very low (<10%) due to the CT practices applied. In contrast, Gibbs et al. (1993) reported a weak correlation ($r^2$ = 0.44) between annual runoff and annual rainfall from fallow plots over 10 years at a trial site in the KwaZulu-Natal region. Only 15% of the mean annual rainfall was lost as runoff. The trial site was characterised by a clay loam soil with high organic matter with low potential of surface crusting, partially explaining the low runoff values. The advantages of a crop residue cover were shown by Lang and Mallett (1984) in similar soil and climate conditions as reported by Gibbs et al. (1993). After wetting trial plots to field water capacity

24 hours prior to the experiment, 63.5 mm of rainfall was applied using a rainfall simulator. Despite small differences in infiltration percentage and infiltration rate from plots with 30-75% crop residue cover, the accompanying sediment concentration measured in the runoff water decreased ($P \leq 0.05$) with increasing crop residue cover (Table 2.3). Soil erosion from plots under fallow was, on average, seven-, four-, and threefold the soil erosion on plots with 75, 45, and 30% soil cover, respectively. Although the abovementioned trials were conducted several decades ago, the data generated from these trials are still relevant in present times, as similar growing and climate conditions are currently faced in the rainfed maize production systems.

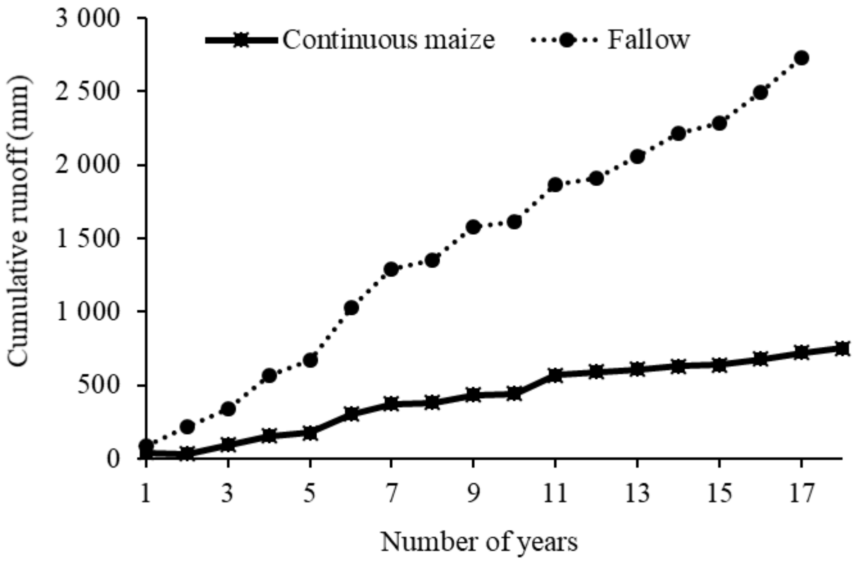


**Figure 2.4:** Cumulative runoff measured at a trial site in the Western region for plots under continuous maize and permanent fallow for 18 years. Source: Adapted from Du Plessis and Mostert (1965).

Although rainfall is the main factor causing soil erosion in the KwaZulu-Natal and eastern parts of the Eastern production region, intense wind erosion causes significant soil losses in the Eastern and Western production regions (Le Roux et al., 2008). Strong winter winds from July to September are common in both the Western and Eastern regions, whereas strong winds associated with intense thunderstorms occur during summer in all maize production regions. If not covered by living plants or crop residues, the highly erodible sandy soils are exposed to the wind causing severe dust storms. In addition, the wind-carried soil particles cause great damage to maize seedlings, with producers attempting to counteract this effect using interrow cultivators equipped with wide blades or sweeps to roughen the soil surface. Late arrival of

**Table 2.3:** The effect of crop residues on water infiltration percentage, infiltration rate and soil loss at a trial site in the KwaZulu-Natal region. Adapted from Lang and Mallett (1984).

| **Maize residue cover (%)** | **Infiltration (%)** | **Infiltration rate (mm $h^{-1}$)** | **Soil erosion (kg $ha^{-1}$)** | **Sediment concentration (kg $m^{-3}$)** |
|---|---|---|---|---|
| 0 | 31 | 19.8 | 5 989 | 13.7 |
| 10 | 37 | 23.1 | 3 761 | 9.6 |
| 20 | 39 | 24.6 | 2 812 | 7.4 |
| 30 | 41 | 26.6 | 1 999 | 5.3 |
| 45 | 48 | 30.7 | 1 501 | 4.6 |
| 75 | 46 | 29.2 | 869 | 2.5 |
| LSD (0.05) | 8.9 | 5.0 | 907 | 1.3 |
| CV (%) | 12.3 | 10.9 | 18.1 | 10.1 |

rains and prolonged drought periods during the last decade intensified these events. Wiggs and Holmes (2011) quantified the degree of wind erosion of a recent mouldboard-ploughed, fallow soil in the Western region from late winter to spring. Soil dust deposition was at a maximum during October (spring) at approximately 1.923 g $m^{-2}$ $d^{-1}$. Overall, soil dust deposition equalled an average of 0.48 g $m^{-2}$ $d^{-1}$ over 3 months. Producers opt to use mouldboard or chisel ploughs to roughen the soil surface prior to fallow in winter or the lengthy 15- to 17-month fallow period. In addition, maize grain yields achieved in the maize-fallow production systems are high, which partly explains why adoption of NT and more intensive production systems is very low in the semi-arid South African rainfed maize regions, and tilled bare soil surfaces are a common sight. In the Eastern and KwaZulu-Natal regions, with finer soil textures and a wetter and more humid climate, a higher potential exists to adopt alternative soil and crop management principles to counteract the high runoff and soil losses. Less soil disturbance, permanent soil cover by crop residues, and alternative production systems with increased crop frequency and diversification may offer opportunities to producers to lower runoff losses and erosion rates. To promote the mind shift change needed among producers, further research is required to investigate and facilitate the function of less intensive soil tillage practices and alternative crop sequences in the rainfed maize production systems. Although modern scientific data are needed to drive a change in agronomic management practices, extension officers are also required to transfer and disseminate new knowledge. Engagement with and participation of producers in on-farm research demonstrations, trials, and discussion groups are also critical (Morris et al., 1995; Sithole et al., 2016).

## 2.5 Crop management in rainfed maize production systems

### *2.5.1 Maize plant density and hybrid selection*

A recent study by Haarhoff and Swanepoel (2018) indicated that no field trials evaluating maize grain yield response to plant population and row spacing (hereafter termed "plant density") in the rainfed maize production regions of South Africa have been conducted or published the past few decades, explaining the static plant densities and why producers remained sceptical to initiate changes in plant densities. Current plant density guidelines were developed from field trials under CT several decades ago. Current research on maize hybrids is primarily conducted by private seed companies assessing their own genetic material in specific regions. This illustrates the need to re-evaluate optimal plant densities in the South African rainfed maize production regions.

Plant density directly influence maize grain yield (Ciampitti and Vyn, 2012). Adjusting plant density according to soil fertility, soil water content, and climate conditions is necessary to achieve optimal maize grain yields. Plant densities of 17 000 and 30 000 plants ha$^{-1}$ at 0.91 to 2.1 m row spacing are established in the continuous maize and maize-fallow production systems in the Western region. Low plant populations at wide row spacing are established to reduce the risk for crop failure, although a yield penalty can be expected in years with plentiful rainfall (Birch et al., 2008). However, these wide row spacings (> 0.91 m) used in the Western region are not optimised for the balance between narrower row spacings that limit soil surface evaporation, and plant populations that can be supported by the available soil water and nutrients. In the wetter and more humid Eastern and KwaZulu-Natal regions, plant densities range from 25 000 - 50 000 and from 50 000 - 70 000 plants ha$^{-1}$, respectively, established at row spacings of between 0.76 and 1.2 m.

Maize grain yield variability in the Western region is directly linked to erratic rainfall patterns between production seasons (Figure 2.2). Plant density has been increasing in major maize producing countries such as the USA, China, and Argentina, ultimately leading to higher maize grain yields per unit area (Duvick, 2005; Echarte et al., 2000; Li et al., 2011). Alongside global increases in plant density and advances in maize breeding, additional changes in soil management, weed, and pest control and the use of inorganic fertilisers all contributed towards improved maize grain yields. The introduction of NT and increased crop residue levels lead to the redesign of production systems in the semi-arid USA Great Plains (Hansen et al., 2012), allowing alternative crop sequences and significantly reduced soil erosion losses. Soils under NT have higher aggregate stability and organic matter content, thus resulting in an increased infiltration rate and water content (Verhulst et al., 2010). In turn, these soils can potentially sustain higher plant densities, leading to increased maize grain yields per unit area. To fully comprehend the functionality of current and increased plant densities in each rainfed maize production region, independent long-term research is required. There are no current published field trial data available reporting on the three-way association between maize leaf canopy cover, plant density, and available modern hybrids. Modern maize hybrids in the USA and China have an erect leaf structure contributing towards the success of high yields obtained at high planting densities (Duvick, 2005). Future research should entail an integrated approach including crop residue retention, diverse crop sequences, and various levels of soil disturbance. Understanding these aspects offers the opportunity to maximise modern maize hybrid potential and improving soil resource use efficiency in the rainfed maize production systems.

### *2.5.2 Crop sequence and alternative crop options*

Alternative crop sequences in the South African rainfed maize production regions need to be identified to diversify the maize-dominated production systems and improve the management of available soil water and nutrients. The continuous maize and maize-fallow production systems accelerate soil losses (Du Plooy, 1968), with the latter practice associated with low water and nitrogen use efficiency. The advantages of replacing maize with an annual legume in the continuous maize production system to increase crop diversity and provide yield benefits for subsequent maize has been researched. For example, in the Western region, maize grain yield increased by 27, 51, and 90% after rotation with cowpea [*Vigna unguiculata* (L.) Walp.], soybean, and groundnut, respectively (Bloem and Barnard 2001). Likewise, Loubser and Nel (2004) reported that continuous maize grain yield was 16 and 12% lower than yields in groundnut-maize and soybean-maize cropping sequences, respectively. Crop rotational benefits with legumes are more site specific in the Eastern region and are influenced greatly by seasonal climate conditions (Swanepoel et al., 2018).

The trade-offs for diversifying the maize monoculture crop sequence with legumes or sunflower is the low soil water and crop residue levels present following the legume or sunflower growing season. Deep-rooted crops deplete soil water levels to deeper depths and use soil water late in the growing season with less soil water carried over to the next crop planting, which may explain the lower maize grain yields following sunflower (Nel, 2005). Consequently, producers omit a crop from the subsequent summer growing season allowing a 15- to 17-month fallow period to recharge the depleted soil water levels before establishing the next maize planting. In addition, the low-level soil cover promotes soil tillage for controlling weeds and wind erosion during this period. Rainfed maize producers are profit driven and reluctant to include alternative crops in their maize monoculture production systems. Maize is an attractive crop option for several reasons, including wide adaptation to climate conditions, the ease of marketing harvested grain, more consistent performance in dry years, and the availability of large crop residue amounts after harvest. An example of the increased profitability provided by maize was reported by Swanepoel et al. (2018). Over eight production seasons, an average profit of US \$952.48 ha$^{-1}$ was achieved when maize was planted, compared with sunflower (\$847.86 ha$^{-1}$), millet [*Setaria italica* (L.) P. Beauv.] (\$653.64 ha$^{-1}$), and cowpea (\$331.20 ha$^{-1}$). In this study, variability in the grain yields of the various crops was high, and it was concluded that profitability is more strongly related to year-specific crop sequence choice than to changes in soil characteristics due to the various agronomic management practices applied.

The inclusion of annual cover or fodder crops may offer the potential to increase crop diversification and sustainability in the South African rainfed maize production systems. A single summer- or winter-producing cover crop can be established, whereas a multispecies mixture is an additional option. Annual cover crops could replace the short fallow during winter in the continuous maize production systems of the Eastern and KwaZulu-Natal regions using available soil water after maize harvest. Additionally, leguminous cover crops can rotate annually with maize, thereby substituting the prolonged fallow period while providing additional fixed nitrogen for the subsequent maize crops. Despite an urgent call from Nel (2005) to quantify the contribution of fixed nitrogen to subsequent crops in various crop sequence rotations, there is still a paucity of scientific data reporting on this matter in the rainfed maize production regions of South Africa. Cover crop species with a shorter growing season can be a sensible option in years of late rainfall arrival, avoiding inefficient utilisation of available soil water and bare soil surfaces. Importantly, cover crops can be managed as multipurpose crops. Not only providing an economical return on investment if grazed by livestock, the cover crop biomass could serve as a soil cover if not grazed too severely. It is necessary to balance the fodder needs for livestock with the needs for soil cover to promote sustainability and limit soil erosion. Recent research investigated biomass production per growing season for various maize-legume crop sequence combinations in the Eastern region. Swanepoel et al. (2018) reported that millet and cowpea produced average biomass yields of 4.78 and 5.41 t ha$^{-1}$, respectively. In turn, Lang and Mallett (1984) reported that a soil cover of at least 30% is needed to permit adequate water infiltration into the soil. Therefore, producers need to manage cover crop biomass according to the prevailing seasonal climate conditions and farming needs to assure efficient resource use efficiency while conserving the resource base. An expert-based decision making support system would greatly assist producers with these challenging decisions on biomass utilisation across the entire farming system.

It is clear that there exists a need for crop diversification in the South African rainfed maize production systems. Cover crops could provide pathways to introduce crop diversification and lower soil and runoff losses in the continuous maize and maize-fallow production systems while offering a return on investment if utilised by livestock. Economic analyses are necessary evaluating the entire farming system, which includes profitability across various crop sequences and years (including a cover crop year with livestock integration), rather than income generated from a single crop per year. Such analyses may provide further insight to evaluate and facilitate the feasibility and function of legumes and cover crops into more sustainable rainfed maize production systems.

## 2.6 Mixed rainfed crop-livestock systems

Livestock, in particular beef cattle, is a key feature of South African rainfed maize production systems. Livestock provides a more stable cash-flow pattern throughout the year and helps manage risk associated with grain production systems. Cattle graze natural vegetation during summer months and feed on crop residues during winter after harvest. Moving eastwards across the rainfed maize production regions to the more wet (> 600 mm rainfall per annum) Eastern and KwaZulu-Natal regions, the production of more drought-tolerant crops (i.e., sorghum and sunflower) is replaced by production of crops more sensitive to water stress, such as soybean and maize. Corresponding to this crop production shift, producers rely less on residue utilisation by livestock with increasing stock density on natural vegetation.

During the 20th century, producers in the Western region followed a winter-sown spring wheat (*Triticum aestivum* L.)-fallow-maize production system. This production system was managed in a dual-purpose approach with cattle and sheep commonly grazing early vegetative growth of winter wheat, allowing grain harvest early in summer. Winter wheat production in the Western region has declined significantly over the past decades, with producers opting for higher yielding and high-profit-potential crops such as maize and soybean. The exclusion of winter wheat production in the Western region left a void in forage availability during early winter, thereby creating a bigger need for crop residues. Land area under winter producing forage crops triticale (*x Triticosecale* Wittm. ex A. Camus) and black oat (*Avena strigosa* Schreb.) and summer-grown forage sorghum increased to assist forage needs (G. Trytsman, 2019).

Potential trade-offs linked to mixed crop-livestock systems in rainfed maize production systems are shallow soil compaction caused by traffic from livestock hooves and soil cover loss with consequent effects on crop yield and soil organic carbon levels. Data generated from field trials offering a comprehensive understanding of cattle-induced soil compaction on subsequent maize grain yield across the South African rainfed maize production regions are highly limited or unpublished. Also, there exists a poor understanding among producers regarding the interlinked balance between crop residue loads on offer to livestock and the load needed for adequate soil cover to offer protection against erosion and rainfall runoff losses. As a result, producers allow livestock to remove all available crop residues during winter. After the grazing period, fields are tilled several times using chisel ploughs to alleviate shallow soil compaction, combat wind erosion, and eliminate winter weeds. These management practices result in a soil cover of less than 10%. The quantity of soil water loss caused by these soil tillage actions is unknown, which may contribute to the fact that producers do not hesitate to graze available crop residues maximally and consequently make use of several soil tillage operations before the next maize crop.

Valk (2013) and Batidzirai et al. (2016) estimated the amount of maize residue cover required annually to maintain soil organic carbon levels at 2.0% in the various rainfed maize production regions in a continuous maize production system (Table 2.4). Overall, less maize residue is required under NT compared with CT. The humid and wet climate of the Eastern and KwaZulu-Natal regions can lead to fast degradation of residues, explaining the small difference in maize residue cover required between the wetter regions and the semi-arid Western region.

**Table 2.4:** Annual maize residue cover required to maintain soil organic carbon at 2.0% in a continuous maize production system under conventional tillage and no-tillage in the various rainfed maize production regions. Adapted from Valk (2013) and Batidzirai et al. (2016).

| Production region | Maize residue cover (kg $ha^{-1}$) | |
|---|---|---|
| | Conventional tillage | No-tillage |
| Western | 4 400 - 5 800 | 3 800 - 5 000 |
| Eastern | 4 100 - 4 400 | 3 300 - 3 800 |
| KwaZulu- Natal | 4 200 - 4 700 | 3 600 - 3 800 |

## 2.7 Outlook for sustainable rainfed maize production

Rainfed maize production is important in addressing high food and livestock feed demands in South Africa. South African rainfed maize production regions are diverse in climate conditions and soil types, giving rise to numerous advantages and disadvantages within each maize production system and consequently the agronomic management practice followed (Tables 2.5 and 2.6). More complex cropping systems through increased crop sequence diversity and frequency should increase resource use efficiency and may offer tools to overcome the disadvantages faced within continuous maize and maize–fallow systems. As demonstrated for the small grain crop rotation systems produced in the Western Cape of South Africa (MacLaren et al., 2019), diversified cropping and mixed crop-livestock systems offer alternative tools to combat weed and disease problems compared with continuous crop and crop-fallow systems. The current use of rigorous soil tillage practices, maize monoculture, and fallow periods will continue to result in excessive soil erosion and water losses and further lower the availability of already limited crop residues, especially in the semi-arid Western region.

There is growing concern among local maize producers regarding variable maize grain yields achieved globally under NT (Pittelkow et al., 2015), especially during the initial stages of adoption. The origins of these maize grain yield penalties should be identified to minimise largescale maize grain yield reductions in local rainfed maize production systems. To achieve this, contributions will be needed from all participating agriculturalists such as soil, plant, and breeding scientists, field technicians, and maize producers. The trade-offs associated with crop residue utilisation in mixed crop-livestock systems should be considered within each farming system, exploring the possibilities of including forage or cover crops to increase the availability of fodder. An adaptable approach is called for (Findlater et al., 2019; Van der Laan et al., 2017), whereby all aspects regarding in-field activities are taken into consideration, resulting in a wide spectrum of agronomic management options. Unfavourable climate conditions, such as prolonged droughts and damaging winds across the South African maize production regions inherently call for such adaptable approach.

## 2.8 Current research needs for rainfed maize production systems in South Africa

To address on-farm challenges and to enhance the facilitation of proposed alternative approaches, long-term research is required to provide producers with a knowledge base to make informed decisions on available soil and crop management tools and technology to include in their unique rainfed maize production system. We propose the following future research recommendations for the South African rainfed maize production systems:

- Evaluation of the effects of soil tillage practices (CT, RT and NT) on rainfed maize growth and yield using new hybrid releases and newly adapted planter technology. Conclusions and recommendations regarding the feasibility of the soil tillage practices should follow a farming system analysis, considering economics (potential savings in fuel and labour) and effects across the rotation in time.
- How soil-related challenges associated with NT can be dealt with using strategic tillage or a controlled traffic farming system.
- Conduct a farming system analysis of diverse crop sequences evaluating resource use efficiency, crop productivity, and the influence of each crop within the crop sequence on the performance of the subsequent crops. The overall resource use efficiency and crop productivity should be evaluated for a wide range of diverse crop sequences.
- Investigation of the effects of livestock-induced soil compaction and to provide pathways to limit the effects of livestock on soil structure and subsequent crop yields.
- Incorporation of cover/forage crops (leguminous and non-leguminous) into mixed rainfed crop-livestock systems to improve crop residue (i.e. soil cover) management and increase crop diversity, while offering a return on investment by livestock grazing. Economic analyses are necessary evaluating the entire mixed crop-livestock system, which includes profits across various crop sequences and years (including a cover crop year with livestock integration), rather than income generated from a single crop per year.
- Quantification of the contribution of fixed nitrogen to subsequent crops in various crop sequence rotations.

**Table 2.5:** A summary of advantages, disadvantages and possible tools to overcome the disadvantages of current and proposed rainfed maize production systems in South Africa.

| **Production system** | **Advantages** | **Disadvantages** | **Tools to overcome disadvantages** |
|---|---|---|---|
| Continuous maize | High rainfall use efficiency<br>Delayed planting date<br>High crop residue volumes<br>Grain easily marketed | Weed control challenges<br>Nutrient depleted soils<br>High disease pressure<br>Inconsistent yields<br>Inconsistent grain markets | Maintain high soil cover<br>Diverse crop sequence<br>Mixed crop-livestock system<br>Intercropping<br>Integrated weed management |
| Maize-fallow | Lower risk for crop failure<br>Planting date more optimal<br>Planting depth more optimal<br>Grain easily marketed | One harvest in two years<br>Bare soil for long period<br>Low rainfall use efficiency<br>Increased weed control costs<br>Enhance soil erosion and degradation<br>Nutrient leaching<br>Low livestock feed levels<br>Inconsistent grain markets | Increase crop frequency<br>Increase crop diversity<br>Cover crops<br>Maintain crop residues |
| Diverse crop sequences | High rainfall use efficiency<br>Lowers disease pressure<br>Improved weed control<br>Utilisation of crop residues/cover crops<br>Increased annual biomass production<br>Increased production intensity<br>High livestock feed levels<br>Crop diversity | Inconsistent grain markets<br>Low soil water levels following cash crop | Include cover/forage crops<br>Integrate livestock<br>Maintain high soil cover |
| Mixed crop-livestock | Stable cash flow throughout year<br>Risk better managed<br>Improved biomass utilisation<br>Crop diversity<br>Improved weed control | Shallow soil compaction<br>Soil cover loss<br>Low soil water levels after cash crop | Strategic tillage<br>Establish cover/forage crops<br>Improved biomass management<br>High intensity grazing |

**Table 2.6:** A summary of advantages, disadvantages and possible tools to overcome the disadvantages of agronomic management practices followed in the rainfed maize production systems of South Africa.

| **Agronomic management practice** | **Approach** | **Advantages** | **Disadvantages** | **Tools to overcome disadvantages** |
|---|---|---|---|---|
| Soil tillage practice | Conventional tillage | Short term weed control<br>Alleviate soil compaction<br>Uniform seedbed<br>Soil amendment incorporation | Enhance soil erosion and degradation<br>No soil cover<br>High production costs<br>Inconsistent yields<br>Enhance soil organic matter loss | Lower soil disturbance<br>Maintain soil cover<br>Diversify crop sequence |
| | No-tillage | Low production costs<br>Good soil cover<br>Lower erosion<br>Improved soil organic matter<br>Increased water infiltration<br>Lower runoff losses | Soil compaction<br>Inconsistent yields<br>Costly planter equipment<br>Higher herbicide use<br>Nutrient stratification | Controlled traffic farming<br>Strategic tillage<br>Cover crops<br>Integrated weed management |
| Plant density | Low plant density | Less risk for crop failure<br>Low seed costs | Yield penalty in good rainfall seasons<br>Poor weed suppression<br>Poor sunlight use efficiency<br>Low biomass production<br>High soil evaporation losses | Optimise row spacing and plant population for available soil resources<br>Maintain soil cover |
| | High plant density | High yields in good rainfall seasons<br>Improved soil resource use<br>Improved sunlight interception<br>High biomass production<br>Suppress weeds more easily | High risk for crop failure<br>High seed costs | Maintain soil cover<br>Less soil disturbance<br>Diversify crop sequence |

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# CHAPTER 3

# Plant population and maize grain yield: A global systematic review of rainfed trials

**Abstract**

Maize (*Zea mays* L.) productivity has increased globally as a result of improved genetics and agronomic management practices. Plant population and row spacing are two key agronomic practices known to have a strong influence on maize grain yield. A systematic review was conducted to investigate the effects of plant population on maize grain yield, differentiating between rainfall environments, nitrogen (N) input, and soil tillage practice (conventional tillage [CT] and no-tillage [NT]). Data were extracted from 64 peer-reviewed articles reporting on rainfed field trials, representing 13 countries and 127 trial locations. In arid environments, maize grain yield was low (mean maize grain yield = 2 448 kg ha$^{-1}$) across all plant populations with no clear response to plant population. Variation in maize grain yield was high in semi-arid environments where the polynomial regression ($P < 0.001$, $n = 951$) had a maximum point at approximately 140 000 plants ha$^{-1}$, which reflected a maize grain yield of 9 000 kg ha$^{-1}$. In sub-humid environments, maize grain yield had a positive response to plant population ($P <$ 0.001). Maize grain yield increased for both CT and NT systems as plant population increased. In high-N input ($r^2 = 0.19$, $P < 0.001$, $n$ = 2 018) production systems, the response of plant population to applied N was weaker than in medium-N-input ($r^2 = 0.49$, $P < 0.001$, $n = 680$) systems. There exists a need for more metadata to be analysed to provide improved recommendations for optimising plant populations across different climate conditions and rainfed maize production systems. Overall, the importance of optimising plant population to local environmental conditions and farming systems is illustrated.

**Keywords:** corn, soil tillage, plant density, row width, conservation agriculture

## 3.1 Introduction

Maize (*Zea mays* L.) plays a critical role in meeting the high food demand and is globally one of the most widely cultivated crops (FAO, 2017). Both the land area used for maize grain production and the amount of maize produced per unit area have been increasing in recent years (FAO, 2017). For example, from 2000 to 2014, maize crop area harvested in the USA, China, and Brazil increased by approximately 13, 38, and 25%, respectively (FAO, 2017). During the same period, the total maize production in these three countries increased by 31, 49, and 60%, respectively, indicating that productivity (yield per ha) increased dramatically since the start of the 2000s in these countries. In 2014, the projected total global production of maize grain was approximately 1 038 million tons (FAO, 2017).

Recent increases in maize grain yield can be attributed to genetic advances and to improved agronomic practices, including optimising plant population (Ciampitti and Vyn, 2012). Plant population has a strong influence on maize grain yield (Van Roekel and Coulter, 2011), but this relationship is highly variable (Assefa et al., 2016) and can be affected by factors such as rainfall, soil tillage practice, fertilisation and soil type. The optimum plant population depends on several crucial factors, including soil fertility, soil water holding capacity, and hybrid maturity group (Sangoi et al., 2002). Interactions between plant genotype and plant population can also affect maize grain yield, with a recent study, conducted by DeBruin et al. (2017), finding a positive relationship between maize grain yields and plant population in modern hybrids, but a contrasting response in older hybrids. Modern hybrids possess the ability to withstand greater stress attributable to high population densities than older hybrids, which in turn enables producers to establish higher plant populations leading to higher yields per unit area (Duvick, 1997; Russell, 1984). The agronomic practices implemented in a production system should allow the selected germplasm to react positively to the increased plant populations when favourable environmental conditions occur (Haegle et al., 2014), while also be tolerant to increased plant-to-plant competition under sub-optimal growing conditions (Tokatlidis and Koutroubas, 2004). Changes in agronomic practices, such as fertilisation, effective weed control and tillage practices can further alter the relationship between population density and maize grain yield. Thus, it is important to adjust plant population accordingly to achieve optimal grain yields.

During the past six decades, much work has been done to evaluate the effects of plant population on maize grain yield in a wide variety of environments and regions (e.g., Assefa et al., 2016; Ciampitti and Vyn, 2012; Duncan, 1958; Hörbe et al., 2013; Pretorius and Human, 1987; Qin et al., 2016). Rainfall is a major determinant of differences in agronomic practices used between regions. In arid and semi-arid regions, rainfall is scarce and variable, and soil water is often the most limiting factor for grain production. Climate conditions affect soil water content throughout the growing season, influencing the number of plants per unit area the soil can maintain throughout this period and, therefore, the optimal plant population. Both plant population and row spacing affect leaf canopy architecture (Sharrat and McWilliams, 2005) and, in turn, affect crop uptake of water and nutrients as well as light interception. To justify the establishment of low plant populations, rapid canopy closure is needed for efficient resource use. Hammer et al. (2009) found that at high plant populations, root architecture was more important than canopy architecture and light interception for increasing grain yield. The optimum plant population in low rainfall environments is not only the function of precipitation, but also a function of the storage capacity of the soil in the rooting zone of crops.

Precipitation can also influence the choice of tillage practice, as soil water content affects the level of soil compaction during tillage (Voorhees, 1987). However, the choice of tillage practice can also affect soil-water dynamics, which in turn influences the optimal plant population. For example, reducing soil tillage, in association with retaining crop residues to increase water infiltration and reduce run-off from the soil surface, will enhance crop yield potential under specific climate conditions (Adekalu et al., 2007; Findeling et al., 2003; Thierfelder et al., 2015).

Maize producers in many parts of the world, particularly in developing countries where good quality data from local trials are not available, rely on published information to make agronomic decisions. Many papers have been published on the effects of plant population on yield, but the results are associated with prevailing local environmental conditions and agronomic practices of each study. This could lead to confusion among maize producers regarding the most appropriate agronomic management decision for their specific conditions and farming systems. Thus, there is a need to consolidate these global findings to identify how plant population affects maize grain yield under different climate and agronomic conditions. To address this, we have conducted a systematic global review of published data from rainfed (non-irrigated) maize production field trials to i) investigate the effects of plant population on maize grain yield and ii) determine the influence of mean annual rainfall, soil tillage, and applied nitrogen (N) on the relationship between plant population and maize grain yield.

## 3.2 Materials and methods

### *3.2.1 Selection of studies*

To collate peer-reviewed articles, a literature search was conducted using the Institute for Scientific Information Web of Science Database (http://apps.webofknowledge.com). The "Web of Science Core Collection" option was used. No timeframe limitation was set and the last online search was conducted on 5 September 2017. The keywords used included combinations of "corn yield", "maize yield", "plant population", "planting density", "sowing rate", "planting rate", "corn population", and "maize population". When articles were unavailable online or from local libraries, a request was made directly to author(s) of the particular article to provide a reprint. Articles were read in full text and examined on the basis of the following eligibility criteria: (i) plant population was evaluated as a treatment to investigate the effects thereof on maize grain yield, (ii) data reported were generated by field experiments with sound statistical designs, and (iii) field trials received no irrigation prior to planting or during the growing season. Any article that was not in English or did not meet the abovementioned eligibility criteria was excluded. Field trial data generated for modelling purposes were included. To overcome publication bias challenges, studies selected for analysis were not geographically limited. This ensured the inclusion of field trial data from various climate conditions, combined with different agronomic management systems.

### *3.2.2 Data collection and extraction*

Data extracted from each eligible article included spatial data [trial location and global positioning system (GPS) coordinates], temporal data (trial year), climate factors (mean annual precipitation), and agronomic information and data (tillage practice, plant population, row spacing, applied N rate, and maize grain yield). Data were directly extracted from published tables or from digitised graphs by using WebPlotDigitizer (Rohati, 2015). Maize grain yield data were standardised to a moisture content of 15.5% and expressed in kg ha$^{-1}$. Only "treatment mean" values were extracted, regardless of the number of replications. If no values were reported in the publication for plant population or if grain yield and rainfall data were reported across varying plant populations, it was recorded as a missing data point in the database. For the purpose of this study, the plant population established at planting was extracted, except in cases where the plots were deliberately planted to a higher population and thinned at an appropriate time during the growing season to achieve specific plant populations. In such instances, the final plant populations were extracted**.** If GPS coordinates of the trials were not reported, the GPS coordinates of the nearest town to the trial location were used.

### *3.2.3 Spatial and temporal distribution of research*

A total of 64 articles met the eligibility criteria, which represented 13 countries from five continents. A list of articles included for analysis can be found in Table A1 (Appendix A) with a full reference list provided in Appendix B. A total of 117 trial locations were from the northern hemisphere but only 10 were from the southern hemisphere. Out of these 127 trial locations, trials from North America were dominant (76%), followed by Asia (14%), and South America (4%) (Figure 3.1). The least number of trial locations were from Africa and Europe, both contributing 3%. Most research locations represented humid environments. Sixteen field trials were conducted in semi-arid and super-humid environments, whereas only three had been conducted in arid environments. A spatial distribution of research in our study was biased towards the northern hemisphere, the southern hemisphere being poorly represented (Figure 3.2).

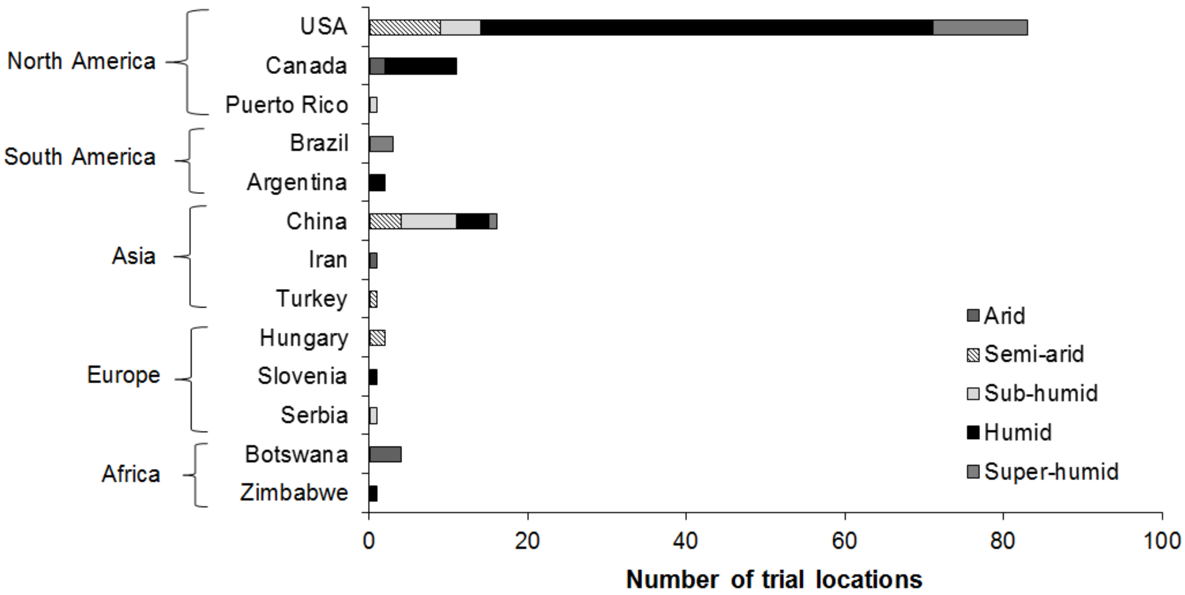


**Figure 3.1:** Distribution of field trial locations in different countries and continents located in the various rainfall groups.


**Figure 3.2:** Spatial distribution of field trial locations, as extracted from peer-reviewed articles.

From 1966 to 2015, the majority of plant population field trials had been conducted under conventional tillage (CT) practices, with trials under no-tillage (NT) first performed only in 1986 (Figure 3.3). Both CT and NT showed an increase in the number of trials conducted during 1996 to 2000, with 19 and 14 trials, respectively. Establishing the optimal plant population is basic agronomic information needed for newly introduced NT systems, and thus trials on NT increased noticeably after 1995, as NT systems increased in popularity around the world. The number of trials involving NT decreased after 2000 and remained fairly constant until 2015, presumably because the optimal plant population was established for NT systems by 2000. However, even though there was an increase in trials under NT after 1995, the number of trials conducted under CT remained higher.

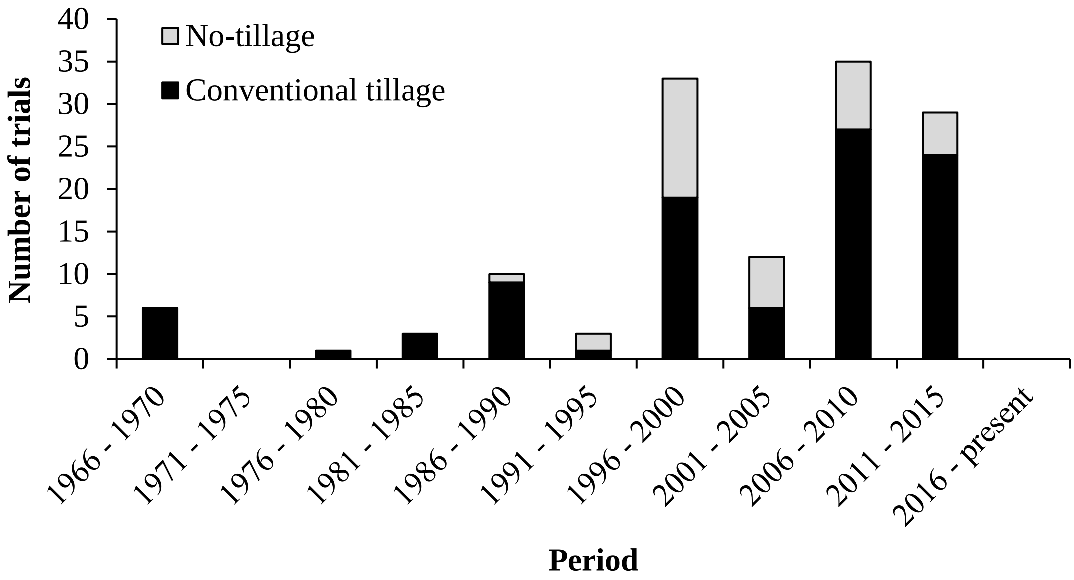


**Figure 3.3:** Number of field trials involving conventional tillage or no-tillage practices between 1966 and present.

### *3.2.4 Dependent variables of interest*

In this study, plant population refers to the seeding rate at the start of the growing season (i.e. the intended number of plants per unit area). Producers can alter both plant population and row spacing independently: for example, by keeping the plant population constant while increasing the row spacing, altering the intra-row spacing (spacing between two plants in the same row) but keeping the row spacing constant, and different intermediate configurations. The optimal plant population for a region is dependent on the prevailing soil and climate conditions. Therefore, comparing studies conducted in regions with dissimilar soil physical characteristics that influence water holding capacity, or with dissimilar mean annual rainfall will lead to erroneous results and conclusions. To avoid this, eligible studies were categorised into five groups according to long-term mean annual rainfall as arid (200 - 400 mm), semi-arid (400 - 600 mm), sub-humid (600 - 800 mm), humid (800 - 1 000 mm), and super-humid (>1 000 mm). The effect of tillage practice was analysed by comparing NT systems with CT systems across different plant populations. For the purpose of this study, any form of tillage or soil disturbance other than by direct drilling with seed-drills was described as CT, as suggested by Reicosky (2015). Minimum-tillage (strip-tillage) was performed in three studies, which were classified as CT (soil cover percentage was either not reported or low). Possible interactions between rainfall and tillage practices could not be investigated because of the absence of NT trials in several rainfall categories.

The effect of plant population and N fertiliser input on maize grain yield was also investigated for studies that reported N fertiliser input. Studies were categorised into three groups according to the total N applied: low (< 100 kg N ha$^{-1}$), medium (100 - 200 kg N ha$^{-1}$) and high N input (> 200 kg N ha$^{-1}$). This includes N applied before planting, at planting, and side-dress applications at various growth stages.

Data were also stratified according to soil textural class, organic matter content, soil bulk density, percentage soil cover, and previous crop. However, the aforementioned results are not shown, as there was either no clear response, or not enough reports of these factors to reflect a representative situation.

### *3.2.5 Statistical analysis*

A General Regression Model (GRM) was used to plot standardised maize grain yield against plant population. Different regression models were tested and a quadratic regression model provided the best fit to the data, as measured by the coefficient of determination. The coefficient of determination was calculated based on the proportion of variability around the mean for maize grain yield that was explained by plant population.

Data were optimised by profiling the desirability of maize grain yield responses to plant population and row spacing simultaneously according to procedures described by Derringer and Suich (1980). This technique is commonly used for analysis of industrial data where multiple operating conditions must be optimised at the same time (Silva et al., 2013). The procedure involved two steps. Firstly, the responses of maize grain yield ($Y_n$) were predicted by fitting the observed responses in maize grain yield using Equation 1 that was produced from a GRM:

$$Y_n = 0.15(\text{PP}) + 8\,261(\text{RS}) - 3\,000(\text{RS})^2 - 2\,880 \quad (1)$$

where PP is plant population (plants ha$^{-1}$) and RS is row spacing (m). Secondly, the plant population and row spacing were then obtained that simultaneously produced the most desirable (highest) predicted maize grain yield. This transformation was performed by the following desirability (*d*) function in Equation 2.

$$d_n = \begin{cases} 0 & if\ \hat{Y} < Y_{min} \\ \left(\frac{\hat{Y}-Y_{min}}{Y_{max}-Y_{min}}\right)^s & if\ Y_{min} \leq \hat{Y} \leq Y_{max} \\ 1 & if\ \hat{Y} > Y_{max} \end{cases} \quad (2)$$

Scores were assigned to predicted maize grain yield ranging from 0 (very undesirable, i.e. low maize grain yield) to 1 (very desirable, i.e. high maize grain yield). The individual desirability scores were then combined to obtain an overall desirability (D) as a geometric mean (Equation 3).

$$D = (d_1 \times d_2 \times \cdots \times d_n)^{1/n} \quad (3)$$

The regression coefficients of Equation 1 were standardised to a mean of 0 and a standard deviation of 1 to evaluate the relative contribution of plant population and row spacing to the overall prediction of maize grain yield. The standardised coefficients were 1.35, -0.86, 0.39, and -0.30 for plant population, (plant population)$^2$, row spacing, and (row spacing)$^2$, respectively. The computer package Statistica Version 13 was used for all statistical analyses (TIBCO Software Inc., 2017).

## 3.3 Results

### *3.3.1 Impact of plant population on maize grain yield*

The responses of maize grain yield to plant population in rainfall groups are presented in Figure 3.4. In arid environments (Figure 3.4a), maize grain yield was low across all plant populations ($r^2 = 0.05$, $P < 0.001$, $n = 87$), with no clear response to plant population. Maize grain yield was highly variable across the reported plant populations in the semi-arid, sub-humid and humid environments. In semi-arid environments, the polynomial regression ($r^2$ = 0.131, $P$ < 0.001, $n$ = 951) had a maximum point at approximately 140 000 plants ha$^{-1}$, which reflected a maize grain yield of 9 000 kg ha$^{-1}$ (Figure 3.4b). In sub-humid environments (Figure 3.4c), maize grain yield could not be explained by plant population ($r^2$ = 0.07, $P$ < 0.001, $n$ = 937). Most studies on plant population had been conducted in humid environments (Figure 3.4d, $n$ = 1 794). An increase in maize grain yield was recorded up to a plant population of 120 000 plants ha$^{-1}$, after which yield declined. The polynomial regression indicated a maize grain yield of approximately 11 000 kg ha$^{-1}$ at a plant population of 120 000 plants ha$^{-1}$ ($r^2$ = 0.233, $P$ < 0.001). In super-humid environments (Figure 3.4e), a positive response of maize grain yield to plant population was found ($r^2$ = 0.48, $P$ < 0.001, $n$ = 133) with a maximum yield (12 000 kg ha$^{-1}$) at approximately 110 000 plants ha$^{-1}$.

### *3.3.2 Relationship between plant population and row spacing*

A desirability function was used to express the relationship between plant population and row spacing (Figure 3.5) where 0 indicated a very undesirable score (i.e. a low maize grain yield) and 1 indicated a very desirable score (i.e. a high maize grain yield). The desirability contours ran mostly in parallel to row spacing, indicating that row spacing had a small effect on maize grain yield, explaining only 23.80% of variance in maize grain yield, according to the GRM. Plant population had the most important influence on maize grain yield, explaining 76.20% of the variance. The highest desirability scores were achieved at plant populations of ≥ 80 000 plants ha$^{-1}$. The lowest desirability was obtained when plant population was low in combination with narrow row spacing.

### *3.3.3 Soil tillage practices*

Maize grain yield increased for both CT and NT systems, as plant population increased (Figures 3.6a-b). The polynomial regressions showed maximum points at approximately 120 000 and 110 000 plants ha$^{-1}$ for CT ($r^2$ = 0.19, $P$ < 0.001, $n$ = 2 542) and NT ($r^2$ = 0.66, $P$ < 0.001, $n$ = 381), respectively. Maximum points on the regression line corresponded to maize grain yields of approximately 9 000 and 11 000 kg ha$^{-1}$ for CT and NT systems, respectively. More variation in the data was found across all plant populations for CT systems compared with NT systems. Maize grain yield varied from 110 - 18 800 kg ha$^{-1}$ for plant populations of

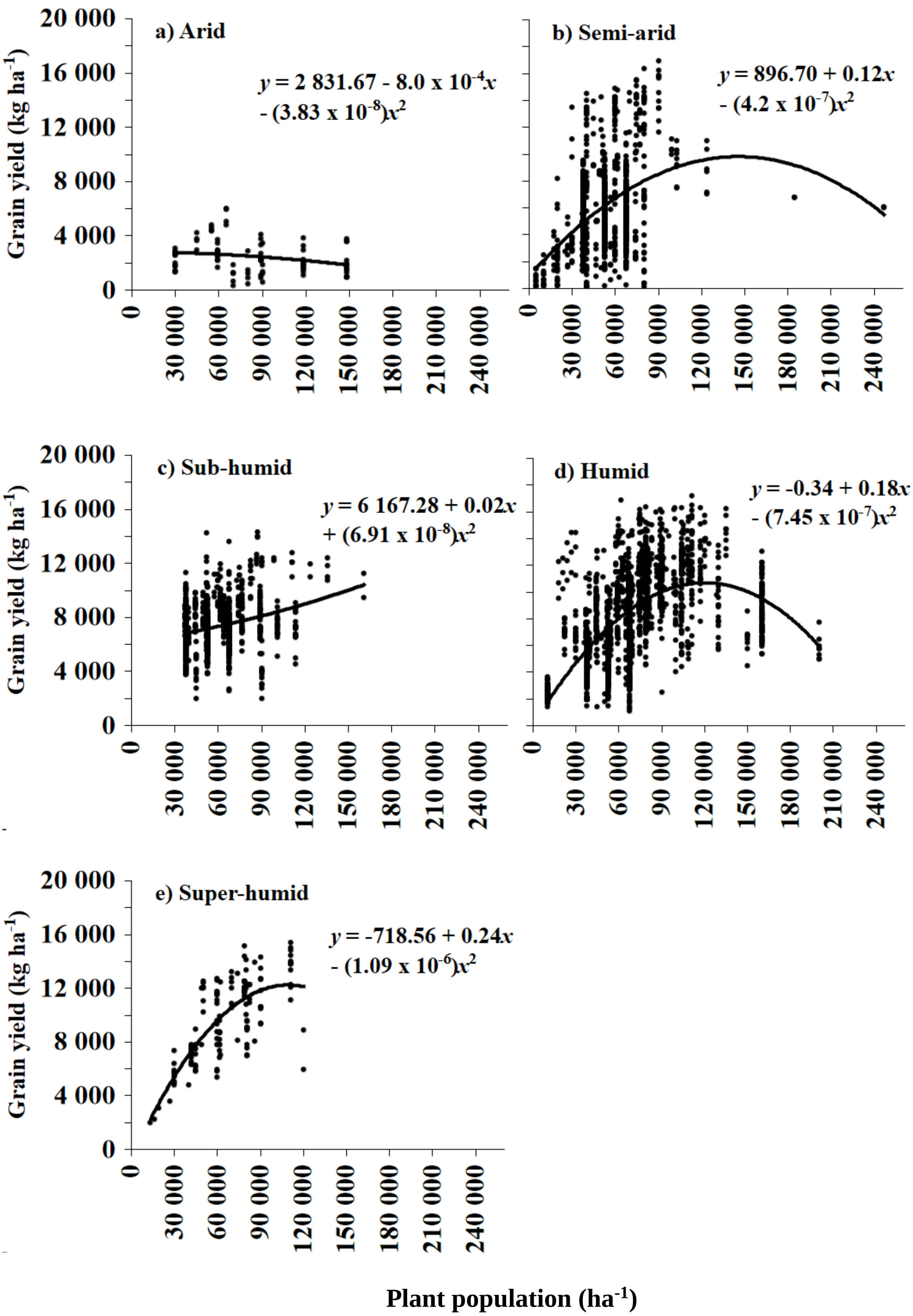


**Figure 3.4:** The effect of plant population on maize grain yield in a) arid, b) semi-arid, c) sub-humid, d) humid and e) super-humid environments.

between 60 000 and 90 000 plants ha$^{-1}$ in CT systems (Figure 3.6a) and between 700 - 16 100 kg ha$^{-1}$ in NT systems (Figure 3.6b). Low yields at the higher plant populations were reported for both CT and NT systems. The severe constraints on maize grain yield might be unrelated to plant population and could have been the effects of poor agronomic management or soil factors in combination with the tillage practice. For example, NT in a poorly drained or easily compacted soil could cause low maize grain yield regardless of the plant population. We examined whether soil textural class may be contributing to the variable yields for the CT and NT systems by stratifying the data by soil texture class. However, there were too few data points for the tillage practices in each of the soil texture classes to identify a significant impact of textural class.

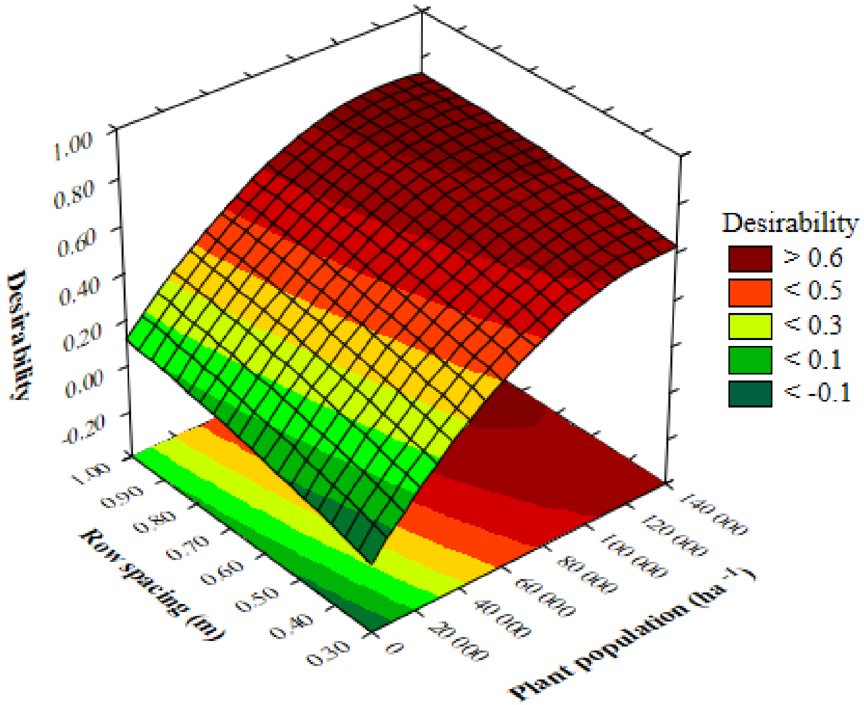


**Figure 3.5:** The relationship between predicted responses of maize grain yield on plant population and row spacing and the desirability of responses (0, very undesirable; 1, very desirable).

### *3.3.4 Response of plant population to applied nitrogen*

The response of grain yield to plant population at different N levels are presented in Figures 3.7a-c. Large variation was found in all N input systems, particularly in low N input systems. As a result, no clear-cut responses of plant population to applied N in these systems were noted

($r^2$ = 0.07, $P$ < 0.001, $n$ = 525) (Figure 3.7a). As plant population increased in medium N input systems, maize grain yield increased and reached a maximum point at approximately 110 000 plants ha$^{-1}$, corresponding to an average maize grain yield of 10 500 kg ha$^{-1}$ ($r^2$ = 0.49, $P$ < 0.001, $n$ = 680) (Figure 3.7b). For maize plant populations higher than 110 000 plants ha$^{-1}$ in medium N input systems, maize grain yield penalties could be expected. In high N input systems, the response to applied N was weaker compared with medium N input systems (Figure 3.7c) although not as weak as in the low N input systems. The quadratic regression ($r^2$ = 0.19, $P$ < 0.001, $n$ = 2 018) showed a maximum point at 150 000 plants ha$^{-1}$, reflecting a maize grain yield of approximately 10 000 kg ha$^{-1}$. Beyond this maximum point, maize grain yields declined. For all N input production systems, it was clear that N fertilisation did not explain much of the variation in maize grain yield in studies in which effects of plant population were evaluated.

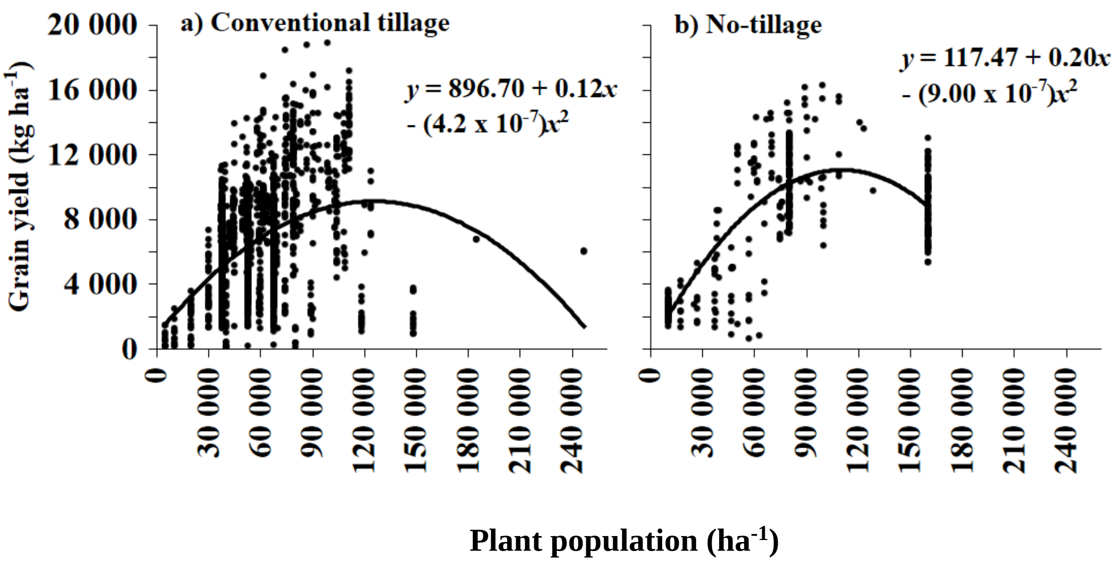


**Figure 3.6:** Maize grain yield as affected by plant population in a) conventional tillage and b) no-tillage across rainfall groups.

## 3.4 Discussion

### *3.4.1 Impact of plant population on maize grain yield*

Across all plant populations, very few observations were obtained for arid environments (Figure 3.4a), as rainfed maize production is uncommon in arid regions because of low and erratic rainfall. Plant population appeared to have no effect on maize grain yield in arid environments, even when plant population increased from 30 000 to more than 120 000 plants ha$^{-1}$. Arid regions are usually characterised by high annual and seasonal rainfall variability.

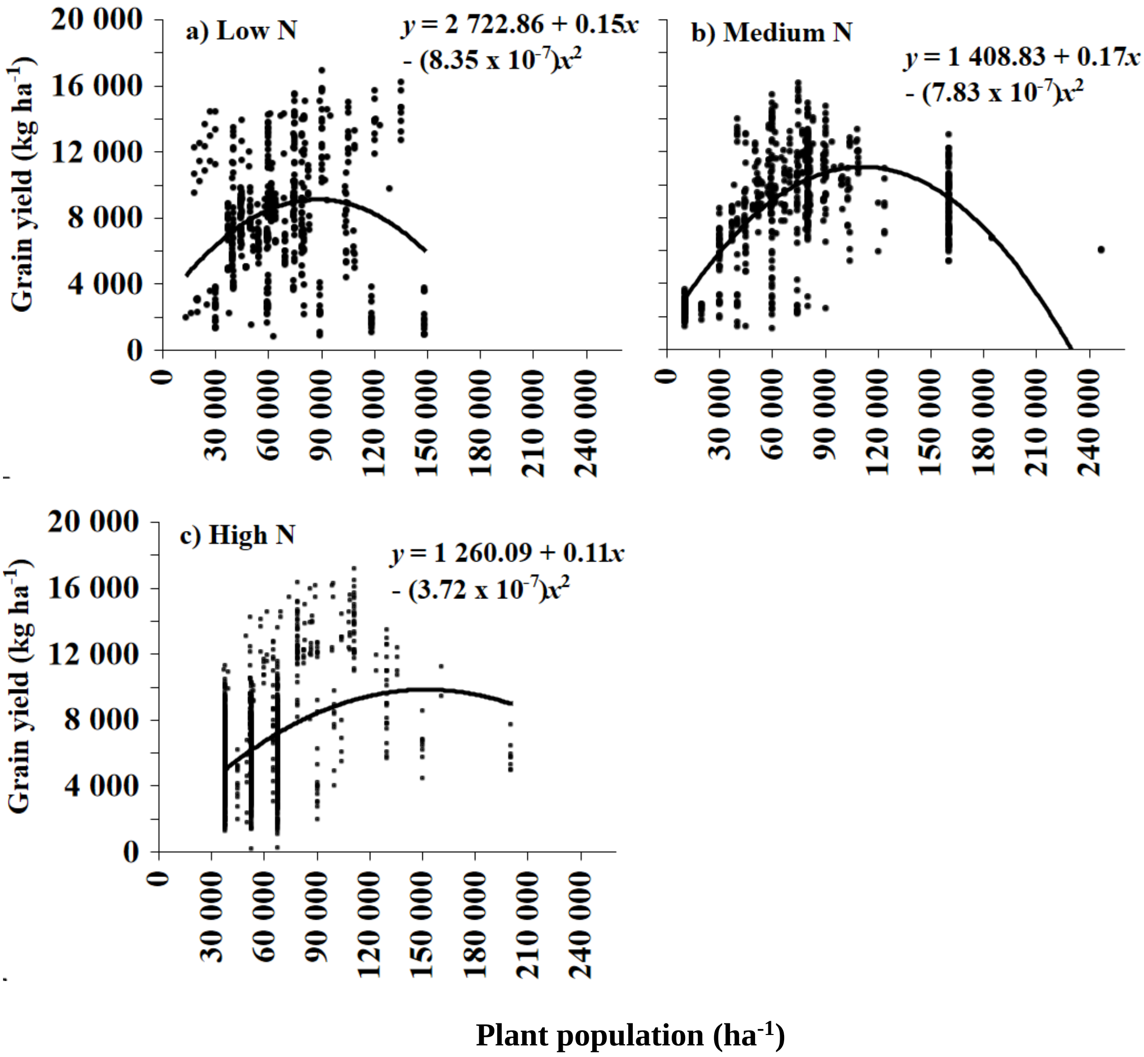


**Figure 3.7:** Maize grain yield as affected by plant population in a) low nitrogen (N), b) medium N and c) high N input systems across rainfall groups.

Low plant populations in arid environments would usually be expected to carry less risk of crop failure, even though a yield penalty could be expected in good rainfall years (Birch et al., 2008). This could possibly be a reason for data showing that plant populations as high as 150 000 plants ha$^{-1}$ could have similar yields to that of 30 000 plants ha$^{-1}$. Another factor that could explain yields obtained at high plant populations in arid environments could be soil characteristics such as texture and organic matter content that affect soil water holding capacity. Usually, in environments with such low mean annual rainfall, irrigation practices are followed to ensure crop growth throughout the growing season. A few studies reported very low yields at plant populations of more than 80 000 plants $ha^{-1}$ (Figures 3.4b and 3.4d). In one study, where plant populations of 180 000 and 250 000 plants $ha^{-1}$ were evaluated in a semi-arid environment, a soil-water deficit was observed during the silking stage in one of the trial years (Westgate et al., 1997). It has been shown that water stress during this critical growth stage decreased kernel set in the apical ear region as well as kernel dry matter yield (Setter et al. 2001). Apart from varying plant populations, hybrid choice to match the duration of the growing season and to avoid water and heat stress during critical growth stages should also be a strategy producers should use to minimise risk of crop failure.

Rainfed maize production in semi-arid environments plays an important role in grain production in various countries, such as the USA, China, Hungary, and South Africa (Bennie and Hensley, 2001; Blumenthal et al., 2003; Lente, 2009; Li et al., 2011). Our findings indicate that maize grain yield varied substantially in these environments (Figure 3.4b), which can be attributable to inconsistency in rainfall (Allen, 2012; Blumenthal et al., 2003). Blumenthal et al. (2003) suggested that, if possible, producers could use long-range weather forecasts to estimate potential grain yield at planting and alter the plant population accordingly to limit the chance for grain yield losses.

The highest maize grain yields were found in more humid environments at plant populations of between 90 000 and 120 000 plants $ha^{-1}$. Maize grain yield typically decreased when plant population reached more than 120 000 plants $ha^{-1}$ (Figure 3.4d). In these environments, variation in maize grain yield can be caused by factors such as competition for water, nutrients, sunlight and space, as well as agronomic factors such as planting date, hybrids, weed and pest control, and tillage (Begna et al., 2001; Crozier et al., 2014; Pedersen and Lauer, 2003; Shrestha et al., 2001; Van Roekel and Coulter, 2011). For example, when water stress occurs, crop responses to applied N are poor and lead to yield decreases (Clay et al., 2005). Split applications of N fertiliser would be recommended in order to apply proportionally more fertiliser during times when soil water is still available. Therefore, various factors modify the effects of plant population on maize grain yield and should be managed according to the prevailing conditions and resources.

Modern maize hybrids exhibit tolerance to drought, pests and diseases, contributing to the well-documented increase in maize yields over time. From a comprehensive review of maize yield advances through breeding by Duvick (2005), it is clear that most maize hybrids has a similar production potential when grown in a stress-free environment, i.e. very low plant populations. However, modern hybrids' tolerance to stress, which is induced by greater plant to plant competition, has increased as a result of breeding for yield under higher plant populations. Maize breeding has therefore resulted in an increased production potential when interplant competition occurs, but have not increased production potential per plant (Duvick et al., 2004). Manipulating plant population is therefore an important consideration for producers to realise maize production potential.

### *3.4.2 Soil tillage and crop management*

The optimum plant population was lower for NT than CT systems, but at a given plant population, maize yields were higher in NT than CT systems. When cultivating maize in soils sensitive to compaction and poor drainage, tillage may be advantageous by increasing drainage and root growth to deeper soil layers. This may, in turn, enable these soil types to sustain higher plant populations and narrower row spacings. Conversely, soils managed under NT practices can have higher water content in variable climates than soils managed under CT. Improved water storage, infiltration and movement in soil, due to higher aggregate stability and organic matter content, are among the most important characteristics of NT soils (Verhulst et al., 2010; Yimer et al., 2008).

No-tillage is often, though not always, practiced as part of a conservation agriculture (CA) management system. Conservation agriculture is based on a combination of agronomic practices, including minimum or NT, a permanent soil cover by either crop residues or cover crops, and crop rotations with three or more different crops. When assessing the effects of NT, it is important to keep in mind that NT alone may not be sufficient in achieving positive grain yield results. Higher grain yields attributed to NT may be the combined effect of multiple factors, such as retention of crop residues, crop rotation, and improved technology. This, in turn, may lead, *inter alia,* to reduced pest infestation, improved soil quality, specifically increased organic matter content, and increased water use efficiency (Rusinamhodzi et al., 2011).

Our results show the number of plant population trials involving NT increased significantly after 1995 (Figure 3.3). As expected, trials conducted under CT remained high throughout all eras, with an increase in the number of trials carried out after 1995. These results correspond with the findings of Derpsch (1998), Triplett and Dick (2008), Derpsch et al. (2010), and Derpsch and Friedrich (2010). Derpsch (1998) and Derpsch et al. (2010) attribute the rise of NT adoption since the 1990s to expansion into climates and soil types earlier thought to be unsuitable for crop production. However, CT remains popular where the adoption of NT is inhibited by several environmental factors, such as climate conditions, soil types, and crop requirements. Socio-economic factors can also play a strong role, as Giller et al. (2009) concluded that the critical constraints for CA adoption in sub-Saharan Africa are competition for crop residues, labour issues, and the lack of external inputs.

In recent decades, maize grain yields improved with unchanged N inputs, clearly showing more effective N use by modern hybrids (Duvick, 2005; DeBruin et al., 2017). The application rate and timing of N may be altered by the producer according to the prevailing soil and environmental conditions. In regions where heavy downpours are frequent, side-dress N applications may reduce N leaching and losses and improve N uptake by the crop. Crozier et al. (2014) found yield increases when N application was delayed until side-dress, with an interaction between row spacing and N timing. Furthermore, Ciampitti and Vyn (2011) found that both plant population and N rate had a large influence on maize grain yield, highlighting the significance of agronomic management practices to maximise maize grain yields.

#### *3.4.3 Spatial and temporal distribution of data*

The distribution of trial locations in this study was biased towards the northern hemisphere (Figures 3.1 and 3.2). Most trial locations were located in the USA, China, and Canada, each contributing 91, 18, and 12 trial locations, respectively. This could be ascribed mostly to the large number of trial locations in the major maize production zone of the USA where favourable weather conditions for maize production combined with deep, well-drained soils result in high maize yield potentials. Interestingly, there is a shortage of research focusing on the impact of plant population on maize grain yield in countries that depend heavily on grain maize as a primary food source. According to FAO (2017), the food supply quantity (maize and its products) for Africa was 121.87 g capita$^{-1}$ day$^{-1}$ during 2013. During the same year, it was 75.88, 35.34, 26.85, and 19.75 g capita$^{-1}$ day$^{-1}$ for South America, North America, Asia, and Europe, respectively (FAO, 2017). The populations of the latter three regions do not depend as heavily on grain maize for their daily diet as the former two regions, but still most research is conducted in both North America and Asia. Maize grain is primarily used as livestock feed in China and the USA, with some also used for ethanol production more recently (Ensia, 2013; IATP, 2014). Many of the countries that rely on maize for human diets are developing countries. The lack of national capacity in these countries to provide the necessary tools and materials, such as *inter alia* fertiliser, improved cultivars, and machinery likely significantly limit maize grain yields.

### 3.5 Limitations and challenges

In the current study, it was found that there is a need for better metadata in plant population studies to help explain anomalous data points in a compiled dataset. Poor reporting of trial protocols made it challenging to understand methods used in trials and consequently erroneous conclusions could result when comparing data. In a meta-analysis on NT and crop yield by Pittelkow et al. (2015) several critical management factors such as N rate and residue management were not reported adequately, which limited the utility of the extracted data for explaining the impact of plant population on maize grain yield. Derpsch et al. (2014) suggested there should be a set of questions that need to be answered in research protocols. Poor reporting of trial protocols is considered to be of particular concern with regard to the ambiguity with the role of NT in CA research (Derpsch et al., 2014). For example, in this review, only two out of the 10 articles reporting on field trials evaluating plant population under NT management recorded the type and/or amount of soil cover in the fields used for the trials. Many authors have highlighted the importance of adequate soil cover in an NT system (Derpsch et al., 2014; Sayre et al., 2006; Verhulst et al., 2010; Wall, 1999). Maintaining a permanent soil cover can be advantageous, with reduced water and wind erosion in combination with a decrease in evaporation and run-off from soil surfaces as benefits. These benefits contribute to a more sustainable cropping system and improved crop growth. Therefore, the effects of NT with CT on crop growth cannot be rigorously compared if all practices associated with NT management were not implemented.

Because of the geographical bias in the distribution of trial locations towards North America, most of the field trials included in this study were conducted at agricultural research stations. As reported by Pittelkow et al. (2015), research stations are often located on more fertile soils when compared with on-farm soils and conditions. This may impact the results regarding the effects of NT and CT under different plant populations or row spacings at the farm-level. To reduce challenges posed by the above-mentioned bias, it is recommended that more field trials should be conducted in poorly represented environments, particularly in the southern hemisphere. This should improve our understanding of the effects of agronomic management practices on crop growth in challenging environments. This can help elucidate those practices contributing to improved maize grain yields and more sustainable maize production systems.

## 3.6 Conclusion

This global systematic review was conducted to investigate the effects of plant population on maize grain yield. It was shown that the optimal plant population is dependent on rainfall and that maize grain yield varies significantly across environments with different climate conditions. Overall, our results suggest that plant populations of 90 000 - 120 000 plants $ha^{-1}$ are optimal to maximise maize grain yield across most rainfall environments. When the effects of plant population on maize grain yield were investigated for CT and NT systems, we found that optimum plant population was lower for NT than CT systems, but that, at a given plant population, maize grain yields were higher in NT than CT systems. With regard to N fertility the response of maize grain yield to plant population was weaker at high rates of N (> 200 kg N $ha^{-1}$) compared to N rates from 100 - 200 kg N $ha^{-1}$. The large variability among studies and the small number of studies in certain environments and soil tillage practices indicate that these conclusions should be applied cautiously. It is evident that there is a shortage of research in more arid environments across the world, a knowledge gap that should be addressed rapidly, given the dependence of many semi-arid regions on rainfed maize production. Recommendations for plant populations in these environments must be derived from field trials conducted under the same conditions, because of the specific challenges posed by low and inconsistent rainfall. More research is also needed to understand the response of maize grain yield to NT alone compared with NT as part of a CA system, where practices, such as crop diversification and maintaining crop residues on the soil surface, are integrated. Finally, there is a need for more metadata to provide better recommendations for optimising plant populations in various climate conditions and rainfed maize production systems.

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# CHAPTER 4

# Narrow rows and high maize plant population improve water use and grain yield under Conservation Agriculture

**Abstract**

The relationship between maize (*Zea mays* L.) population density and grain yield is influenced by soil and crop management strategies, including conservation agriculture (CA). Yet little is known about the response of maize grain yield to varying plant population and/or row spacing under CA. A three-year study was conducted under CA to evaluate the effects of plant population and row spacing on maize grain yield, plant available soil water and soil temperature. Plant populations ranging from 40 000 to 80 000 plants ha$^{-1}$ were evaluated at three row spacings (0.5, 0.76 and 1.0 m). The response of maize grain yield to plant population was highly variable between seasons: it was not affected by plant population in the season with the highest early-season rainfall but increased with increasing plant population in the driest season and in the season with well-distributed near average rainfall. Higher plant populations resulted in lower soil water levels, presumably due to greater water extraction. Plant population affected soil water availability in the 20-80 cm soil layer in Season 2, while plant population affected soil water availability at all soil layers except the 10-20 and 60-80 cm soil layers in Season 3. Rapid maize leaf-canopy closure provided by increased plant population and narrower row spacing is critical to adequately utilise the benefits associated with CA.

**Keywords:** Corn, maize management, soil fertility, sustainable food production, soil tillage

## 4.1 Introduction

Recent global maize grain yield increases were primarily driven by progress in genetic breeding and improved agronomic management practices (Ciampitti and Vyn, 2012; Duvick, 2005). The development of maize hybrids with improved ability to withstand environmental stress factors has enabled producers to attain higher yields from higher plant populations (Duvick, 1997, Duvick, 2005). Improved weed and pest control strategies (Svobodová et al., 2018) and new or diversified crop rotation sequences (Berzsenyi et al., 2000) also contributed towards higher maize grain yields.

Changes in maize aboveground morphology traits have contributed to the success of modern hybrids established at high plant populations (Duvick, 2005). Leaves situated above ears of modern maize hybrids grow more vertically following decades of genetic breeding (Boomsma et al., 2009; Duvick, 2004) leading to improved sunlight interception (Tetio-Kagho and Gardner, 1988). At high plant populations, a well-developed leaf canopy cover is present. Root architecture and distribution at high plant populations is also of critical importance (Hammer et al., 2009). During water stress periods, modern and commercially available hybrids are more effective in extracting soil water at deeper soil layers, whereas older hybrids from the 20th century utilise more water from shallow soil layers (Campos et al., 2004). Narrowing row spacing further contributed toward the success of increased plant populations (Sangoi, 2001). Improved soil resource utilisation is a benefit associated with decreased row spacing at equivalent plant populations, thereby resulting in more uniform plant-to-plant spacing, quicker leaf canopy closure and a more uniform root distribution.

Interactions between plant population and soil tillage can also influence maize grain yield. Pittelkow et al. (2015) found lower maize grain yields under no-tillage (NT) compared to conventional tillage in a comprehensive global meta-analysis. Poor crop establishment, waterlogging in poorly drained soils and subsoil compaction have been listed as factors leading to the reduced yield under NT (Derpsch et al., 2014; Halvorson et al., 2006; Iragavarapu and Randall, 1995). In addition, plant population and row spacing have a strong influence on maize grain yield (Van Roekel and Coulter, 2011). Optimum plant population and row spacing may vary with management system, such as NT, to maximise maize grain yield and improve soil resource-use efficiency (Haarhoff and Swanepoel, 2018). Numerous studies have been conducted over the past few decades to investigate the response of maize grain yield to plant population and row spacing under rainfed conditions in a wide range of rainfall environments (Alessi and Power, 1974; Balkcom et al., 2011; Pretorius and Human, 1987; Qian et al., 2016; Westgate et al., 1997; Widdicombe and Thelen, 2002). Optimum plant populations and row spacings differ between conventional tillage and NT practices (Haarhoff and Swanepoel, 2018). Between 1966 and 2017, only 40 out of 104 trials investigating the response of maize grain yield at varying plant population and/or row spacing were performed under NT with less than 10% performed under conservation agriculture (CA) (Haarhoff and Swanepoel, 2018).

Conservation agriculture is based on three principles, viz. (i) crop rotation, (ii) permanent organic soil cover, and (iii) no- or minimum soil disturbance (FAO, 2019). The benefits associated with CA include improved soil water holding capacity (Verhulst et al., 2010), increased infiltration rates (Thierfelder and Wall, 2009) and reduced weed pressure (MacLaren et al., 2018). Conservation agriculture has been adopted largely to counter soil erosion and other forms of soil degradation, and to improve resource use efficiency. Soils under CA are associated with increased soil water content (Thierfelder and Wall, 2009) and plant population and row spacing should be adapted accordingly.

Derpsch et al. (2014) called for a more optimised systems approach when investigating crop performances under NT. Studies conducted under NT often label the cropping system as "conservation agriculture", despite only one or two CA principles being practiced due to the practical challenges of incorporating all three principles. Applying CA partly may lead to the misinterpretation of crop performances under NT, crop rotation and high residue levels and may cause concerns among producers and crop researchers regarding the viability of CA. Despite the growing amount of research reporting on maize grain yield response to varying plant population and row spacing under NT, there exist a need to investigate similar maize responses under a complete CA system. The objective of this study was to evaluate maize grain yield, soil temperature and soil water content in response to varying plant population and row spacing configurations under CA.

## 4.2 Materials and methods

### *4.2.1 Site description*

Field trials were conducted near Reitz (27°46' S, 28°25' E; elevation 1 630 m) in the Eastern Free State, South Africa, during the 2015/16 (Season 1), 2016/17 (Season 2) and 2017/18 (Season 3) production seasons. The region is characterised by a subtropical highland climate

(Cwb) (Kottek et al., 2006) with a mean annual rainfall of 709 mm. Approximately 85% of the rainfall occurs during the maize growing season (October to April). Soil type was a sandy-loam Typic Plinthaqualf (Soil Survey Staff, 2003) with 1.24% soil organic matter, 1.52 cm$^{-3}$ soil bulk density and a pH(KCl) of 5.32 at the beginning of Season 1. According to the South African soil classification system, the soil form is a soft-eluvic Longlands (Soil Classification Working Group, 1991). Rainfall was measured at the trial site using a rain gauge. Average daily maximum temperature was recorded at a weather station approximately 40 km from the trial site.

### *4.2.2 Trial design and treatments*

Three target populations (40 000, 60 000 and 80 000 plants ha$^{-1}$) and three row spacings (0.50, 0.76 and 1.0 m) were studied in a factorial arrangement using a randomised block design with three replications. Plots were 24 m in length and consisted of twelve crop rows. A JM3080 PD planter [Jumil Pty (Ltd.), Castelo, Espírito Santo, Brazil] was used to establish the maize at all row spacings. The optimal seeding date in the eastern Free State range from mid-October to mid-November. However, planting is only feasible when soil water is adequate and so planting was delayed in Seasons 1 and 3 beyond the optimal dates. Crops were planted on 14 December 2015, 23 November 2016 and 4 December 2017. The maize cultivar DKC 7374BR (123 days to maturity) was used in all three seasons as it is one of the top yielding rainfed cultivars in the region and frequently planted by local maize producers.

The trials were established in a soybean [*Glycine max* (L.) Merr.]-winter sown wheat (*Triticum aestivum* L.)-maize rotation system, which has been managed under CA since 2011. The winter wheat served as a cover crop between summer grains. In Season 1, 75 kg ha$^{-1}$ N, 19 kg ha$^{-1}$ P and 9 kg ha$^{-1}$ K were applied at planting as the compound fertiliser 8:2:1 (28% purity). In Season 2 and 3, crop nutrition was applied in two equal split applications as the compound fertiliser 6:2:1 (31% purity): 35 kg ha$^{-1}$ N, 12 kg ha$^{-1}$ P, and 6 kg ha$^{-1}$ K at planting and as a top-dressing at the fifth-leaf collar (V5) leaf growth stage. Weeds were chemically controlled with pre- and post-emergence herbicides according to seasonal needs during all three seasons. Hand weeding was done where necessary to keep all plots weed free. Crop residue cover was approximately 95% during the first few weeks after harvest. Strong winter winds lowered soil cover prior to planting and soil cover generally ranged from 40 to 55% at the end of each season before planting.

### *4.2.3 Sampling and calculations*

Target plant populations were not always achieved as a result of challenging growing conditions during emergence and seedling growth and/or planter performance during all three seasons. To overcome biased reporting of results, final populations were estimated from plant counts in the eight central rows of each plot at harvest. The central eight crop rows of each plot were hand harvested at physiological maturity to determine maize grain yield. All grain yield data were standardised to a moisture content of 12.5%.

Soil temperature and water content was evaluated in Seasons 2 and 3 using AquaCheck capacitance-based soil water probes (AquaCheck Ltd., Durbanville, South Africa). The soil water probes were installed halfway between two central rows 30 days after emergence (DAE). Soil water content and temperature were recorded in 10 cm increments to 80 cm soil depth every 30 minutes from 30 to 120 DAE. In Season 2, the soil temperature, soil water content and corresponding yield data were determined as the average of three plots with two similar final plant populations (28 000 and 50 200 plants $ha^{-1}$) within the 0.5 and 1.0 m row spacings to ensure a sufficient number of replicates. The final plant population of the three plots grouped for each treatment did not differ by more than 10%. Due to a limited number of available soil water probes in Season 3, soil temperature and water data are reported as an average across row spacings to ensure three replicates in each final plant population treatment (35 000 and 50 000 plants $ha^{-1}$). Soil temperature is expressed as daily mean temperature, averaged over 30 days for the 30-60, 60-90 and 90-120 DAE growth stages at soil layers 0-10, 10-20, 20-40, 40-60 and 60-80 cm deep.

Soil water data were field calibrated as discussed by Hajdu et al. (2019). In short, gravimetric soil samples were taken from each soil layer (0-10, 10-20, 20-40, 40-60 and 60-80 cm) using a hand auger (diameter 7 cm), while calibration readings were recorded simultaneously at the corresponding soil layers. Soil sampling was done approximately 60 cm from the probe locations. Probe readings were also taken in water-filled containers (saturated readings) and in the air (dry readings). Gravimetric soil water content was consequently determined following the standard gravimetric technique (Schmugge et al., 1980). The soil samples were immediately placed in sealed containers and weighed to determine wet mass. The soil samples were oven-dried at 105°C until constant weight to remove all water. The gravimetric water content of each soil sample was then converted to volumetric water content by multiplying by the soil bulk density. A linear regression of calibration readings against volumetric water values was calculated and used to calculate volumetric water content from the growing season soil water readings. Soil water content of each soil layer was determined by multiplying the volumetric water content by the depth (mm) of the particular soil layer. Soil water content was reported as percentage plant available water (PPAW), which was determined using equation (1):

$$\text{PPAW} = \frac{\text{SWC}-\text{PWP}}{\text{PAW}} \text{x } 100 \qquad (1)$$

where SWC is soil water content, i.e. the accumulated soil water in the particular soil layer at each measurement in mm, PWP is permanent wilting point in mm, and PAW is plant available water in mm. Plant available water was calculated as the difference between field water capacity (FWC) and PWP (Table 4.1). The FWC and PWP were estimated for each soil layer using a soil water characteristics model (Saxton and Rawls, 2006).

**Table 4.1:** Soil particle size distribution, accumulated soil water content at field water capacity (FWC) and permanent wilting point (PWP), as well as accumulated plant available water (PAW) for each soil layer at the trial site near Reitz, South Africa.

| **Soil layer (cm)** | **Soil particle size distribution (%)** | | | **FWC †** | **PWP †** | **PAW** |
|---|---|---|---|---|---|---|
| | **Sand** | **Silt** | **Clay** | | **(mm)** | |
| 0-10 | 79 | 6 | 15 | 21.1 | 10.5 | 10.6 |
| 10-20 | 81 | 6 | 13 | 19.6 | 9.2 | 10.4 |
| 20-40 | 79 | 6 | 15 | 21.1 | 10.5 | 21.2 |
| 40-60 | 76 | 8 | 16 | 22.2 | 11.3 | 21.8 |
| 60-80 | 74 | 8 | 18 | 23.7 | 12.7 | 22.0 |
| Total (0-80) | | | | | | 86.0 |

†Values estimated with the Soil Water Characteristics Model (Saxton and Rawls, 2006).

### *4.2.4 Statistical analyses*

Multiple linear regression analyses were used to investigate the effect of plant population on maize grain yield within each row spacing during Seasons 1 to 3. Grain yield per plant was also analysed using multiple linear regression analyses across years and row spacings. Maize grain yield data of Seasons 1 - 3 were combined and optimised by constructing a 3-D quadratic spline curve to express predicted maize grain yield response to plant population and row spacing simultaneously according to procedures described by De Boor (1978). The 3-D spline curve was approximated by using a sequence of third-order (cubic) polynomials. When using a bivariate data set (correlations that involve two variables, in this study plant population and row spacing), the spline procedure solves cubic equations for each data point at a regular interval to determine the curve. A surface was fitted to the XYZ coordinate data using the bicubic spline smoothing procedure (De Boor, 1962).

Analysis of variance (ANOVA) was used to test the effects of plant population and row spacing on soil temperature and water content during Seasons 2 and 3. The restricted maximum likelihood (REML) procedure was followed with $P$-values for the significance of each variable calculated using a type III ANOVA based on Satterthwaite's approximation for degrees of freedom. Fixed effects were plant population, row spacing and soil depth (where applicable). Block was set as a random effect in the model. Pairwise comparisons of least square means were conducted between plant population and row spacing effects that were found to be significant at $P \leq 0.05$ in the ANOVA. Statistical analyses were conducted using Statistica (version 13.5.0.17) (TIBCO Software Inc., 2018).

## 4.3 Results

### *4.3.1 Growing conditions*

Considerable variability occurred in seasonal rainfall and rainfall distribution between the three seasons, reflecting the erratic rainfall pattern of the particular region (Table 4.2). Below-average rainfall (approximately 50% of the 30-year average seasonal rainfall) and above-average daily maximum temperatures were recorded from October to April in Season 1, while approximately 85% of the 30-year average rainfall was received in Seasons 2 and 3. Overall, dry conditions characterised Season 1 and consequently resulted in low crop establishment and poor maize growth. The onset of Season 2 was considerably wetter allowing a more optimal planting date, which enabled crops to take advantage of available soil water from early vegetative growth to the silking (R1) stage. Rainfall during the kernel filling growth stage was well below the 30-year average; however, adequate mid-season rainfall in Season 2 provided adequate available soil water for pollination and kernel development. Despite the delayed planting in Season 3 due to the late arrival of rains, rainfall in late December improved soil water levels allowing suitable growing conditions during the early vegetative growth stages. Subsequent rainfall (255 mm) created drought-free conditions from the R1 growth stage to physiological maturity (R6).

**Table 4.2:** Monthly and total seasonal rainfall and average daily maximum temperatures recorded during the 2015/16 (Season 1), 2016/17 (Season 2) and 2017/18 (Season 3) production seasons at the trial site near Reitz, South Africa.

| **Season** | **Monthly rainfall (mm)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Oct** | **Nov** | **Dec** | **Jan** | **Feb** | **Mar** | **Apr** | **Total** |
| Season 1 | 20 | 22 | 34 | 102 | 53 | 45 | 36 | 312 |
| Season 2 | 95 | 165 | 87 | 104 | 143 | 24 | 0 | 518 |
| Season 3 | 38 | 48 | 165 | 89 | 110 | 145 | 20 | 515 |
| 30-year average | 79 | 96 | 110 | 114 | 91 | 84 | 48 | 622 |
| **Season** | **Average daily maximum temperature (°C)** | | | | | | | **Mean** |
| Season 1 | 25.2 | 25.0 | 26.5 | 26.7 | 26.4 | 24.8 | 22.9 | 25.4 |
| Season 2 | 24.2 | 25.1 | 25.8 | 24.9 | 24.1 | 24.4 | 22.6 | 24.4 |
| Season 3 | 24.9 | 24.8 | 25.4 | 25.8 | 25.4 | 22.8 | 21.9 | 24.4 |
| 30-year average | 24.6 | 25.1 | 26.4 | 26.4 | 24.9 | 24.7 | 21.9 | 24.8 |

### *4.3.2 Yield response to plant population and row spacing*

The response of maize grain yield to plant population and row spacing are presented in Figures 4.1 and 4.2. Maize grain yield increased as plant population increased in Season 1 at 0.5, 0.76 and 1.0 m row spacings (Figures 4.1a-c). In contrast, maize grain yield was not affected ($P$ > 0.05) plant population in Season 2 at 0.5, 0.76 and 1.0 m row spacings (Figures 4.1d-f). In Season 3, plant population had a significant effect on maize grain yield at 0.5, 0.76 and 1.0 m row spacings (Figures 4.2a-c). In Seasons 1 and 3 maize grain yield increased with increasing plant population at all three row spacings. In Season 2 similar trends were evident but were not statistically significant.

The response of grain yield per plant to plant population is presented in Figure 4.3. As plant population increased grain yield per plant decreased ($P < 0.001$). A maximum grain yield per plant of approximately 240 g was found at a plant population of 30 000 plants ha$^{-1}$.

### *4.3.3 Relationship between plant population and row spacing*

A 3-D quadratic spline curve was used to express predicted maize grain yield response to various plant population and row spacing combinations (Figure 4.4). The contour lines were

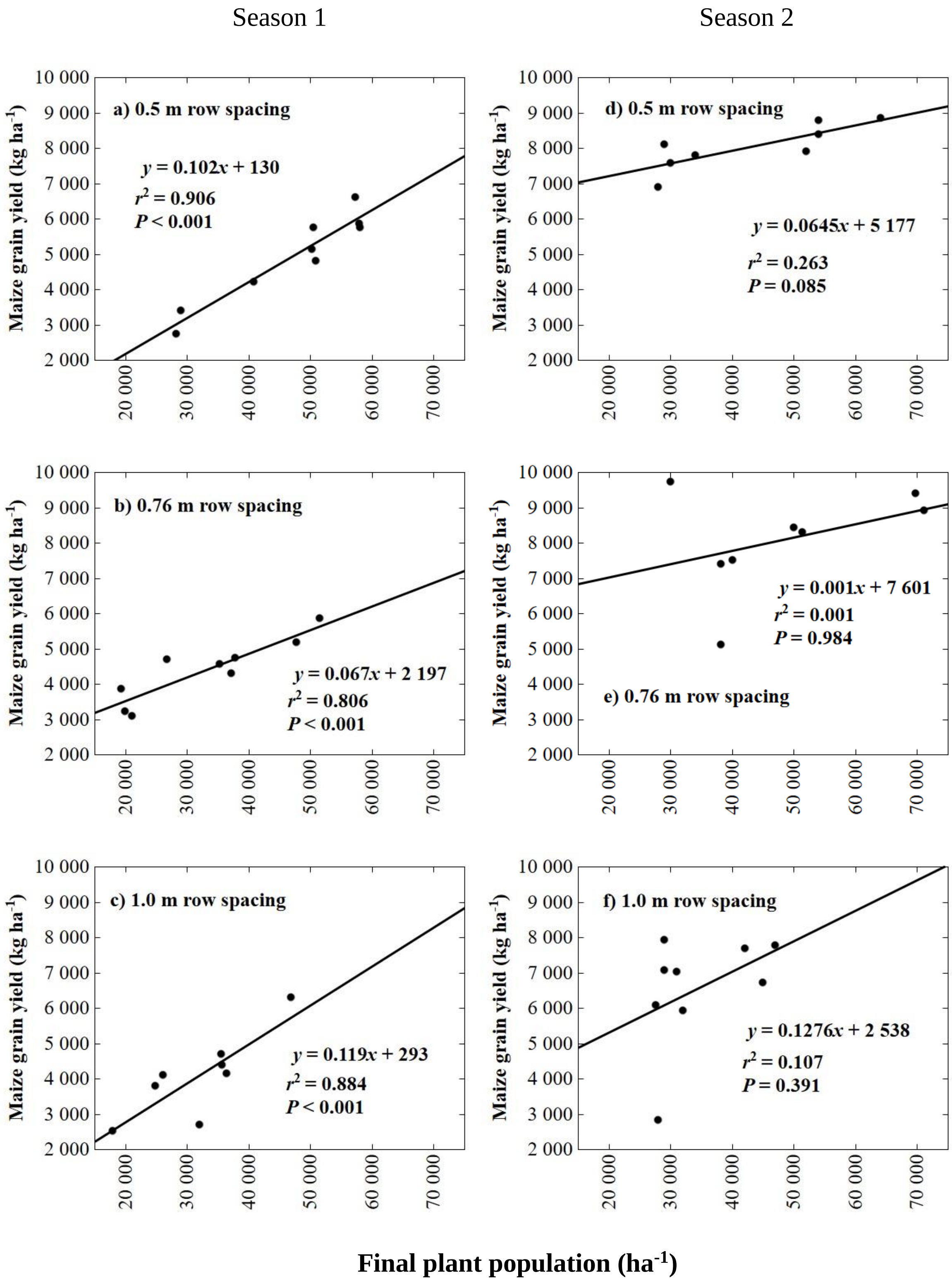


**Figure 4.1:** The response of maize grain yield to plant population in Season 1 (left) and Season 2 (right) at 0.5 m, 0.76 m and 1.0 m row spacing.

Season 3

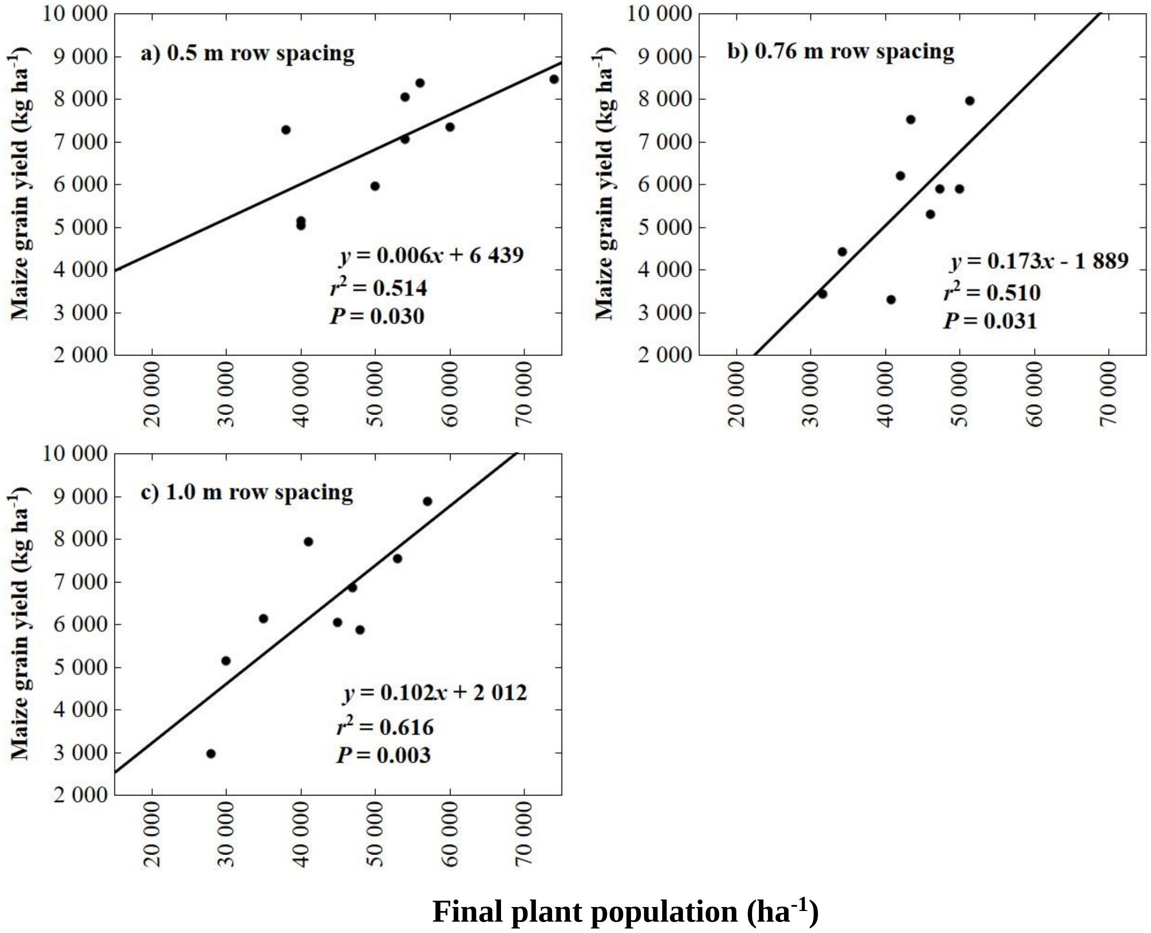


**Figure 4.2:** The response of maize grain yield to plant population in Season 3 at (a) 0.5 m, (b) 0.76 m and (c) 1.0 m row spacing.

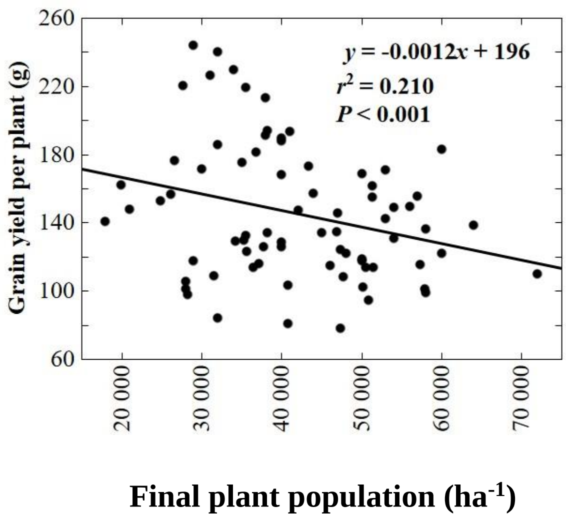


**Figure 4.3:** The response of grain yield per plant to plant population across seasons and row spacings.

primarily arranged in parallel to row spacing, indicating row spacing had a smaller effect on maize grain yield than plant population. This observation concurs with the results reported by Haarhoff and Swanepoel (2018). The highest maize grain yield was found when plant population ranged between 60 000 and 70 000 plants ha$^{-1}$, reflecting a yield of between 8 000 and 10 000 kg ha$^{-1}$. Overall, the lowest maize grain yield was found when plant population was lower than 20 000 plants ha$^{-1}$ at a row spacing of 0.80 m or wider.

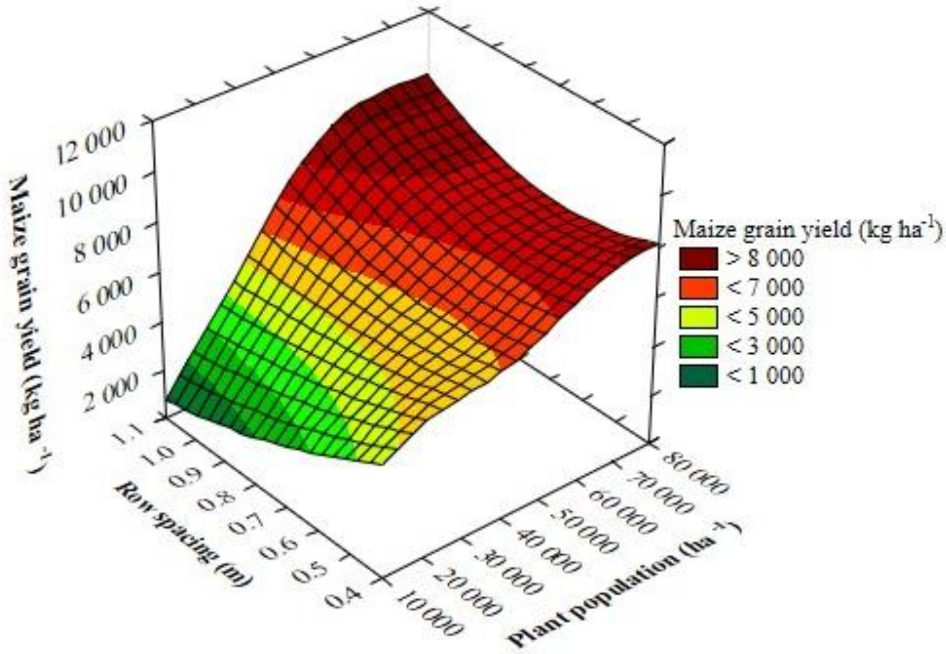


**Figure 4.4:** The relationship between the responses of maize grain yield to the combined effect of plant population and row spacing.

### *4.3.4 Soil temperature*

Daily average soil temperature was similar ($P > 0.05$) between 0.5 and 1.0 m row spacings during the 30-60 DAE growth period (Figure 4.5a). From 60 DAE onwards, daily average soil temperature was higher with 1.0 m row spacing than with 0.5 m row spacing throughout the soil profile (Figures 4.5b and 4.5c) although the effect was only noticeable during the 60-90 DAE growth period. Pairwise comparisons between soil temperatures at the two spacings at each soil depth measured were not significant. Plant population had no effect ($P > 0.05$) on daily average soil temperature in Season 3, with only some evidence ($P < 0.1$) suggesting the higher plant population resulted in lower daily average soil temperature during the 90-120 DAE growth period of Season 3. Since only depth influenced soil temperatures in Season 3, data are not shown.

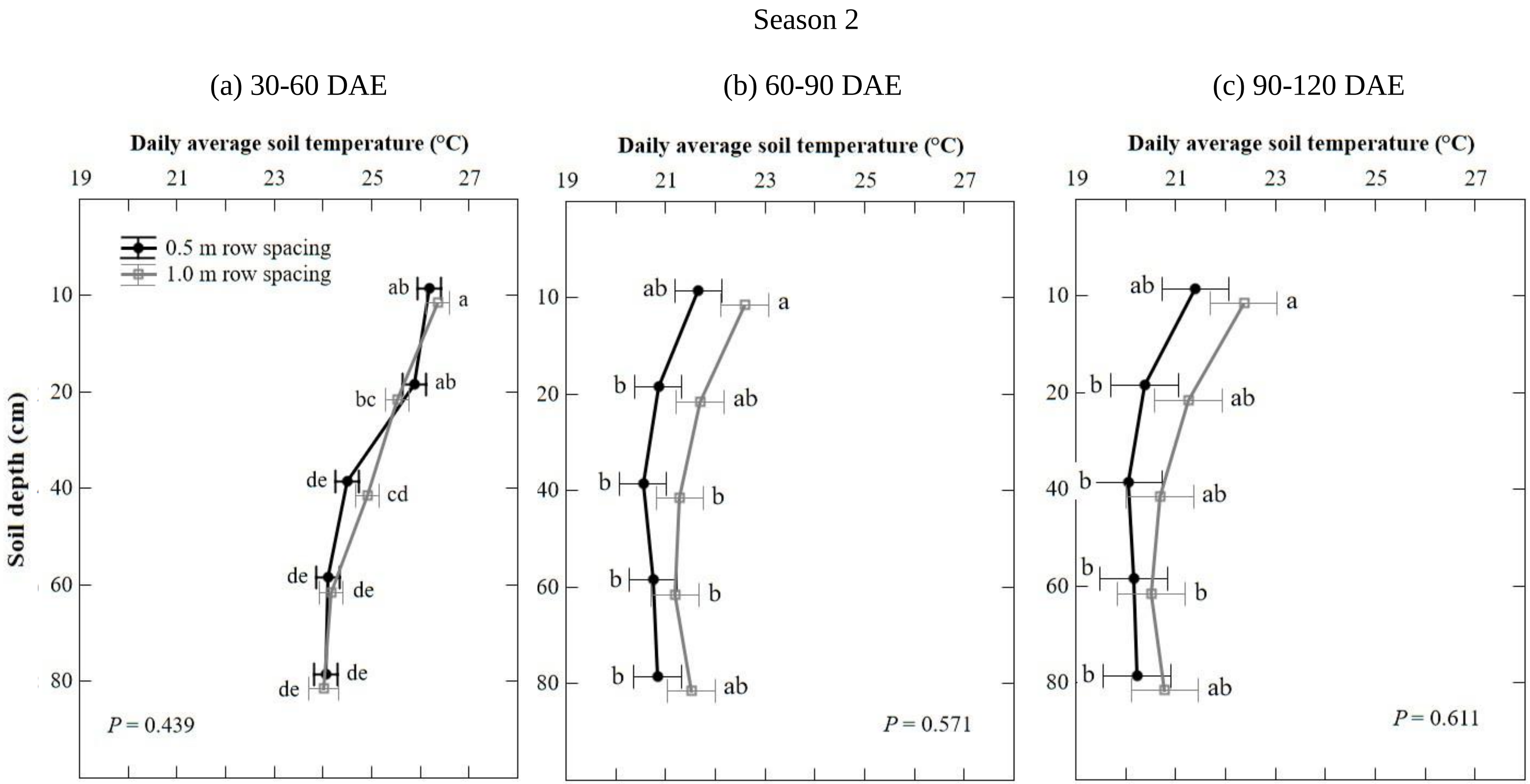


**Figure 4.5:** A comparison of the daily average soil temperature in Season 2 (2016/17) at 0.5 and 1.0 m row spacing with soil depth at (a) 30-60, (b) 60-90 and (c) 90-120 days after emergence (DAE). Means followed by a different letter indicate significant differences at $P \leq 0.05$.

### *4.3.5 Soil water availability*

In Season 2, increasing plant population reduced PPAW ($P \leq 0.05$) throughout the 20-80 cm soil layer (Figure 4.6), while there was no effect of row spacing nor a significant interaction between plant population and row spacing on PPAW. On average, the PPAW at 28 000 and 50 200 plants ha$^{-1}$ across row spacings were 56 and 51% in the 20-40 cm soil layer, corresponding to a soil water content of 11.87 and 10.81 mm, respectively. The PPAW was on average 58 and 49% in the 40-60 cm soil layer at 28 000 and 50 200 plants ha$^{-1}$ during the 30-120 DAE growth period, respectively ($P \leq 0.05$). The high rainfall at 75 DAE was apparent in the PPAW of the top 20 cm soil layer, resulting in an increase in average PPAW of approximately 20%. The high PPAW in the 10-20 cm soil layer might be explained by a possible compacted layer at approximately 20 cm soil depth, leading to the development of a perched water table following a rainfall event. The PPAW was higher ($P \leq 0.05$) at 28 000 plants ha$^{-1}$ than at 50 200 plants ha$^{-1}$ during the first 70 DAE at the 40-60 and 60-80 cm soil layers where after the differences diminished.

Plant population affected ($P \leq 0.05$) PPAW at all soil layers except at 10-20 and 60-80 cm throughout Season 3 (Figure 4.7). The average PPAW in the 0-10 cm soil layer at plant populations 35 000 and 70 000 plants ha$^{-1}$ across row spacings were 57 and 47% during the season, respectively. The PPAW values correspond to 6.04 and 4.98 mm of accumulated soil water at 35 000 and 50 000 plants ha$^{-1}$, respectively. The maize grain yield at 50 000 plants ha$^{-1}$ were higher ($P \leq 0.05$) than the yield achieved at 35 000 plants ha$^{-1}$, indicating the benefits of a high number of plants per unit area when favourable growing conditions prevail. The PPAW was inconsistent in the 0-10 cm soil layer in Season 3, fluctuating between rainfall events for a plant population of 35 000 plants ha$^{-1}$ between 50 and 70% and between 40 and 60% for 50 000 plants ha$^{-1}$. The main effect of plant population at the 20-40 and 40-60 cm soil layers was not sufficiently substantial to detect significant pairwise differences in PPAW between 35 000 and 50 000 plants ha$^{-1}$. Overall, better rainfall distribution in Season 3 resulted in less variable PPAW at soil depths deeper than 10 cm.

## 4.4 Discussion

The ability of modern maize hybrids to withstand stress factors more easily have enabled producers to achieve higher yields at increased plant populations worldwide (Duvick, 1997).

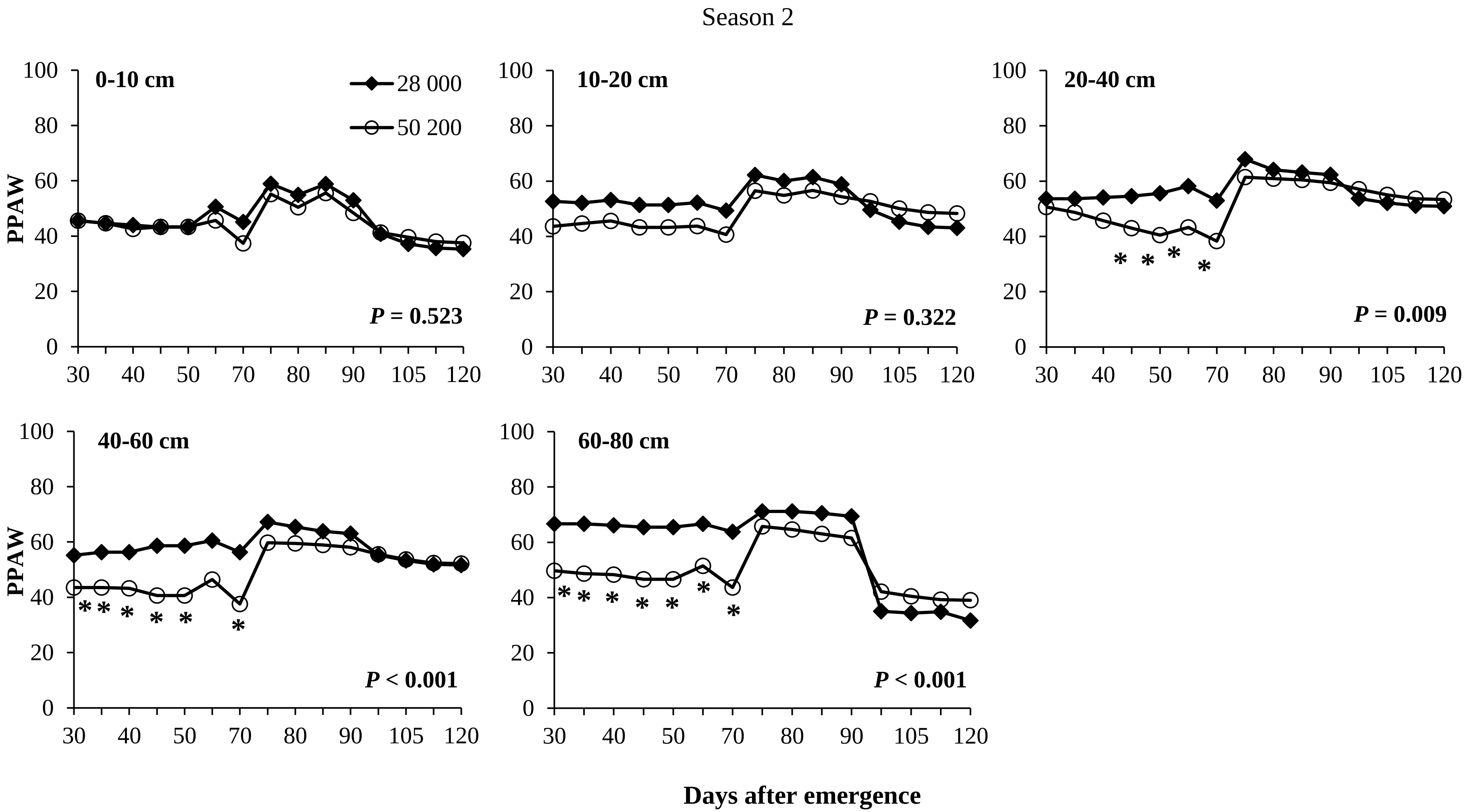


**Figure 4.6:** A comparison of percentage plant available water (PPAW) in Season 2 between plant population treatments at 10 to 20 cm soil depth increments to 80 cm deep, from 30 to 120 days after emergence. Main effects of plant population is reported and significant differences between plant population treatments at $P \leq 0.05$ are indicated by an asterisk.

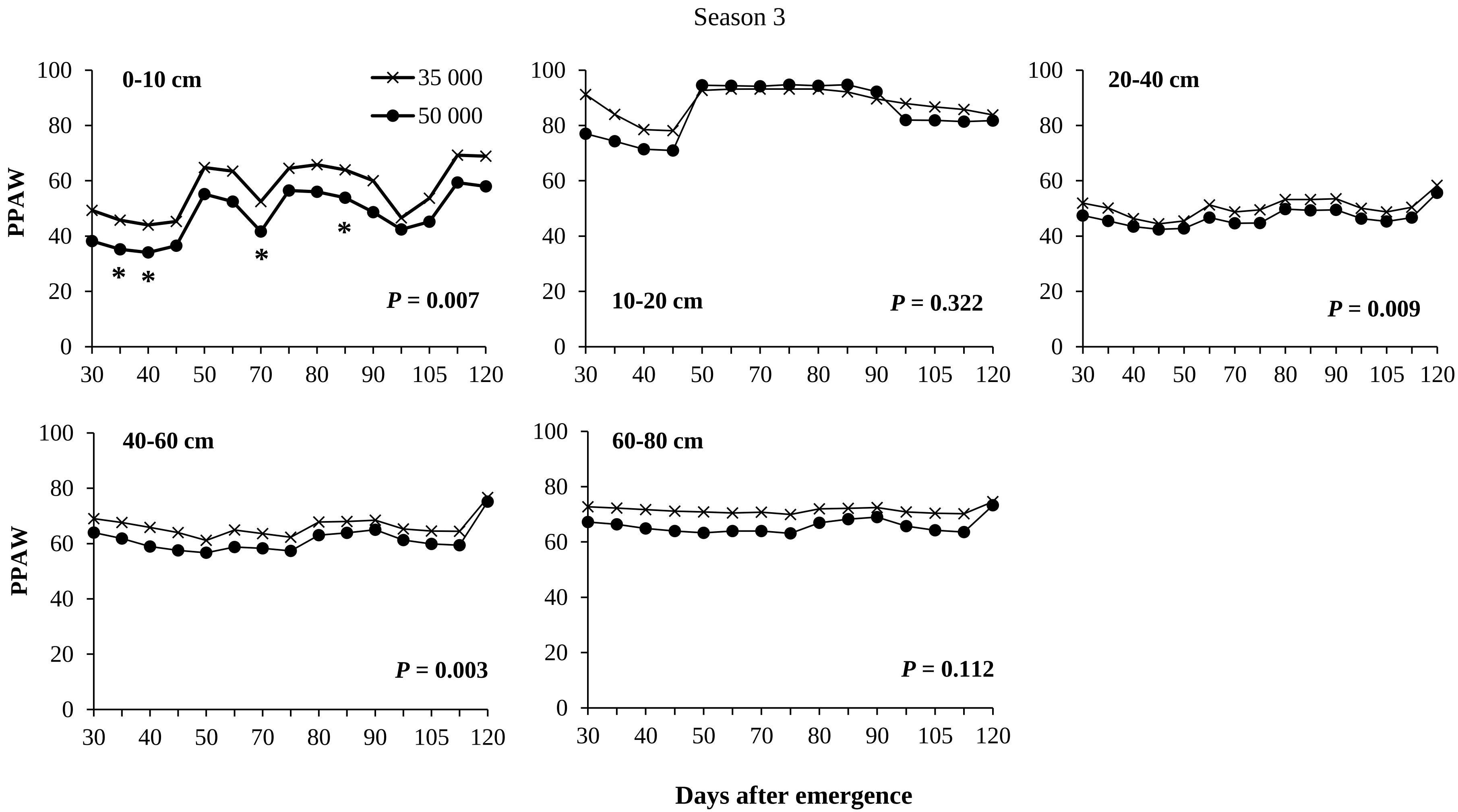


**Figure 4.7:** A comparison of percentage plant available water (PPAW) in Season 3 between plant population treatments at 10 to 20 cm soil depth increments to 80 cm deep, from 30 to 120 days after emergence. Main effects of plant population is reported and significant differences between plant population treatments at $P \leq 0.05$ are indicated by an asterisk.

However, the relationship between increased plant populations and higher yields is highly dependent, *inter alia*, on seasonal rainfall amounts and distribution throughout the growing season. The variability in maize grain yield achieved across seasons in this study support this statement, with average maize grain yield markedly greater in Season 2 (7 530 kg $ha^{-1}$) compared to 4 640 and 6 370 kg $ha^{-1}$ achieved in Seasons 1 and 3, respectively. The delayed planting date and dry conditions impeded overall growth and yield in Season 1. The higher soil water content during the critical growth periods in Season 2 due to adequate rainfall (January to February, Table 4.1) provided optimal growing conditions for maize. Evaluation of the three-way relationship between maize grain yield, plant population and row spacing revealed that yield was the greatest at high plant populations and wide row spacings (Figure 4.4), which is in contrast to previous findings (Sangoi, 2001).

The variability in maximum maize grain yield between seasons highlight the complexities involved when predicting optimum plant population and row spacing across different seasons and hybrids. Producers are understandably cautious to increase plant population considering the inconsistent rainfall pattern between seasons. Although a yield penalty is expected at low plant populations in years with good rainfall (Birch et al., 2008), less risk is involved, and producers resort to low plant populations (< 40 000 plants $ha^{-1}$). In addition, Allen (2012) reported a negative maize grain yield response to increased plant population under NT in seasons characterised with low rainfall. In contrast, the results obtained in our study indicated a positive maize grain yield response to plant population in the drier Season 1, suggesting higher plant populations are more favourable under CA.

In contrast to soil temperature, more significant differences in PPAW were observed between plant population treatments. The PPAW was higher ($P \leq 0.05$) at 28 000 than at 50 200 plants $ha^{-1}$ in Season 2. The higher plant population has led to earlier leaf canopy closure (Ottman and Welch, 1989; Tetio-Kagho and Gardner, 1988) thereby maximising sunlight interception (Ottman and Welch, 1989) and lowered evaporation losses from the soil surface (Karlen and Camp, 1985). At the 28 000 plants $ha^{-1}$ and 1.0 m row spacing configuration, PPAW was inefficiently used by plants and resulted in the lowest maize grain yield among all treatments. Poor leaf canopy cover and ineffective root system distribution across the inter-row soil volume may have led to soil water losses through evaporation. Similar findings were reported by Barbieri et al. (2012) who found a row spacing of 0.35 m consistently increased maize evapotranspiration compared to a wider 0.70 m row spacing during early maize growth stages.

It is clear that rapid canopy closure and a uniform and deep root system are critical aspects needed to efficiently utilise available soil water. This is especially important when producers opt to increase the number of plants per unit area in a rainfed maize production system where soil water is the most limiting factor for maize grain production. At high maize plant populations, root system architecture and related water-uptake is more critical than leaf canopy structure and sunlight interception for increasing biomass production and grain yield (Hammer et al., 2009). Research is needed to fully comprehend the dynamics between root system architecture and leaf canopy at varying maize plant population and row spacings configurations. This gap in knowledge should be met with field research under the various challenges set by soil and climate conditions.

Current plant population and row spacing recommendations in the eastern Free State range from 25 000 to 40 000 plants $ha^{-1}$ at row spacings of 0.76 m and wider. These recommended guidelines were derived from plots under vigorous soil tillage and monoculture maize practices. Despite the low rainfall and late planting date during Season 1, maize grain yield indicated a positive response to increased plant population within each row spacing (Figure 4.1). This suggests increasing plant population may be an important consideration for producers to realize modern hybrids' production potential and more efficient soil resource utilisation under CA. With no clear response of maize grain yield to plant population and row spacing in Season 2, it is evident that the highest maize grain yields were not necessarily associated with the highest plant population. Overall, maize grain yield reached a plateau at approximately 65 000 plants $ha^{-1}$ with a maize grain yield of more than 8 000 kg $ha^{-1}$ (Figure 4.4).

It is essential to consider the complete cropping system when choosing a suitable maize plant population and row spacing configuration. Additional factors to consider include *inter alia* livestock integration, resulting in two cropping system aspects competing for crop residues, i.e. soil cover and animal feed. Rainfed maize is primarily produced on mixed crop-livestock farms in the eastern Free State. Crop residue utilisation during winter months add value to livestock, offer a more stable cash flow pattern throughout the year and help manage risk associated with grain production systems (Bell et al., 2014). Crop residues are a key feature of not only the success of NT (Derpsch et al., 2010), but also the economic viability of the mixed rainfed crop-livestock systems, producers should apply agronomic management practices complementing increased crop residue production. An increase in biomass production has been associated with narrower row spacing (Cox et al., 1998) and increased plant population without any maize grain yield penalty (Raymond et al., 2009). The higher harvest index (ratio of grain yield to biomass) of modern hybrids at higher plant populations is not as a result of increased biomass production but as a result of increased stress tolerance and their capacity to yield higher under stress conditions compared to older hybrids (Duvick, 2005). As a result, the yield potential of individual plants have not increased but rather the yield potential of a population of individual plants (Di Matteo et al., 2016).

The economic dynamics of higher plant populations (higher seed costs) under CA within a farming system is still unknown in the eastern Free State. It is suggested that future research focuses on an economic evaluation of varying plant population levels and associated yield returns, considering a wide variety of hybrids and fertiliser applications. It would be helpful to perform plant population/row spacing trials in diverse soil conditions and crop rotational sequences.

## 4.5 Conclusion

Maize grain yield increased with increasing plant population at 0.5, 0.76 and 1.0 m row spacings in the drier Season 1 as well as in Season 3 which was characterised by more adequate and timely rainfall. Daily average soil temperature was reduced by closer row spacing during the 60-90 DAE growth period in Season 2 with no significant difference between row spacing treatments during the rest of the growing season. Row spacing had no effect on PPAW in Season 2 and 3, however, average PPAW was higher at 28 000 plants ha$^{-1}$ compared to 50 200 plants ha$^{-1}$ during the 0-70 DAE growth period in the 40-80 cm soil layer. Plant population affected PPAW in Season 3 at all soil layers except in the 10-20 and 60-80 cm soil layers. A higher PPAW was found at 35 000 plants ha$^{-1}$ than at 70 000 plants ha$^{-1}$. It appears that rapid maize leaf-canopy closure provided by increased plant population and narrower row spacing is critical to utilise the benefits associated with CA.

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# CHAPTER 5

## Benefits of increased maize plant population and wider rows under no-tillage is season-specific

### Abstract

Increased tolerance to higher competition for soil resources of modern maize (*Zea mays* L.) provide the tools producers need to increase soil resource use efficiency and ultimately yield per unit area. The three-way relationship between plant population, row spacing and maize agronomic growth is further influenced by soil tillage practices. Yet little information is currently available regarding the relationship between maize density and grain yield under no-tillage (NT) in semi-arid environments where soil water is limited. Field trials were conducted during the 2017/18 (Season 1) and 2018/19 (Season 2) production seasons to evaluate plant architecture, grain yield, biomass production, and water use efficiency of rainfed maize established at diverse plant population (20 000 to 60 000 plants ha$^{-1}$) and row spacing (0.52 and 0.76 m) configurations under NT in a semi-arid environment. In Season 1, at physiological maturity, total biomass at 20 000 plants ha$^{-1}$ at 0.76 m row spacing was 11 070 kg ha$^{-1}$, which was lower ($P \leq 0.05$) compared to the 13 071 kg ha$^{-1}$ found at 25 000 plants ha$^{-1}$ at 0.52 m row spacing. In Season 2, at physiological maturity, total biomass was higher ($P \leq 0.05$) at any given plant population at 0.76 m row spacing compared to plant populations at 0.52 m row spacing. In Season 1, a maize grain yield of 8 580 kg ha$^{-1}$ was achieved at 50 000 plants ha$^{-1}$ at 0.76 m row spacing, which was the highest ($P \leq 0.05$) among treatments. In the drier Season 2, maize grain yield varied between 4 120 to 1 318 kg ha$^{-1}$ at 0.52 m row spacing and between 4 685 to 5 280 kg ha$^{-1}$ at 0.76 m row spacing. The decision made by producers on the more optimal plant population and row spacing will ultimately be a compromise between obtaining high maize grain yield and minimising the potential for crop failure in semi-arid environments.

**Keywords:** Conservation agriculture, corn, plant density, row width, soil management, microbial activity.

## 5.1 Introduction

Rainfed maize (*Zea mays* L.) production in semi-arid environments are key in various regions in the world including the USA Great Plains, Northeast China, and Hungary to meet increasing food and animal feed demands (Clay et al., 2014; Lente, 2009; Qin et al., 2016). Semi-arid environments are characterised by high summer temperatures and low or inconsistent rainfall with heavy downpours as thundershowers. The evaporative demand that greatly exceeds rainfall in semi-arid environments highlights the importance of optimising soil available water.

The development of improved agronomic management practices constantly increase global maize grain yield. Novel weed and pest management practices (Teasdale, 1998), crop residue retention (Mupangwa et al., 2012; Sindelar et al., 2013) and soil tillage management strategies (Perez-Bidegain et al., 2007) provide pathways to reduce the risk of crop failure. Genetic advances coupled with increased plant population was a further major cause for recent maize grain yield increases (Duvick, 2005; Duvick et al., 2004). Modern hybrids are more drought-resilient to interplant competition (i.e. higher plant population), enabling producers to increase the number of plants per unit area resulting in higher maize grain yields (Ma et al., 2014). Rapid leaf canopy closure and more uniform root distribution throughout the soil matrix are key features in the success of increased plant population at a narrower row spacing (Hammer et al., 2009). Rapid leaf canopy closure suppresses weed growth (Mashingaidze et al., 2009) and increase sunlight interception (Weiner et al., 2001) allowing better crop growth. The success of increased plant population and/or narrow row spacing is well-known in wet and humid environments such as the USA Corn Belt (Duvick, 2005), Southwestern China (Qin et al., 2016) and the Argentine Pampas (Echarte et al., 2000). In contrast, maize grain yields in semi-arid environments, such as large parts of South Africa, are highly variable with a high risk of crop failure (Alessi and Power, 1974; Blumenthal et al., 2003; Haarhoff and Swanepoel, 2018). In South Africa, approximately 35% of the 12.9 million tons of maize produced per annum is produced in the Western production region characterised by a semi-arid climate regime (CEC, 2019; Schulze, 2016), which receives between 400 and 550 mm of rainfall annually. Although only 35% of the total maize production is produced in the Western production region, it comprises more than 50% of the total area used annually for rainfed maize production.

The relationship between plant population and maize grain yield is further complicated by soil tillage practices. No-tillage (NT) was introduced during the latter stages of the 20$^{th}$ century in response to severe soil erosion and degradation in the USA caused by continuous soil disturbance practices (Six et al., 2002). Although the environmental and economic benefits of NT are well-known, including increased soil organic matter and water content coupled with lower production costs, maize grain yields achieved under NT are inconsistent and highly site- and season-specific (Brouder and Gomez-Macpherson, 2014; Pittelkow et al., 2015; Swanepoel et al., 2018). Variability in maize grain yields has frequently been attributed to poor drainage and reduced growth early in the growing season in cool and humid climates, problems not often associated with drier semi-arid environments. In fact, features associated with NT, such as the retention of crop residues, has been shown to be effective in lowering the risk of crop failure due to increased rainfall retention and use, ultimately contributing towards increased maize grain yields in semi-arid environments (Bationo et al., 2007; Biamah et al., 1993).

Multiple studies have been performed across the world to evaluate rainfed maize agronomic growth and yield under varying plant population and row spacing configurations under NT and conventional tillage (studies cited in Haarhoff and Swanepoel, 2018). However, the majority of studies was performed in humid and tropical environments. Less than 5% of studies were performed under no-tillage in semi-arid environments. Therefore, although the agronomic growth and yield response of various maize plant population and row spacing configurations under no-tillage in high rainfall environments are well-researched, there exist a need to evaluate similar rainfed maize responses under no-tillage in semi-arid environments. The objectives of this study were to investigate the effects of rainfed maize plant population and row spacing on i) plant architecture and biomass production; ii) grain yield, yield components and quality; iii) water use efficiency; and iv) soil β-glucosidase activity under NT in a semi-arid environment.

## 5.2 Materials and methods

### *5.2.1 Site description*

Field trials were conducted near Ottosdal (26°47' S, 25°56' E; altitude 1 490 m), North West Province, South Africa, during the 2017/18 (Season 1) and 2018/2019 (Season 2) production seasons. The region has a semi-arid climate (BSk) with a mean annual rainfall of 591 mm (Kottek et al., 2006). Approximately 90% of the annual rainfall occurs in the summer growing season (October to April). Rainfall patterns are highly inconsistent between seasons and dry spells during the growing season, typically two to eight weeks long, is a common phenomenon.

Soil type was a hard-xanthic Plinthic Haplustox (Soil Survey Staff, 2003). Soil bulk density in the 0-60 cm soil depth was 1.57 kg $cm^{-3}$ at the onset of the trial in Season 1. According to the South African soil classification system, the soil is a Glencoe soil form (Soil Classification Working Group, 1991). A hard plinthic layer occurred at a soil depth of approximately 80 cm. The soil particle size distribution of various soil depths at the trial site is shown in Table 5.1. The experimental site has been under NT since 2011. The previous crop in both seasons was maize. Soil cover was approximately 95% in the two months following harvest. Strong winter winds removed a large portion of the crop residues and remained between 25 and 35% until the end of each cropping season.

**Table 5.1:** Soil particle size distribution of various soil depths at the trial site near Ottosdal, South Africa.

| **Soil depth (cm)** | **Soil particle size distribution (%)** | | |
|---|---|---|---|
| | **Sand** | **Silt** | **Clay** |
| 0-30 | 81 | 5 | 14 |
| 30-60 | 73 | 8 | 19 |
| 60-120 | 72 | 8 | 20 |

### *5.2.2 Experimental layout and treatments*

The experimental design was a split-plot design with four blocked replicates. Whole-plots were row spacing (0.52 and 0.76 m), while plant population formed sub-plots ranging from low to high within each row spacing. For the 0.52 m row spacing, plant populations were 25 000, 38 000, 50 000, and 60 000 plants $ha^{-1}$, and for the 0.76 m row spacing 20 000, 30 000, 40 000, and 50 000 plants $ha^{-1}$ (Appendix C, Figure A1). These plant population and row spacing configurations were chosen to realize a diverse set of intra-row spacings in each row spacing for potential use by local producers. Plot width was 6.24 m consisting of twelve rows for the 0.52 m row spacing. For the 0.76 m row spacing, plot width was 7.6 m and consisted of ten rows. Plot lengths were 20 m. Plots were overplanted at 65 000 plants $ha^{-1}$ to ensure a high stand, and hand-thinned to the target plant populations at the fifth-leaf collar (V5) growth stage, leaving a stand with uniform intra-row spacing in each treatment. The plots used in Season 1 were also used in Season 2 to include additive effects of plant roots because of different density configurations.

### *5.2.3 Experiment management*

Representative soil samples were taken prior to planting of trials in Season 1 and 2 at three soil depth layers, namely 0-15, 15-30 and 30-60 cm to establish baseline chemical properties (Table 5.2). In Season 1 and 2, nitrogen (N) was broadcasted prior to planting as urea at 75 kg N $ha^{-1}$, while 24 kg N $ha^{-1}$ was band-placed as monoammonium phosphate at planting. Maize was planted by means of direct-drilling, using a ten-row John Deere 2117 no-tillage planter [John Deere Pty (Ltd.), Iowa, USA] and a six-row Jumil 2670-EX POP no-tillage planter [Jumil, Pty (Ltd.), Castelo, Espírito Santo, Brazil] for the 0.76 and 0.52 m row spacing plots, respectively.

**Table 5.2:** Soil chemical properties of soil depth 0-60 cm prior to planting of trials in Season 1 and 2. P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; Na, sodium.

| Season | Soil depth (cm) | Organic carbon (%) | pH (KCl) | Extractable P (mg $kg^{-1}$) | Exchangeable cations (mg $kg^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | K | Ca | Mg | Na |
| Season 1 | 0-15 | 0.58 | 6.08 | 64.25 | 233 | 638 | 188 | 6.0 |
| | 15-30 | 0.43 | 5.23 | 36.03 | 210 | 446 | 163 | 5.0 |
| | 30-60 | 0.44 | 5.11 | 3.75 | 96 | 440 | 162 | 5.0 |
| Season 2 | 0-15 | 0.58 | 6.08 | 64.15 | 228 | 514 | 128 | 6.0 |
| | 15-30 | 0.43 | 5.22 | 36.10 | 202 | 334 | 128 | 4.0 |
| | 30-60 | 0.45 | 5.10 | 4.12 | 96 | 410 | 142 | 5.0 |

The trials were established on 14 December 2017 and 4 January 2019 in Season 1 and 2, respectively. The optimal planting window for rainfed maize in the North West Province range between mid-November to mid-December. Due to very hot conditions and low rainfall at the onset of Season 2, planting was delayed beyond these dates. The maize cultivar P2864WBR was used in both seasons. This cultivar was selected because it is one of the highest yielding cultivars in the region and commonly planted by local rainfed maize producers (A. A. Nel, personal communication). Weeds were chemically controlled with pre-emergence herbicides after planting. Although weed pressure was low, hand-weeding was done throughout the growing seasons if necessary to keep plots weed free.

### *5.2.4 Sampling procedure and calculations*

Plant architecture and biomass were evaluated in 30-day intervals after emergence by randomly selecting five plants in each plot at 30, 60, 90 and 120 days after emergence (DAE). At least 75% of plants have reached the sixth-leaf collar (V6) at 30 DAE, tasseling (VT) at 60 DAE, kernel filling (R3-R4) at 90 DAE and physiological maturity (R5-R6) growth stages at 120 DAE. Plant architecture measurements included plant height and number of leaves per plant. Plant height was recorded as the distance from the soil surface and the uppermost extended leaf arch. Tiller and total biomass (tiller and main stalk combined) were recorded. Tiller biomass was only recorded at VT. Hot and dry conditions between 57 to 88 DAE in Season 1 and between 38 to 85 DAE in Season 2 resulted in complete tiller abortion and loss across all treatments. Biomass samples were oven-dried at 60°C for 72 hours.

Intercepted photosynthetically active radiation (IPAR) and leaf area index (LAI) were measured at VT using an LP-80 AccuPAR ceptometer (Decagon Devices Inc., 2017). The 84 cm long probe was placed diagonally across two crop rows, with the two ends of the probe located in subsequent crop rows. This measuring regime is advised for row crops, as it provides a representative sample of the entire PAR environment below and between crop rows (Decagon Devices Inc., 2017). The IPAR and LAI measurements were done at five random spots within each plot above the leaf canopy (reference measurement, Qa) and at ground level (below-canopy measurement, Qb) between 12:00 and 14:00 on clear and windless days. The IPAR is reported as a percentage and was calculated using Equation 1:

$$\text{IPAR (\%)} = [1 - (Qb/Qa)] \times 100 \qquad (1)$$

Soil water content was monitored at two- to three-week intervals in Seasons 1 and 2 from planting until R5-R6. One galvanised access tube (length 120 cm, diameter 4 cm) was installed per plot using a hand auger (diameter 4 cm) immediately after planting in the middle of two crop rows. A neutron probe (503DR Elite Hydroprobe Model, CPN Inc., Concord, CA, USA) was used to record soil water content at 30, 60, 90 and 120 cm soil depths. To calibrate soil water data, gravimetric soil samples were taken simultaneously during neutron probe readings at planting using a hand-auger (diameter 7 cm) at soil layers 0-30, 30-60, 60-90 and 90-120 cm to determine gravimetric soil water content using the standard gravimetric method (Schmugge et al., 1980). Soil sampling was done approximately 100 cm from the access tube locations. The soil samples were oven-dried for 72 hours at 105°C to remove all water. The gravimetric soil water content of each soil sample was converted to volumetric water content by multiplying with the soil bulk density. A linear regression of calibration readings against volumetric water values was calculated and used to calculate volumetric water content from the growing season soil water readings. Volumetric soil water content ($mm^{-1}$ $mm^{-1}$) was then converted to soil water (mm) per layer by multiplying the volumetric soil water content by the depth (mm) of the particular soil layer. Crop evapotranspiration (crop ET) was calculated as rainfall minus the change in soil water content (accumulated 0-120 cm soil depth) between subsequent measurements, minus drainage. Drainage was calculated as the difference between the maximum water holding capacity and measured soil water content for each soil layer. Runoff was considered negligible as the experimental site was flat (< 0.5% slope) and well drained. Water use efficiency for grain production ($WUE_g$) and biomass production ($WUE_b$) were estimated by dividing maize grain yield and total biomass at R5-R6 by the accumulated seasonal crop ET, respectively.

The ability of the soil microbial population to mineralize carbon was assayed by measuring the β-glucosidase activities in the soil. To determine the effects of plant population and row spacing on β-glucosidase activity, composite soil samples were taken at a soil depth of 0-15 cm from each plot in Season 1 at VT, R3-R4 and R5-R6. In Season 2, soil samples were taken at 0-15 soil depth at VT, R3-R4 and R5-R6 between plants in the crop row (in crop rows) and between crop rows (between crop rows), kept separately for analysis. The soil samples were protected from direct sunlight and kept below 10°C immediately after sampling until analysis. β-glucosidase activities were calculated by determining the release of *p*-nitrophenyl after the incubation of soil with *p*-nitrophenyl glucoside (Dick et al., 1996). Results were then calculated with reference to the calibration curve.

Maize grain yield was determined by hand harvesting the full length of the centre eight and six rows for the 0.52 and 0.76 m plots, respectively. Yield components were determined by randomly selecting ten plants per plot at harvest. Grain samples were oven-dried at 60°C until constant weight and kernel weight was calculated by weighing a sample of 300 kernels. Harvest index was calculated by dividing maize grain yield by total biomass as determined at R5-R6. Grain quality indicators protein content, oil content and hectolitre mass were determined using a Perten IM 9500 instrument (PerkinElmer Inc., Waltham, Massachusetts, USA) from representative grain samples taken from each plot at harvest. All grain yield data were standardised to a moisture level of 12.5%.

Cumulative growing degree days (GDD) was calculated according to Gilmore and Rogers (1958) using daily air temperature data provided by the South African Weather Service. The GDD base temperature was set as 10°C. Air temperature was measured at a weather station approximately 10 km from the trial site. Rainfall was recorded at the trial site using a manual rain gauge.

### *5.2.5 Statistical analyses*

Statistical analyses were performed by using Statistica (version 13.5.0.17) (TIBCO Software Inc., 2018). The Restricted Maximum Likelihood (REML) procedure was used to analyse according to the split-plot design. Three treatment factors were specified as fixed effects, i.e. plant population, row spacing and season, as well as the cross between the three at every level. Blocks and the cross between blocks and plant population, as well as blocks and row spacing were specified as random terms. The REML procedure was followed because the random factors of the dependent variables are also estimated, which allowed the evaluation of the effects of both row spacing and plant population as well as the interactions, despite dissimilar plant population treatments between the 0.52 and 0.76 m row spacings. Fisher's least significant differences (LSD) test were conducted at a 5% significance level to determine whether interactions among the three factors of interest were significant. The Bonferroni correction test was used as validation of the Fisher's LSD test to reduce the chances of obtaining false-positive results (type I errors), since multiple pairwise tests was performed on a single set of data. Main effects and interactions were tested. Normality of residuals and homogeneity of variances were tested and fulfilled the assumptions of the statistical model.

## 5.3 Results

### *5.3.1 Growing conditions*

Rainfall amount and distribution varied between Season 1 and 2 with inconsistent rainfall patterns (Figures 5.1 and 5.2). Despite the late planting date in Season 2, average air temperature was comparable between seasons with GDD totalling 1 404 and 1 386 in Season 1 and 2 from seedling emergence (VE) to R5-R6, respectively. The total amount of rainfall for the eight weeks prior to planting of trials in Season 1 and 2 were 83 and 62 mm, respectively. In Season 1, growing conditions during the first two weeks after planting were warm and dry with optimal seed germination and seedling establishment possible. The total amount of rainfall from VE to fourteenth-leaf collar (V14) in Season 1 was 149 mm, corresponding to a deficit of 70 mm compared to the 30-year average. Despite the low rainfall during this period, soil water status was adequate and early vegetative growth was not affected by the prevailing growing conditions. A dry spell occurred from 60 to 85 DAE when plants were in the early reproductive growth stages (VT to R2-R3). Maize plants across all treatments were under high water stress, thereby negatively affecting kernel development. From 88 DAE onwards, wet conditions prevailed with 102 mm received between R3-R4 and R5-R6 allowing satisfactory kernel filling.

Season 2 was characterised by challenging growing conditions from the onset. Between VE and V14, a total of 138 mm of rainfall was received, with only two rainfall events measuring more than 15 mm (Figure 5.2). Between V10 and R3-R4, a prolonged dry spell combined with high air temperatures occurred, with only 15 mm of rainfall received. At this point in the growing season, rainfall received was 130 mm below the 30-year average. Water-stress conditions negatively affected final vegetative growth, pollination and ear growth across all treatments. Wet conditions and cool air temperatures characterised the period between R3-R4 and R5-R6, allowing maize plants to conclude the latter stages of kernel filling under stress-free growing conditions. The total amount of rainfall in Season 1 and 2 was 263 and 310 mm, respectively.

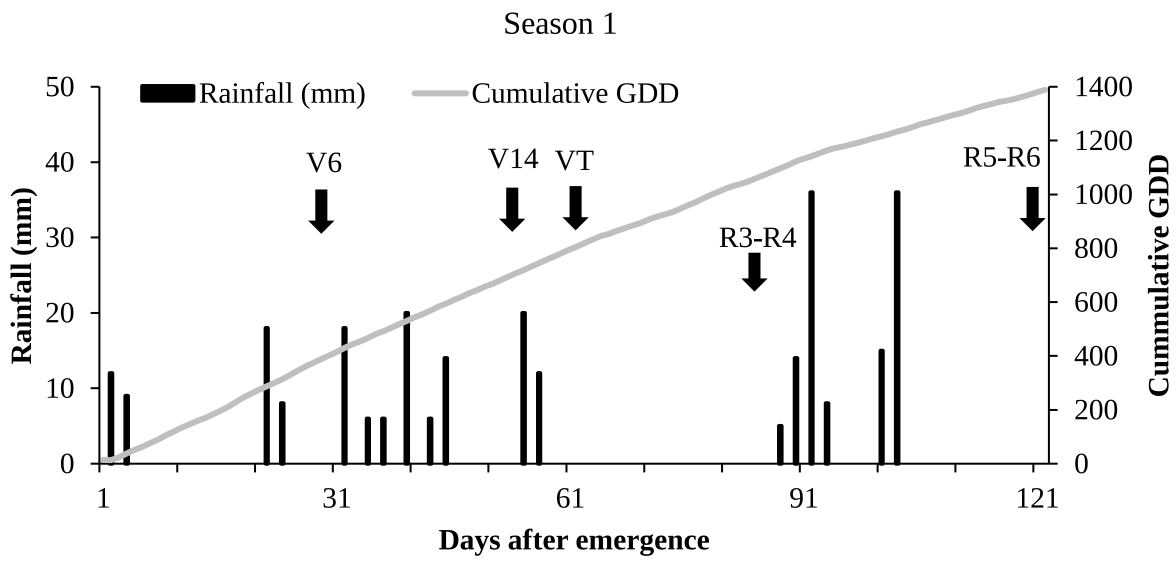


**Figure 5.1:** Rainfall events and cumulative growing degree days (GDD) from 0 to 120 days after emergence (DAE) during Season 1 near Ottosdal, South Africa. V6 = sixth-leaf collar, V14 = fourteenth-leaf collar, R3-R4 = kernel filling, R5-R6 = physiological maturity.

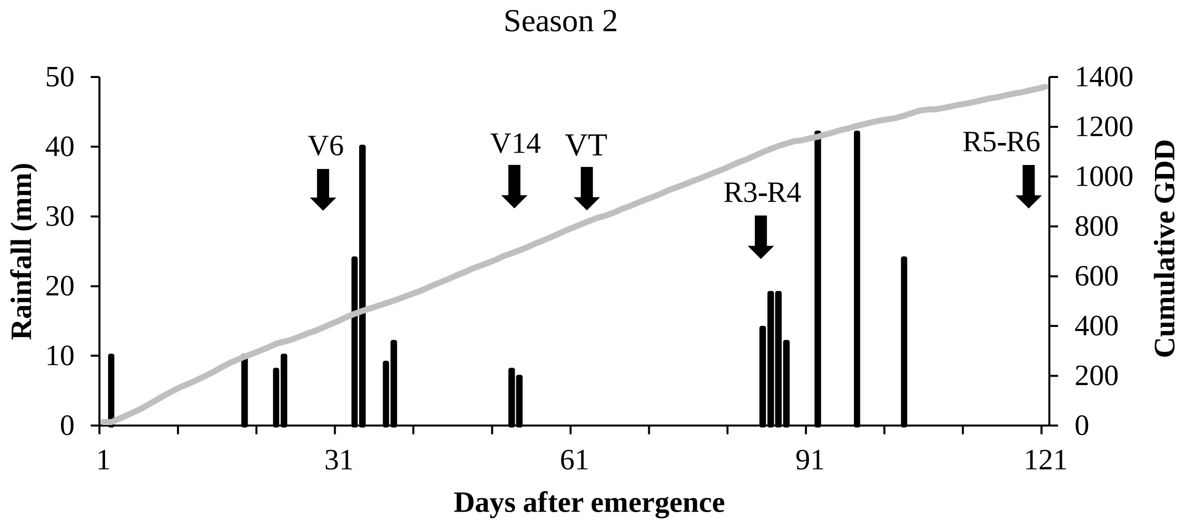


**Figure 5.2:** Rainfall events and cumulative growing degree days (GDD) from 0 to 120 days after emergence (DAE) during Season 2 near Ottosdal, South Africa. V6 = sixth-leaf collar, V14 = fourteenth-leaf collar, R3-R4 = kernel filling, R5-R6 = physiological maturity.

### *5.3.2 Plant architecture, sunlight interception and biomass*

Plant height was not affected ($P > 0.05$) by the treatments and their interactions at V6 ($P > 0.05$, data not shown). In contrast, an interaction between plant population and season and a three-way interaction ($P \leq 0.05$) between row spacing, plant population and season was observed for plant height at VT (Table 5.3). In Season 1 and at 0.52 m row spacing, plant height was lower ($P \leq 0.05$) at any given plant population compared to plant populations at 0.76 m row spacing (Table 5.4). A lower ($P \leq 0.05$) plant height was found at 50 000 plants ha$^{-1}$ at 0.76 m compared to lower plant populations at a similar row spacing. In Season 2, plant height decreased ($P \leq 0.05$) as plant population increased at both row spacings. Number of leaves per plant was not affected ($P > 0.05$) by the treatment factors at V6 and VT in both seasons (data not shown).

For IPAR there was an interaction ($P \leq 0.05$) between row spacing and plant population, row spacing and season, and plant population and season (Table 5.3). IPAR increased as plant population increased at 0.52 and 0.76 m row spacing, reaching a plateau when plant population reached 50 000 and 40 000 plants ha$^{-1}$, respectively (Table 5.5). Similar to IPAR, LAI was affected by the interactive effect of row spacing and season, and that of plant population and season (Table 5.4). In Season, LAI was similar ($P > 0.05$) between row spacings, however, in

Season 2, LAI was higher ($P \leq 0.05$) at 0.52 m row spacing compared to the 0.76 m row spacing (Table 5.6).

For tiller biomass there was an interaction ($P \leq 0.05$) between row spacing and season (Table 3). In Season 1 and 2, tiller biomass was similar ($P > 0.05$) between row spacings (Table 5.7). Tiller biomass was 58 and 71% lower ($P \leq 0.05$) in Season 2 compared to Season 1 at the 0.52 and 0.76 m row spacings, respectively.

Total biomass at V6 was affected ($P \leq 0.05$) by the interaction of row spacing and plant population (Table 5.8). At 0.52 m row spacing, total biomass was higher ($P \leq 0.05$) at plant populations 50 000 and 60 000 plants ha$^{-1}$ compared to plant populations lower than 50 000 plants ha$^{-1}$ (Table 5.9). At 0.76 m row spacing, the lowest ($P \leq 0.05$) total biomass was found at 20 000 plants ha$^{-1}$.

Total biomass at VT, R3-R4 and R5-R6 was affected ($P \leq 0.05$) by the interaction of row spacing and season (Table 5.8). In Season 1 at VT, total biomass was higher ($P \leq 0.05$) at 0.52 m row spacing compared to 0.76 m, with the opposite observed in Season 2 (Table 5.10). In Season 1 at R2-R3 and R5-R6, no difference ($P > 0.05$) in total biomass was found between row spacings, while total biomass was higher ($P \leq 0.05$) at 0.76 m row spacing compared to 0.52 m row spacing in Season 2 at similar growth stages. Overall, total biomass was lower ($P \leq 0.05$) in Season 2 compared to Season 1 irrespective of the row spacing.

**Table 5.3:** Analysis of variance for plant height, intercepted photosynthetically active radiation (IPAR), leaf area index (LAI) and tiller biomass at the tasseling (VT) growth stage indicating *P*-values on main effects and interactions. Bold text is used to indicate *P*-values ≤ 0.05.

| Variable | Plant height | IPAR | LAI | Tiller biomass |
|---|---|---|---|---|
| Row spacing (RS) | **<0.001** | 0.241 | 0.060 | 0.872 |
| Plant population (PP) | **<0.001** | **<0.001** | **<0.001** | 0.641 |
| Season (S) | **<0.001** | 0.625 | 1.000 | **0.011** |
| RS x PP | 0.232 | **0.024** | 0.101 | 0.582 |
| RS x S | 0.162 | **0.017** | **0.011** | **0.013** |
| PP x S | **<0.001** | **0.018** | **0.029** | 0.336 |
| RS x PP x S | **<0.001** | 0.242 | 0.148 | 0.978 |

**Table 5.4:** Effect of row spacing and plant population on plant height at the tasseling (VT) growth stage in Season 1 and 2.

| Season | Row spacing (m) | Plant population ($ha^{-1}$) | Plant height (cm) |
|---|---|---|---|
| Season 1 | 0.52 | 25 000 | $195^{de}$ |
| | | 38 000 | $200^{d}$ |
| | | 50 000 | $197^{de}$ |
| | | 60 000 | $201^{cd}$ |
| | 0.76 | 20 000 | $233^{a}$ |
| | | 30 000 | $233^{a}$ |
| | | 40 000 | $231^{a}$ |
| | | 50 000 | $220^{b}$ |
| Season 2 | 0.52 | 25 000 | $186^{ef}$ |
| | | 38 000 | $182^{fg}$ |
| | | 50 000 | $161^{h}$ |
| | | 60 000 | $131^{i}$ |
| | 0.76 | 20 000 | $212^{bc}$ |
| | | 30 000 | $200^{d}$ |
| | | 40 000 | $171^{gh}$ |
| | | 50 000 | $167^{h}$ |

Different letters indicate statistical significance at level $P \leq 0.05$ within the same column

### *5.3.3 Maize grain yield, yield components and grain quality*

The three-way interaction of row spacing, plant population and season affected maize grain yield (Table 5.11). In Season 1, 60 000 plants $ha^{-1}$ at 0.52 m had a lower ($P \leq 0.05$) maize grain yield compared to 30 000 and 50 000 plants $ha^{-1}$ at 0.76 m row spacing (Table 5.12). The highest ($P \leq 0.05$) maize grain yield was found at 50 000 plants $ha^{-1}$ at 0.76 m row spacing. In Season 2, maize grain yield decreased ($P \leq 0.05$) as plant population increased at 0.52 m row spacing, however, no differences ($P \leq 0.05$) in maize grain yield was found between plant populations at 0.76 m row spacing. Maize grain yield was higher ($P \leq 0.05$) in Season 1 compared to Season 2 for both the 0.52 and 0.76 m row spacings.

The three-way interaction of row spacing, plant population and season affected ($P \leq 0.05$) kernel weight (Table 5.11). This effect, however, was only sufficiently substantial in Season 2

**Table 5.5:** Effect of row spacing and plant population on intercepted photosynthetically active radiation (IPAR) at the tasseling (VT) growth stage across season.

| Row spacing (m) | Plant population ($ha^{-1}$) | IPAR (%) |
|---|---|---|
| 0.52 | 25 000 | 61.50[d] |
| | 38 000 | 74.16[c] |
| | 50 000 | 87.64[a] |
| | 60 000 | 91.34[a] |
| 0.76 | 20 000 | 65.51[d] |
| | 30 000 | 74.10[c] |
| | 40 000 | 81.87[b] |
| | 50 000 | 86.97[ab] |

Different letters indicate statistical significance at level $P \leq 0.05$ within the same column

**Table 5.6:** Effect of season and row spacing on leaf area index (LAI) at the tasseling (VT) growth stage across plant population.

| Season | Row spacing (m) | LAI |
|---|---|---|
| Season 1 | 0.52 | 3.75[bc] |
| | 0.76 | 4.01[ab] |
| Season 2 | 0.52 | 4.36[a] |
| | 0.76 | 3.04[c] |

Different letters indicate statistical significance at level $P \leq 0.05$ within the same column

**Table 5.7:** Effect of season and row spacing on tiller biomass at the tasseling (VT) growth stage across plant population.

| Season | Row spacing (m) | Tiller biomass (kg $ha^{-1}$) |
|---|---|---|
| Season 1 | 0.52 | 1 480[a] |
| | 0.76 | 1 479[a] |
| Season 2 | 0.52 | 630[b] |
| | 0.76 | 423[b] |

Different letters indicate statistical significance at level $P \leq 0.05$ within the same column

**Table 5.8:** Analysis of variance for total biomass during the growing season at sixth-leaf collar (V6), tasseling (VT), kernel filling (R3-R4) and physiological maturity (R5-R6) growth stages indicating *P*-values on main effects and interactions. Bold text is used to indicate *P*-values ≤ 0.05.

| Variable | Total biomass during growing season | | | |
|---|---|---|---|---|
| | **V6** | **VT** | **R3-R4** | **R5-R6** |
| Row spacing (RS) | **0.020** | 0.875 | **0.020** | **0.050** |
| Plant population (PP) | **<0.001** | 0.647 | 0.260 | 0.541 |
| Season (S) | 0.351 | **0.019** | **<0.001** | **<0.001** |
| RS x PP | **<0.001** | 0.583 | 0.130 | **0.010** |
| RS x S | 0.434 | **0.011** | **<0.001** | **0.020** |
| PP x S | 0.831 | 0.330 | **0.040** | 0.080 |
| RS x PP x S | 0.700 | 0.970 | 0.193 | 0.060 |

**Table 5.9:** Effect of row spacing and plant population on total biomass at the sixth-leaf collar (V6) growth stage across season.

| Row spacing (m) | Plant population (ha$^{-1}$) | Total biomass (kg ha$^{-1}$) |
|---|---|---|
| 0.52 | 25 000 | 976$^{de}$ |
| | 38 000 | 1 255$^{bcd}$ |
| | 50 000 | 1 963$^{a}$ |
| | 60 000 | 2 029$^{a}$ |
| 0.76 | 20 000 | 868$^{d}$ |
| | 30 000 | 1 065$^{cde}$ |
| | 40 000 | 1 381$^{bc}$ |
| | 50 000 | 1 465$^{b}$ |

Different letters indicate statistical significance at level $P \leq 0.05$ within the same column

to detect significant pairwise differences in kernel weight between plant population treatments in which kernel weight decreased ($P \leq 0.05$) with increasing plant population within each row spacing (Table 5.12). Similarly, kernels per plant was affected ($P \leq 0.05$) by the three-way interaction of row spacing, plant population and season affected ($P \leq 0.05$) kernel weight (Table 5.11). Kernels per plant was affected by an interactive effects of row spacing, plant population and season. In Season 1, kernels per plant decreased ($P \leq 0.05$) with increasing plant population

**Table 5.10:** Effect of season and row spacing on total biomass at tasseling (VT), kernel filling (R3-R4) and physiological maturity (R5-R6) growth stage across plant population.

| Season | Row spacing (m) | Total biomass (kg ha$^{-1}$) | | |
|---|---|---|---|---|
| | | VT | R2-R3 | R5-R6 |
| Season 1 | 0.52 | 9 483$^{a}$ | 10 476$^{a}$ | 12 796$^{a}$ |
| | 0.76 | 8 175$^{b}$ | 9 887$^{a}$ | 13 425$^{a}$ |
| Season 2 | 0.52 | 4 170$^{d}$ | 5 290$^{c}$ | 6 591$^{c}$ |
| | 0.76 | 6 112$^{c}$ | 7 501$^{b}$ | 9 752$^{b}$ |

Different letters indicate statistical significance at level $P \leq 0.05$ within the same column

at both 0.52 and 0.76 m row spacings. In Season 2, kernels per plant remained constant ($P > 0.05$) when plant population reached 38 000 plants ha$^{-1}$ at 0.52 m row spacing, while a decrease ($P \leq 0.05$) in kernels per plant was only observed at 0.76 m when plant population reached 40 000 plants ha$^{-1}$.

Grain yield per plant was affected ($P \leq 0.05$) by an interaction of row spacing and season (Table 5.11). In Season 1, grain yield per plant was higher ($P \leq 0.05$) at 0.76 m row spacing compared 0.52 m, with the opposite effect observed in Season 2 (Table 5.13). The main effect of plant population and season affected ($P \leq 0.05$) ear length (Table 5.11). The main effect of plant population was only sufficiently substantial in Season 2 to detect significant pairwise differences in ear length between plant population treatments in which ear length was lower ($P \leq 0.05$) at 60 000 compared to 25 000 plants ha$^{-1}$ at 0.52 m row spacing (Table 12). At 0.76 m row spacing, ear length at 50 000 plants ha$^{-1}$ was lower ($P \leq 0.05$) compared to all other plant population treatments at this row spacing.

Harvest index was affected ($P \leq 0.05$) by the three-way interaction of row spacing, plant population and season (Table 5.11). No differences between treatments were observed in Season 1 (Table 5.12). In contrast, in Season 2, harvest index decreased ($P \leq 0.05$) as plant population increased from 25 000 to 60 000 plants ha$^{-1}$ at 0.52 m row spacing. This decrease in harvest index was expected due to lower maize grain yields with increased plant population at 0.52 m row spacing. No differences ($P > 0.05$) in harvest index were found between plant population treatments at 0.76 m row spacing in Season 2. Overall in Season 2, any given plant population treatment at 0.76 m row spacing indicated a higher ($P \leq 0.05$) harvest index compared to 50 000 and 60 000 plants ha$^{-1}$ at 0.52 m row spacing.

**Table 5.11:** Analysis of variance for maize grain yield, kernel weight, kernels per plant, grain yield per plant, ear length and harvest index indicating *P*-values on main effects and interactions. Bold text is used to indicate *P*-values ≤ 0.05.

| **Variable** | **Maize grain yield** | **Kernel weight** | **Kernels plant$^{-1}$** | **Grain yield plant$^{-1}$** | **Ear length** | **Harvest index** |
|---|---|---|---|---|---|---|
| Row spacing (RS) | **<0.001** | 0.522 | **0.012** | **0.014** | 0.181 | **0.041** |
| Plant population (PP) | 0.161 | **<0.001** | **<0.001** | **<0.001** | **0.032** | **0.012** |
| Season (S) | **<0.001** | 0.123 | **0.020** | **0.041** | **0.026** | **0.011** |
| RS x PP | **<0.001** | **0.025** | 0.802 | 0.273 | 0.151 | **0.010** |
| RS x S | **0.013** | **<0.001** | **0.023** | **<0.001** | 0.184 | 0.062 |
| PP x S | **<0.001** | **<0.001** | **<0.001** | 0.123 | 0.163 | **0.021** |
| RS x PP x S | **0.034** | **0.024** | **0.012** | 0.063 | 0.371 | **<0.001** |

Maize grain quality parameters and treatment effects are shown in Tables 5.14 and 5.15. In Season 1, no differences ($P > 0.05$) in protein content, oil content and hectolitre mass was found between treatments and ranged between 7.6 to 8.5%, 4.33 to 4.6%, and 71 to 74 kg hL$^{-1}$, respectively (data not shown). Protein content was affected ($P \leq 0.05$) by the interactions of row spacing and plant population, and plant population and season (Table 5.14).

In Season 2, protein content was the lowest ($P \leq 0.05$) at 60 000 plants ha$^{-1}$ at 0.52 m row spacing (Table 5.15). Oil content was affected ($P \leq 0.05$) by the interactions of row spacing by plant population, and row spacing and season. Oil content decreased ($P \leq 0.05$) when plant population reached 38 000 plants ha$^{-1}$ at 0.52 m in Season 2, with no differences ($P > 0.05$) between plant population treatments at 0.76 m row spacing (Table 5.15). Hectolitre mass was affected ($P \leq 0.05$) by the row spacing and plant population and plant population by season. In Season 2, hectolitre mass decreased ($P \leq 0.05$) when plant population reached 38 000 plants ha$^{-1}$ at 0.52 m row spacing while no differences ($P > 0.05$) in hectolitre mass was found between plant population treatments at 0.76 m row spacing (Table 5.15).

**Table 5.12:** Effect of row spacing and plant population on maize grain yield, kernel weight, kernels per plant, grain yield per plant, ear length and harvest index in Season 1 and 2.

| Season | Row spacing (m) | Plant population ($ha^{-1}$) | Maize grain yield ($kg\ ha^{-1}$) | Kernel weight (g) | Kernels $plant^{-1}$ | Grain yield $plant^{-1}$ (g) | Ear length (mm) | Harvest index |
|---|---|---|---|---|---|---|---|---|
| Season 1 | 0.52 | 25 000 | 6 745$^{bc}$ | 0.41$^{bcde}$ | 656$^{b}$ | 270$^{b}$ | 154$^{abc}$ | 0.52$^{abc}$ |
| | | 38 000 | 6 804$^{bc}$ | 0.41$^{bcde}$ | 439$^{de}$ | 179$^{efg}$ | 149$^{abc}$ | 0.51$^{abc}$ |
| | | 50 000 | 6 739$^{bc}$ | 0.38$^{cd}$ | 357$^{fgh}$ | 135$^{gj}$ | 144$^{bcdef}$ | 0.54$^{abc}$ |
| | | 60 000 | 6 366$^{c}$ | 0.39$^{bcde}$ | 274$^{i}$ | 106$^{iklm}$ | 147$^{abcde}$ | 0.52$^{abc}$ |
| | 0.76 | 20 000 | 6 850$^{bc}$ | 0.44$^{abd}$ | 759$^{a}$ | 342$^{a}$ | 158$^{a}$ | 0.61$^{a}$ |
| | | 30 000 | 7 185$^{b}$ | 0.43$^{bcde}$ | 535$^{c}$ | 240$^{cd}$ | 154$^{abc}$ | 0.53$^{ab}$ |
| | | 40 000 | 6 970$^{bc}$ | 0.41$^{bcde}$ | 422$^{de}$ | 174$^{efg}$ | 158$^{a}$ | 0.50$^{abc}$ |
| | | 50 000 | 8 580$^{a}$ | 0.42$^{bcde}$ | 450$^{d}$ | 172$^{efg}$ | 155$^{ab}$ | 0.56$^{ab}$ |
| Season 2 | 0.52 | 25 000 | 4 120$^{e}$ | 0.54$^{a}$ | 404$^{def}$ | 219$^{bce}$ | 138$^{cdefg}$ | 0.58$^{ab}$ |
| | | 38 000 | 3 001$^{f}$ | 0.35$^{de}$ | 379$^{efg}$ | 131$^{ghi}$ | 129$^{fgh}$ | 0.45$^{c}$ |
| | | 50 000 | 1 952$^{g}$ | 0.26$^{f}$ | 329$^{ghi}$ | 87$^{jkl}$ | 125$^{ghi}$ | 0.33$^{d}$ |
| | | 60 000 | 1 318$^{g}$ | 0.19$^{h}$ | 327$^{ghi}$ | 70$^{lm}$ | 121$^{hi}$ | 0.21$^{e}$ |
| | 0.76 | 20 000 | 5 280$^{d}$ | 0.47$^{bc}$ | 418$^{def}$ | 201$^{df}$ | 141$^{bcdef}$ | 0.52$^{abc}$ |
| | | 30 000 | 4 685$^{de}$ | 0.25$^{fg}$ | 401$^{def}$ | 104$^{jk}$ | 133$^{efgh}$ | 0.50$^{bc}$ |
| | | 40 000 | 4 855$^{de}$ | 0.21$^{gh}$ | 356$^{efghi}$ | 79$^{lm}$ | 134$^{defgh}$ | 0.51$^{abc}$ |
| | | 50 000 | 5 100$^{d}$ | 0.20$^{h}$ | 292$^{hi}$ | 62$^{m}$ | 112$^{i}$ | 0.51$^{abc}$ |

Different letters within the same column indicate statistical significance at level $P \leq 0.05$

**Table 5.13:** Effect of season and row spacing on grain yield per plant across plant population.

| Season | Row spacing (m) | Grain yield per plant (g) |
|---|---|---|
| Season 1 | 0.52 | 172bc |
| | 0.76 | 232a |
| Season 2 | 0.52 | 127b |
| | 0.76 | 112c |

Different letters indicate statistical significance at level $P \leq 0.05$ within the same column

**Table 5.14:** Analysis of variance for maize grain quality indicators protein content, oil content and hectolitre mass indicating *P*-values on main effects and interactions. Bold text is used to indicate *P*-values ≤ 0.05.

| Variable | Maize grain quality parameters | | |
|---|---|---|---|
| | Protein content | Oil content | Hectolitre mass |
| Row spacing (RS) | **0.035** | 0.063 | 0.063 |
| Plant population (PP) | **0.010** | **0.032** | **<0.001** |
| Season (S) | **<0.001** | **<0.001** | **<0.001** |
| RS x PP | **<0.001** | **<0.001** | **0.021** |
| RS x S | 0.074 | **0.050** | 0.062 |
| PP x S | **0.041** | 0.056 | **0.022** |
| RS x PP x S | 0.123 | 0.163 | 0.061 |

**Table 5.15:** Effect of row spacing and plant population on maize grain protein content, oil content and hectolitre mass in Season 2. Different letters indicate statistical significance at level $P \leq 0.05$ within the same column

| Season | Row spacing (m) | Plant population (ha$^{-1}$) | Protein content (%) | Oil content (%) | Hectolitre mass (kg hL$^{-1}$) |
|---|---|---|---|---|---|
| Season 2 | 0.52 | 25 000 | 7.25$^{de}$ | 4.14$^{bcd}$ | 67$^{cd}$ |
| | | 38 000 | 7.94$^{abcde}$ | 4.18$^{bcd}$ | 69$^{abcd}$ |
| | | 50 000 | 6.26$^{f}$ | 3.54$^{e}$ | 59$^{e}$ |
| | | 60 000 | 5.15$^{g}$ | 2.97$^{f}$ | 48$^{f}$ |
| | 0.76 | 20 000 | 8.03$^{abcd}$ | 4.17$^{bcd}$ | 71$^{abcd}$ |
| | | 30 000 | 7.71$^{bcde}$ | 4.04$^{cd}$ | 68$^{abcd}$ |
| | | 40 000 | 7.83$^{abcde}$ | 4.21$^{bcd}$ | 68$^{bd}$ |
| | | 50 000 | 7.13$^{ef}$ | 3.99$^{d}$ | 65$^{de}$ |

### *5.3.4 Water use efficiency*

Crop ET was affected ($P \leq 0.05$) by the main effect of season only and was 255 and 333 mm in Season 1 and 2, respectively (Table 5.16, data not shown). Similar to crop ET, $WUE_b$ was affected ($P \leq 0.05$) only by season, with a higher ($P \leq 0.05$) $WUE_b$ found in Season 2 compared to Season 1. The $WUE_b$ was 24.58 and 51.85 kg mm$^{-1}$ in Season 1 and 2, respectively (data not shown). Water use efficiency for grain production was affected ($P \leq 0.05$) by the interactions of row spacing and plant population, row spacing and season, and plant population and season.

In Season 1, $WUE_g$ ranged from 24.78 to 31.26 kg mm$^{-1}$, with differences ($P \leq 0.05$) between 25 000 and 60 000 plants ha$^{-1}$ at 0.52 m row spacing and between 50 000 plants ha$^{-1}$ and 20 000 and 40 000 plants ha$^{-1}$ at 0.76 m row spacing (Table 5.17). In Season 2, $WUE_g$ decreased with increasing ($P \leq 0.05$) plant population at 0.52 m row spacing, while $WUE_g$ remained constant ($P > 0.05$) across plant population at 0.76 m row spacing. Treatment and seasonal effects on crop ET, $WUE_b$ and $WUE_g$ during two-week periods throughout the growing season were explored, however, no differences ($P > 0.05$) were found between treatments (data not shown).

**Table 5.16:** Analysis of variance for seasonal crop evapotranspiration (crop ET), water use efficiency for biomass ($WUE_b$) and grain production ($WUE_g$) indicating *P*-values on main effects and interactions. Bold text is used to indicate *P*-values $\leq 0.05$.

| Variable | Crop ET | $WUE_b$ | $WUE_g$ |
|---|---|---|---|
| Row spacing (RS) | 0.139 | 0.111 | **<0.001** |
| Plant population (PP) | 0.136 | 0.712 | 0.089 |
| Season (S) | **<0.001** | **<0.001** | **<0.001** |
| RS x PP | 0.537 | 0.184 | **0.016** |
| RS x S | 0.965 | 0.148 | **0.012** |
| PP x S | 0.537 | 0.372 | **0.017** |
| RS x PP x S | 0.997 | 0.099 | 0.121 |

**Table 5.17:** Effect of row spacing and plant population on water use efficiency for grain production ($WUE_g$) in Season 1 and 2.

| Season | Row spacing (m) | Plant population ($ha^{-1}$) | $WUE_g$ ($kg\ mm^{-1}$) |
|---|---|---|---|
| Season 1 | 0.52 | 25 000 | 28.81$^{ab}$ |
| | | 38 000 | 28.08$^{abc}$ |
| | | 50 000 | 25.98$^{bc}$ |
| | | 60 000 | 24.78$^{c}$ |
| | 0.76 | 20 000 | 26.68$^{bc}$ |
| | | 30 000 | 29.11$^{ab}$ |
| | | 40 000 | 26.96$^{bc}$ |
| | | 50 000 | 31.26$^{a}$ |
| Season 2 | 0.52 | 25 000 | 13.20$^{de}$ |
| | | 38 000 | 9.39$^{ef}$ |
| | | 50 000 | 5.79$^{fg}$ |
| | | 60 000 | 3.97$^{g}$ |
| | 0.76 | 20 000 | 15.79$^{d}$ |
| | | 30 000 | 14.40$^{d}$ |
| | | 40 000 | 14.35$^{d}$ |
| | | 50 000 | 14.47$^{d}$ |

Different letters indicate statistical significance at level $P \leq 0.05$.

### *5.3.5 β-glucosidase activity*

In Season 1, β-glucosidase activity was not affected ($P > 0.05$) by the treatments and their interactions at VT, R3-R4 and R5-R6 (Table 5.18). In Season 1 at VT and R3-R4, β-glucosidase activity ranged between 938 to 1 175 and 938 to 1 285 $\mu g\ g^{-1}\ h^{-1}$, respectively (data not shown). In Season 2 and in crop rows, plant population affected ($P \leq 0.05$) β-glucosidase activity at R5-R6 and was higher ($P \leq 0.05$) at 60 000 plants $ha^{-1}$ at 0.52 m row spacing compared to all other treatments except 50 000 plants $ha^{-1}$ at 0.76 m row spacing (Tables 5.19 and 5.20). In Season 2 at VT, plant population affected β-glucosidase activity between crop rows. β-glucosidase activity remained constant ($P > 0.05$) across plant population treatments at 0.52 m row spacing and reached a maximum at when plant population reached more than 30 000 plants $ha^{-1}$ at the 0.76 m row spacing.

**Table 5.18:** Analysis of variance for β-glucosidase activity indicating *P*-values on main effects and interactions at the tasseling (VT), kernel filling (R3-R4) and physiological maturity (R5-R6) growth stages in Season 1. Bold text is used to indicate *P*-values ≤ 0.05.

| **Variable** | **β-glucosidase activity at various growth stages** | | |
|---|---|---|---|
| | **VT** | **R3-R4** | **R5-R6** |
| Row spacing (RS) | 0.562 | 0.587 | 0.458 |
| Plant population (PP) | 0.123 | 0.147 | 0.089 |
| RS x PP | 0.366 | 0.258 | 0.312 |

**Table 5.19:** Analysis of variance for β-glucosidase activity indicating *P*-values on main effects and interactions at the tasseling (VT), kernel filling (R3-R4) and physiological maturity (R5-R6) growth stages in crop rows and between crop rows in Season 2. Bold text is used to indicate *P*-values ≤ 0.05.

| **Variable** | **β-glucosidase activity at various growth stages** | | | | | |
|---|---|---|---|---|---|---|
| | **In crop rows** | | | **Between crop rows** | | |
| | **VT** | **R3-R4** | **R5-R6** | **VT** | **R3-R4** | **R5-R6** |
| Row spacing (RS) | 0.123 | 0.212 | 0.200 | 0.154 | 0.232 | 0.355 |
| Plant population (PP) | 0.325 | 0.128 | **0.023** | **0.035** | 0.478 | 0.189 |
| RS x PP | 0.045 | 0.197 | 0.410 | 0.199 | 0.696 | 0.212 |

**Table 5.20:** Effect of row spacing and plant population on β-glucosidase activity at the physiological maturity (R5-R6) and tasseling (VT) growth stages in crop rows and between crop rows in Season 2. Different letters indicate statistical significance at level *P* ≤ 0.05.

| **Row spacing (m)** | **Plant population ($ha^{-1}$)** | **β-glucosidase activity (*p*-nitrophenol µg $g^{-1}$ $h^{-1}$)** | |
|---|---|---|---|
| | | **In crop rows** | **Between crop rows** |
| | | **R5-R6** | **VT** |
| 0.52 | 25 000 | 1 023$^{b}$ | 1 161$^{abc}$ |
| | 38 000 | 954$^{bc}$ | 1 337$^{ab}$ |
| | 50 000 | 1 052$^{bc}$ | 1 416$^{a}$ |
| | 60 000 | 1 276$^{a}$ | 1 282$^{abc}$ |
| 0.76 | 20 000 | 928$^{bc}$ | 925$^{bc}$ |
| | 30 000 | 967$^{bc}$ | 893$^{c}$ |
| | 40 000 | 827$^{bc}$ | 1 484$^{a}$ |
| | 50 000 | 1 133$^{ab}$ | 1 468$^{a}$ |

## 5.4 Discussion

In Season 1, plant height was lower at any given plant population at 0.52 m row spacing compared to plant population treatments at 0.76 m (Table 5.4). The lower plant height observed in Season 2 compared to Season 1 was a combined effect of increasing interplant competition for limited soil water and unfavourable rainfall distribution during the vegetative growth period, similar to the findings of Lenssen et al. (2018).

Intercepted photosynthetically active radiation increased as plant population increase at both row spacings (Table 5.5). Increased IPAR with increasing LAI has been previously associated with higher plant populations (Fromme et al., 2019; Maddonni and Otegui, 1996; Portes and Melo, 2014; Van Roekel and Coulter, 2012). The IPAR and LAI found at 38 000 plants ha$^{-1}$ at a 0.52 m row spacing was lower ($P \leq 0.05$) compared to 40 000 plants ha$^{-1}$ at a wider 0.76 m in Season 1. However, when plant population was higher than 38 000 plants ha$^{-1}$ at 0.52 m, both IPAR and LAI was similar ($P > 0.05$) to plant populations of more than 40 000 plants ha$^{-1}$ at 0.76 m row spacing. Sunlight interception increase when high plant populations are established at row spacings less than 0.76 m due to a more evenly distributed leaf canopy cover (Maddonni et al., 2001) when suitable growing conditions prevail. When water-stress conditions occurred in Season 2, the opposite effect was observed with higher IPAR and LAI values at high plant populations at 0.52 m compared to high plant populations at 0.76 m. Due to a lack in available soil water, the higher levels of intercepted sunlight at plant populations of 38 000 plants ha$^{-1}$ and higher at a row spacing of 0.52 m could not be converted into biomass or maize grain yield. The lower IPAR and LAI obtained in Season 2 compared to Season 1 at 40 000 and 50 000 plants ha$^{-1}$ at 0.76 m is attributed to less vigorous leafy and total biomass growth. Total biomass at R5-R6 increased with increasing plant population at 0.76 m row spacing in Season 1 (Figures 5.3 and 5.4). The higher LAI and consequent IPAR lead to higher leaf canopy photosynthesis and total biomass (Connor et al., 2011). In contrast, Allen (2012) found increased biomass at lower plant populations when less than 300 mm of rainfall was received during the growing season.

Growth conditions had a substantial effect on maize grain yield and yield components in Season 1 and 2. High rainfall during R3-R4 in Season 1 provided favourable growth conditions from kernel development onwards and may have reduced the competition for carbon-assimilates in the developing kernels (Uribelarrea et al., 2008). Timing of water-stress influences the relationship between maize grain yield and yield components (Milander, 2015). The below-average rainfall during the vegetative growth stages reduced the number of kernels per plant but had no significant effect on kernel weight. The 41% decrease in kernel number per plant in combination with no significant decrease in kernel weight from the lowest to highest plant population at 0.52 m and 0.76 m row spacings counterbalanced the increase in the number of plants per ha, resulting in no maize grain yield response to plant population in Season 1, except for the 50 000 plants ha$^{-1}$ established at 0.76 m treatment. Consequently, the response of harvest index, crop ET, $WUE_b$ and $WUE_g$ to plant population were muted in Season 1 (Tables 5.12 and 5.17). A similar decrease in kernel number per plant and ear length with increasing plant population was reported by other authors in below-average rainfall seasons (Cox and Cherney, 2012; Reeves and Cox, 2013; Zhang et al., 2014).

The prevailing water-stress conditions from V10 to R3-R4 in Season 2 lowered yield potential by decreasing kernel number per plant (Grant et al., 1989) as plant population increased. Plant-to-plant competition for limited soil water increased as plant population was increased, thereby inhibiting photosynthesis, pollination and carbohydrate translocation to kernels (Boyer, 1982; Schussler and Westgate, 1991; Westgate and Boyer, 1985). Water-stress conditions during silking drastically decrease kernel set in the apical maize ear region, kernel dry matter and consequently maize grain yield (Setter et al., 2001). The high amount of rainfall received at R3-R4 was too late to be effectively utilised for grain production.

Rainfall during kernel filling is key for maize kernel weight and yield (Nielsen et al., 2010). Protein content, oil content and hectolitre mass decreased 29, 28 and 28% from the lowest to highest plant population at 0.52 m row spacing in Season 2, respectively. Similarly, Liangming et al. (2008) and Zhang et al. (2014) found a negative response in grain quality indicators to increased plant population. The decrease in kernel weight was sufficiently substantial to lower grain yield per plant to such level that, despite the higher number of plants present at high plant populations, maize grain yield and harvest index decreased ($P \leq 0.05$) from the lowest to highest plant population at 0.52 m row spacing.

Cautious consideration must be given to not only plant population, but also the combination of plant population and row spacing. A reasonable maize grain yield of between 6 000 and 7 000 kg ha$^{-1}$ is possible with plant populations of between 20 000 and 40 000 plants ha$^{-1}$ irrespective of the row spacing. To increase maize grain yield to more than 7 000 kg ha$^{-1}$, it appears that a plant population in excess of 40 000 plants $ha^{-1}$ is required at a row spacing of 0.76 m. The evidence of improved sunlight interception and ultimately higher biomass and maize grain yields at high plant populations and 0.76 m row spacing in seasons with more timely rainfall are clear, however, deciding on the more optimal plant population and row spacing will ultimately be a compromise between obtaining high maize grain yield and minimising the potential for crop failure in semi-arid environments. In seasons with low rainfall, lower plant populations (< 40 000 plants $ha^{-1}$) will be associated with lower risk, but in seasons with adequate or plentiful rainfall a maize grain yield penalty could be expected (Birch et al., 2008). Although producers can use seasonal forecasts to adjust plant population at a given row spacing, rainfall amount and distribution throughout the particular season will ultimately determine if the approach is successful or not (Adisa et al., 2018; 2019). The higher seed costs associated with increased plant populations have a further impact on the decision-making process of producers, as economic losses increase when higher plant populations are established in dry seasons.

## 5.5 Conclusion

Overall plant architecture and maize grain yield responded inconsistently to plant population and row spacing between Season 1 and 2. Growing conditions were more challenging in Season 2 compared to Season 1 and treatments had a greater impact on overall maize growth and yield. This was mainly attributed to the variable rainfall amount and distribution between the seasons. In seasons with more uniform rainfall distribution, a higher biomass and maize grain yield is possible with increased plant population at 0.76 m row spacing. In seasons with low and poorly distributed rainfall, there was no clear indication of biomass, grain yield or water use efficiency benefits with increased plant population at both 0.52 and 0.76 m row spacings, although plant population treatments at 0.76 m row spacing outperformed plant population treatments at 0.52 m row spacing. Rainfall amount and distribution in each season ultimately determine the success of a particular plant population and row spacing configuration.

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# CHAPTER 6

## Rainfed maize root morphology response to plant population under no-tillage

**Abstract**

The effect of plant population on aboveground maize (*Zea mays* L.) growth is well-recognised, but little is known regarding the effects on maize root morphology. The aim was to quantify rainfed maize root morphology response to plant population under no-tillage (NT). A two-year study was conducted to evaluate the effects of plant populations 20 000, 30 000 and 40 000 plants $ha^{-1}$ at 0.76 m row spacing on volumetric root length density ($RLD_v$), root diameter, lateral root length and branching angle. Also, the relationship between $RLD_v$ and maize grain yield was explored. Digital images were collected in minirhizotron tubes at 15 cm increments to 60 cm soil depth, using a CI-600 *In Situ* Root Imager at the sixth leaf collar, tasselling and kernel filling growth stages. Images were analysed using *RootSnap!* software. Volumetric root length density against crop rows was higher in the 15-60 cm soil depths compared to 0-15 cm throughout Season 1. In the season with low and erratic rainfall occurrence, $RLD_v$, average root diameter and lateral root length was lower compared to Season 1 with more optimal rainfall distribution. Average lateral root length and branching angle was only affected by season and soil depth, respectively. In Season 1, a high RLDv was required to uphold yield increases as plant population increased. In Season 2 and between the crop rows, an RLDv of more than 1.5 cm $cm^{-3}$ was required to achieve a yield of more than 6 000 kg $ha^{-1}$. The low soil water levels during the growing season due to low rainfall might have impeded any plant population treatment effects on maize root growth and development.

**Keywords:** corn, plant density, row width, nutrient uptake, soil fertility, root phenology

## 6.1 Introduction

In highly intensive managed maize cropping systems, roots provide fundamental functions such as water and nutrient uptake, plant anchorage and resource storage (Eisenhauer et al., 2017). Linking these functions with overall maize root growth by identifying the optimal agronomic management practices is needed to improve external inputs' use efficiencies and optimise maize grain production.

Genetic advances coupled with newly developed agronomic management practices have resulted in maize grain yield increases globally (Duvick, 2005). Modern hybrids' improved ability to endure water stress conditions and increased plant-to-plant competition for soil resources facilitated the higher maize grain yields per unit area, using increased plant populations (Duvick et al., 2004; Lobell et al., 2014). Changes in aboveground plant architecture contributed considerably towards the achievement of higher maize grain yields with higher plant populations (Duvick, 2005). More erect maize leaf angles (Ma et al., 2014), decreased tassel size (Duvick et al., 2004) and a reduction in ear height (Russell, 1984) all contributed towards the success of increased plant populations. Although the effects of plant population on the aboveground growth of maize is well recognised (Boomsma et al., 2009; Portes et al., 2014; Van Roekel and Coulter, 2011; 2012), little is known about the response of rainfed maize root morphology to varying levels of plant population.

Evaluating maize root morphology under field conditions is key to understanding the response of maize plants to different crop and soil management practices and to improve the ability of maize root systems to capture limited soil water and nutrients. Evaluation of maize root growth and development under field conditions are challenging (Bardgett et al., 2014). The spatial challenges experienced when investigating maize roots *in situ* are highlighted when root structural and functional changes occur during the growing season. The inaccessibility of the soil matrix complicates the accurate tracking of any maize root temporal changes, thus limiting our knowledge of possible agronomic management practices that can be applied to lessen the adverse effects of environmental challenges such as droughts.

In recent times, there has been an increase in global interest regarding advances and challenges in crop root ecology (Erktan et al., 2018), the linkage between crop root system and grain yield (Palta and Yang, 2014) and the interactions between crop roots and the soil (Ryan et al., 2016). Accompanying these reports on root functioning and growth, there have been numerous urgent calls to improve our knowledge of crop root functioning coupled with current agronomic management practices to improve crop productivity. Thorup-Kristensen and Kirkegaard (2016) demonstrated the importance of synchronising crop root morphological traits with the entire farming system in a review, thereby including all crop, soil and environmental aspects and needs to improve overall crop productivity. Despite the growing number of crop root research studies globally, the effects of plant population on rainfed maize root morphology under no-tillage (NT) remains highly unverified. The aim of this study was to quantify rainfed maize root morphology in response to varying levels of plant population under NT.

## 6.2 Materials and methods

### *6.2.1 Site description*

A two-year field trial was conducted near Ottosdal (26°47' S, 25°56' E; altitude 1 490 m), North West Province, South Africa, during the 2017/18 (Season 1) and 2018/2019 (Season 2) production seasons. The site is characterised by a semi-arid climate regime (BSk) (Kottek et al., 2006) with a mean annual rainfall of 591 mm. Approximately 90% of the annual rainfall occurs from October to April (summer growing season). Seasonal rainfall and distribution are highly variable between seasons and erratic hot and dry periods commonly occur during the growing season. The soil type at the experimental site was described as a hard-xanthic Plinthic Haplustox (Soil Survey Staff, 2003), with a soil bulk density of 1.57 cm$^{-3}$ from the 0-60 cm soil depth at the beginning of the trial in Season 1. According to the South African Soil Classification System, the soil was classified as a Glencoe soil form (Soil Classification Working Group, 1991). Soil particle distribution and baseline chemical properties of the experimental site sampled at the beginning of each season are presented in Table 6.1. The experimental site had been under NT for seven years prior to the trial in Season 1. The previous crop was maize in both seasons and soil residue cover was 25 and 35% in Season 1 and 2, respectively.

### *6.2.2 Experimental layout, treatments and management*

The experimental layout was randomised block design with three treatments replicated in three blocks. Treatments were plant populations of 20 000, 30 000, and 40 000 plants ha$^{-1}$, established at 0.76 m row spacing. Experimental plot dimensions were 7.6 x 20 m and each plot consisted of ten crop rows. Experimental plots were overplanted at 65 000 plants ha$^{-1}$ and

**Table 6.1:** Soil particle size distribution and chemical properties of soil depths 0-60 cm prior to planting of the trials in Season 1 and 2. P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; Na, sodium.

| Season | Soil depth (cm) | Particle size distribution (%) | | | Organic carbon (%) | pH (KCl) | Extractable P (mg kg$^{-1}$) | Exchangeable cations (mg kg$^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sand | Silt | Clay | | | | K | Ca | Mg | Na |
| Season 1 | 0-15 | 81 | 5 | 14 | 0.58 | 6.08 | 64.25 | 233 | 638 | 188 | 6.0 |
| | 15-30 | 75 | 9 | 16 | 0.43 | 5.23 | 36.03 | 210 | 446 | 163 | 5.0 |
| | 30-60 | 73 | 8 | 19 | 0.44 | 5.11 | 3.75 | 96 | 440 | 162 | 5.0 |
| Season 2 | 0-15 | 81 | 5 | 14 | 0.58 | 6.08 | 64.15 | 228 | 514 | 128 | 6.0 |
| | 15-30 | 75 | 9 | 16 | 0.43 | 5.22 | 36.10 | 202 | 334 | 128 | 4.0 |
| | 30-60 | 73 | 8 | 19 | 0.45 | 5.10 | 4.12 | 96 | 410 | 142 | 5.0 |

hand-thinned three weeks after emergence (V5, fifth-leaf collar stage) to ensure a uniform intra-row spacing in each plant population treatment (Ritchie et al., 1986). Treatments were repeated on the same plots in Season 2 as in Season 1. In Season 1 and 2, nitrogen (N) was broadcasted as urea prior to planting at 75 kg N ha$^{-1}$, while 24 kg N ha$^{-1}$ was band-placed as monoammonium phosphate at planting. A ten-row John Deere 2117 no-tillage planter [John Deere Pty (Ltd.), Iowa, USA] was used to direct-drill maize 5 cm deep. The optimal planting window in the North West Province ranges from mid-November to mid-December. Due to dry soil conditions planting was delayed beyond the optimal dates in Season 2. Maize was planted on 14 December 2017 and 4 January 2019 in Season 1 and 2, respectively. The maize cultivar P2864WBR was used in both seasons. This cultivar is commonly planted by local producers under rainfed conditions and is also one of the top performing cultivars in the region (A.A Nel, personal communication). Pre-emergence herbicides were used to control weeds and hand-weeding was done throughout the season as needed to keep plots weed free.

### *6.2.3 Root sampling procedure and quantification*

To evaluate maize root morphology, acrylic minirhizotron tubes (length 1 m; diameter 7 cm) were installed immediately after planting. Two minirhizotron acrylic tubes were installed per plot: one tube was placed halfway between two central rows (between crop rows), while the second tube was positioned 10 cm from a central row (against crop rows) (Figure 6.1, Appendix D). This tube placement allowed observation of maize root morphology across the crop row soil matrix. A hand-auger of a similar diameter as the tubes were used to bore holes in which the tubes were installed facilitating secure tube-soil contact. The upper 5 cm of the tubes protruding the soil surface was covered with black duct tape to restrict incoming sunlight which may affect root growth in the upper soil layers. Tube placement was in parallel alignment with the adjacent rows, at an angle of 45° relative to the soil surface. The 45° angle was selected in order to quantify maize root morphology at multiple soil depths and to avoid preferential root growth along the tube (Johnson et al., 2001).

Digital images were collected at four soil depths in each tube, i.e. 0-15, 15-30, 30-45, and 45-60 cm using a CI-600 *In Situ* Root Imager (CID Bio-Science in Camas, WA, USA) (Figure B1), at four measurement dates, corresponding to four growth stages: sixth-leaf collar (V6), tasseling (VT), kernel filling (R3-R4), and physiological maturity (R5-R6). All plants adjacent to the installed tubes reached the aforementioned growth stage at each measurement date. The digital images were analysed using the *RootSnap!* image analysis software (CI-690, Version 1.3.2.25, CID Bio-Science Inc., Camas, WA, USA) to quantify the maize root morphology parameters within each image. Maize root morphology parameters were selected to provide a complete representation of the maize root morphology in response to different interplant competition and included volumetric root length density (root length per unit soil volume, $RLD_v$), average root diameter, lateral root branching angle, and lateral root length. Lateral roots were identified as all roots that branched from other roots. To investigate the relationship between maize root morphology and grain yield, grain yield was determined by hand harvesting the full length of the central six rows of each plot. Representative grain samples were oven-dried at 60°C until constant weight and yield data were standardised to a moisture content of 12.5%.

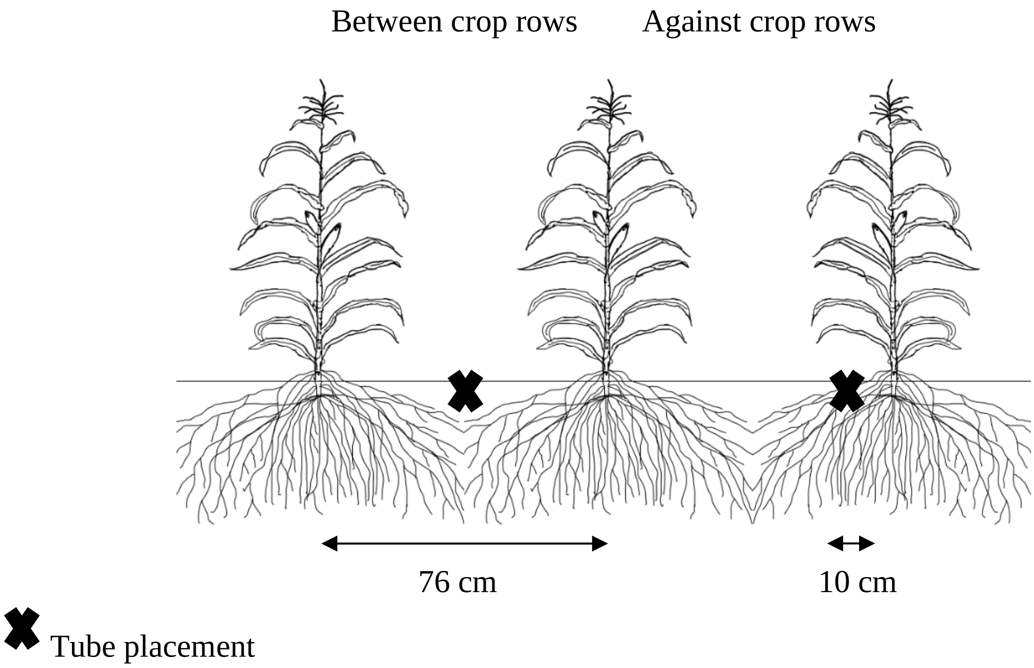


**Figure 6.1:** Layout of the minirhizotron tube placement for maize root observations between and against crop rows at 0.76 m row spacing. Tubes were installed in parallel alignment with the adjacent crop rows at an angle of 45° relative to the soil surface.

### *6.2.4 Calculations, estimates and statistical analyses*

Individual root length (of both primary and lateral roots) and diameter were manually determined for each digital image using *RootSnap!*, while average root diameter, average lateral root length and average lateral root branching angle for each digital image were estimated by *RootSnap!*. Volumetric root length density was calculated using equation 1:

$$\text{RLDv} = \frac{\text{L}}{\text{A}} \text{x DOF} \tag{1}$$

where L is the total root length manually determined in the digital image, A is the digital image area observed (422.3 $cm^2$), and DOF is depth of field. This approach assumes that the two-dimensional digital image has a small depth of field surrounding the observation tube, within which all observed roots are present. In this study, a depth of field of 2.5 mm was used as it is midway between previously used values of 2 to 3 mm (Itoh, 1985; Steele et al., 1997) and resulted in $RLD_v$ that corresponded to values determined by destructive methods (Gao et al., 2010; Wu et al., 2018).

Analysis of variance (ANOVA) was used to test the effect of plant population on maize root parameters. The restricted maximum likelihood (REML) procedure was followed with *P*-values for the significance of each variable calculated using type III ANOVA, based on Satterthwaite's approximation for degrees of freedom. Fixed effects were plant population, season and soil depth. Block was set as random factor. Maize root parameters were analysed separately for against crop row and between crop row measurements. Pairwise comparisons of least square means between plant population treatments were conducted. Contrasts were only conducted between levels of factors that were found to be significant at $P \leq 0.05$ in the ANOVA.

The relationship between plant population, accumulated $RLD_v$ at R5-R6 (0-60 cm soil depth) and maize grain yield were visualised simultaneously by constructing a 3-D quadratic spline curve as described by De Boor (1978). The 3-D spline curve was approximated by using a sequence of third-order (cubic) polynomials. Plant population, accumulated $RLD_v$ and maize grain yield each represented the x, y, and z coordinates of each individual point in the 3-D space, respectively. Consequently, a surface function was fitted to a 3-D scatterplot using the bicubic spline smoothing procedure (De Boor, 1962) in order to reveal hidden patterns of the obtained data and detect relationships among the three variables. Statistical analyses were conducted using Statistica (version 13.5.0.17) (TIBCO Software Inc., 2018).

## 6.3 Results

### *6.3.1 Growing conditions*

Variability in rainfall amount and distribution was observed between Season 1 and 2. Dry spells were common in Season 1 and 2 (Table 6.2). The rainfall prior to planting was 83 and 62 mm in Season 1 and 2, respectively. Cumulative growing degree days (GDD) totalled 1 404 and 1 386 in Season 1 and 2, respectively, despite the later planting date in the latter season. In Season 1, a dry spell occurred from VT to R2-R3 with maize plants subjected to water stress conditions. The dry spell was followed with a very wet period at the onset of R3-R4, allowing maize plants to complete kernel filling under stress-free conditions. Total rainfall for the growing season (mid-December to mid-April) in Season 1 was 263 mm, reflecting a deficit of 55 mm in comparison to the 30-year average for this period.

Dry and challenging growing conditions characterised the vegetative and early reproductive growth stages in Season 2. Only two rainfall events measured above 15 mm from seedling emergence to V14, impeding overall aboveground and root growth. Until the onset of R3-R4, the rainfall was 130 mm below the 30-year average. The high water stress conditions hindered pollination, ear growth and the early stages of kernel filling. High rainfall occurred during mid-kernel filling allowing maize plants to reach R5-R6 in stress-free conditions. The growing season rainfall (January to May) in Season 2 was 335 mm, corresponding to 47 mm below the 30-year average for this period.

**Table 6.2:** Monthly rainfall in Season 1 and at 2 near Ottosdal, North West Province. The anomalies from the long-term mean are in parentheses. Rainfall was recorded at the trial site using a manual rain gauge.

| **Season** | **Monthly rainfall (mm)** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Nov** | **Dec** | **Jan** | **Feb** | **Mar** | **Apr** | **May** |
| Season 1 | 0 (-70) | 61 (-18) | 68 (-52) | 57 (-18) | 102 (14) | 67 (19) | 0 (-18) |
| Season 2 | 15 (-55) | 15 (-64) | 39 (-81) | 105 (30) | 15 (-73) | 176 (128) | 0 (-18) |

### *6.3.2 Root length density, root diameter, lateral root length and branching angle*

Maximum root growth was reached at VT with no change ($P > 0.05$) in maize root parameters following VT (data not shown). Maize root senescence was found from R3-R4 onwards, a period in which maize allocates carbon assimilates stored in roots to growing kernels (Mengel and Barber, 1974). As a result, only data obtained at V6 and VT are reported.

An interaction between soil depth and season was observed for $RLD_v$ against the crop rows at V6 ($P \leq 0.05$), while only soil depth affected $RLD_v$ at VT ($P \leq 0.05$) (Table 6.3). The main effect of season showed that $RLD_v$ against the crop rows at V6 was higher ($P \leq 0.05$) in Season 1 compared to Season 2 at soil depths deeper than 0-15 cm (Figure 6.2a). In Season 1 at V6, $RLD_v$ increased with increasing soil depth reaching a maximum at the 30-45 soil depth layer (Figure 6.2a). In Season 2 at V6, $RLD_v$ was constant ($P > 0.05$) across all soil depths. The main effect of season showed that $RLD_v$ against the crop rows at VT was higher ($P \leq 0.05$) in Season 1 compared to Season 2 at soil depths of 15-30 and 30-45 cm (Figure 6.2b). No main effects or interactions ($P > 0.05$) were observed for $RLD_v$ between crop rows at V6 (Table 6.3), with only some evidence ($P < 0.1$) that $RLD_v$ increased with increasing soil depth. No differences ($P > 0.05$) in $RLD_v$ were found between crop rows at V6 between Season 1 and 2 at all soil depths (Figure 6.3). In contrast, a three-way interaction of plant population, soil depth and season was observed for $RLD_v$ between crop rows at VT. This effect was only sufficiently substantial to detect significant pairwise differences in $RLD_v$ between plant populations in Season 2 (Figure 6.4). In Season 2, at VT, a lower $RLD_v$ ($P \leq 0.05$) was found at 30 000 plants ha$^{-1}$ compared to 20 000 plants ha$^{-1}$ at the 15-30 cm soil depth. A lower $RLD_v$ ($P \leq 0.05$) was found at 20 000 plants ha$^{-1}$ compared to 30 000 plants ha$^{-1}$ at the 30-45 cm soil depth. Finally, the lowest $RLD_v$ ($P \leq 0.05$) at the 45-60 cm soil depth was found at 20 000 plants ha$^{-1}$.

Average root diameter against the crop rows at V6 was affected ($P \leq 0.05$) by the main effect of season and was higher ($P \leq 0.05$) in Season 1 compared to Season 2 at V6 at all soil depths (Tables 6.4 and 6.5). Interactions between soil depth and season and between plant population and soil depth was observed for average root diameter against crop rows at VT. Similar to average root diameter at V6, the average root diameter was higher ($P \leq 0.05$) in Season 1 compared to Season 2 at VT at all soil depths. Average root diameter was only affected ($P \leq 0.05$) by the main effects of plant population and season between crop rows at V6 and VT, respectively, and was higher ($P \leq 0.05$) in Season 1 compared to Season 2 at all soil depths (Tables 6.4 and 6.5).

Lateral root length and branching angle was only evaluated at the VT growth stage, when lateral growth and development reached a maximum. Lateral root length was affected by season against crop rows and were 37 and 39% higher ($P \leq 0.05$) in Season 1 compared to Season 2 at 15-30 and 30-45 cm soil depths, respectively (Tables 6.6 and 6.7). No main effects or interactions were observed for lateral root length between crop rows, with only some evidence ($P < 0.1$) that soil depth and season had an effect. The main effect of season showed that lateral root length between crop rows were 25 and 20% higher ($P \leq 0.05$) in Season 1 compared to

Season 2 at 15-30 and 30-45 cm soil depths, respectively (Tables 6.6 and 6.7). Lateral root branching angle was only affected ($P \leq 0.05$) by soil depth against and between crop rows (Table 6.6). Lateral root branching angle was lower ($P \leq 0.05$) at the 0-15 cm soil depth compared to 15-30 cm soil depth against and between the crop rows (Table 6.8).

**Table 6.3:** Analysis of variance for volumetric root length density ($RLD_V$) at the sixth-leaf collar (V6) and tasseling (VT) growth stages measured against and between crop rows indicating *P*-values on main effects and interactions. Bold text is used to indicate $P \leq 0.05$.

| Variable | RLD<sub>V</sub> at various growth stages | | | |
|---|---|---|---|---|
| | **Against crop rows** | | **Between crop rows** | |
| | **V6** | **VT** | **V6** | **VT** |
| Plant population (PP) | 0.603 | 0.651 | 0.291 | 0.201 |
| Soil depth (SD) | **<0.001** | **<0.001** | 0.062 | **<0.001** |
| Season (S) | 0.059 | 0.080 | 0.391 | 0.294 |
| PP x SD | 0.314 | 0.401 | 0.487 | **0.012** |
| PP x S | 0.160 | 0.392 | 0.922 | 0.508 |
| SD x S | **<0.001** | 0.233 | 0.120 | 0.057 |
| PP x SD x S | 0.202 | 0.150 | 0.941 | **0.040** |

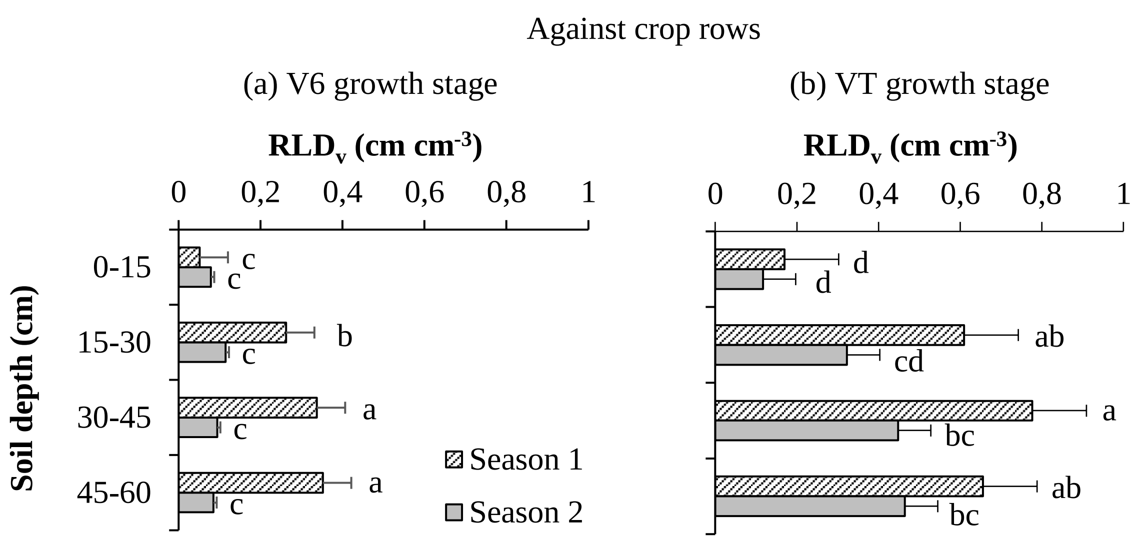


**Figure 6.2:** Response of volumetric root length density ($RLD_V$) to soil depth and season at the a) sixth-leaf collar (V6) and b) tasseling (VT) growth stages against crop rows. Treatments in the same growth stage with a different letter are significantly different at $P \leq 0.05$. Bars denote the standard error of the mean ($n = 3$).

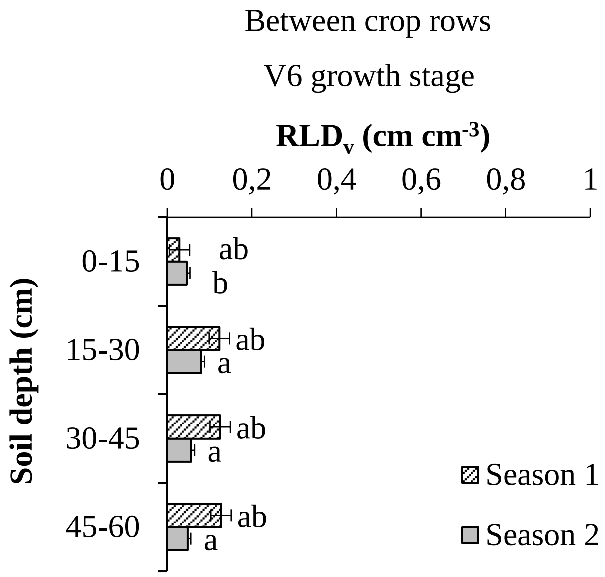


**Figure 6.3:** Response of volumetric root length density ($RLD_v$) to soil depth and season at the sixth-leaf collar (V6) growth stage between crop rows. Treatments in the same growth stage with a different letter are significantly different at $P \leq 0.05$. Bars denote the standard error of the mean ($n$ = 3).

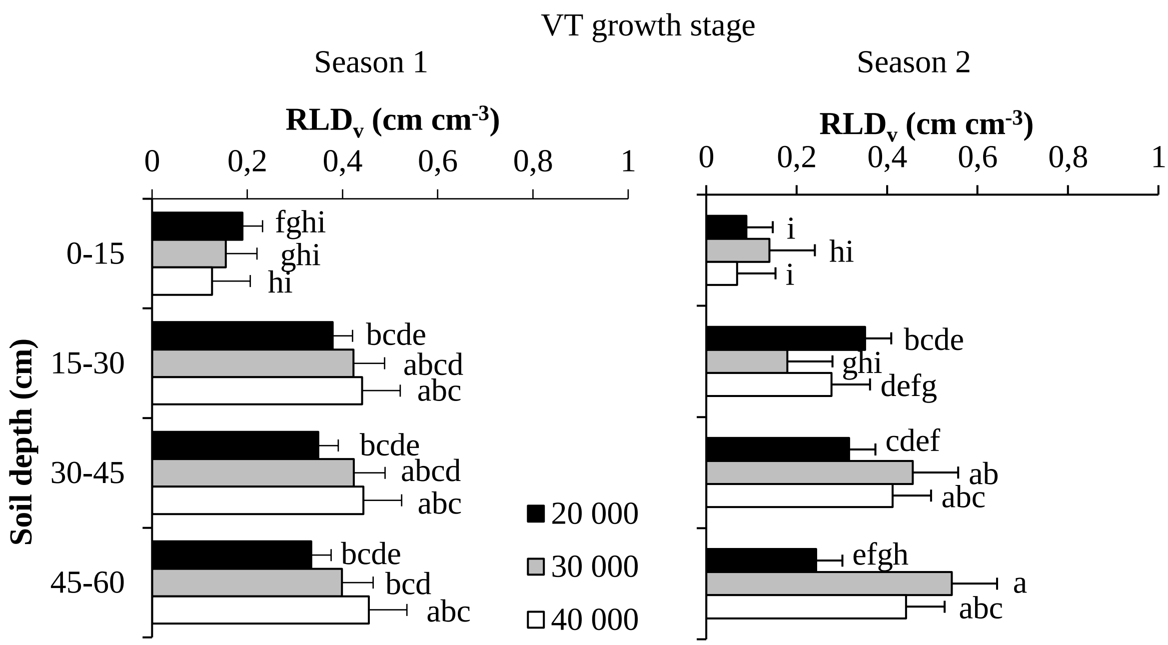


**Figure 6.4:** Response of volumetric root length density ($RLD_v$) to plant population at various soil depths in Season 1 (left) and Season 2 (right) at the tasseling (VT) growth stage between crop rows. Treatments in the same season with a different letter are significantly different at $P$ $\leq 0.05$. Bars denote the standard error of the mean ($n$ = 3).

**Table 6.4:** Analysis of variance for average root diameter at the sixth-collar leaf (V6) and tasseling (VT) growth stages measured against and between crop rows indicating *P*-values on main effects and interactions. Bold text is used to indicate *P*-values ≤ 0.05.

| Variable | Average root diameter at various growth stages | | | |
|---|---|---|---|---|
| | Against crop rows | | Between crop rows | |
| | **V6** | **VT** | **V6** | **VT** |
| Plant population (PP) | 0.681 | 0.925 | **0.093** | 0.802 |
| Soil depth (SD) | 0.160 | 0.174 | 0.700 | 0.773 |
| Season (S) | **0.032** | **0.011** | 0.300 | **0.012** |
| PP x SD | 0.271 | **0.032** | 0.212 | 0.745 |
| PP x S | 0.634 | 0.099 | 0.253 | 0.151 |
| SD x S | 0.843 | **0.024** | 0.444 | 0.603 |
| PP x SD x S | 0.532 | 0.177 | 0.546 | 0.155 |

**Table 6.5:** The response of average root diameter to soil depth and season across plant population treatments in Season 1 and 2 against and between crop rows at the sixth-leaf collar (V6) and tasseling (VT) growth stages. Treatments in the same growth stage with a different letter are significantly different at $P \leq 0.05$.

| Tube placement | Growth stage | Season | Average root diameter (mm) at various soil depths | | | |
|---|---|---|---|---|---|---|
| | | | **0-15 cm** | **15-30 cm** | **30-45 cm** | **45-60 cm** |
| Against crop rows | V6 | Season 1 | $0.387^{ab}$ | $0.442^{a}$ | $0.436^{a}$ | $0.424^{a}$ |
| | | Season 2 | $0.253^{c}$ | $0.290^{c}$ | $0.322^{bc}$ | $0.276^{c}$ |
| | VT | Season 1 | $0.364^{b}$ | $0.446^{a}$ | $0.460^{a}$ | $0.425^{a}$ |
| | | Season 2 | $0.235^{c}$ | $0.251^{c}$ | $0.212^{c}$ | $0.212^{c}$ |
| Between crop rows | V6 | Season 1 | $0.420^{a}$ | $0.393^{ab}$ | $0.369^{ab}$ | $0.370^{ab}$ |
| | | Season 2 | $0.263^{c}$ | $0.257^{c}$ | $0.313^{bc}$ | $0.250^{c}$ |
| | VT | Season 1 | $0.374^{a}$ | $0.386^{a}$ | $0.371^{a}$ | $0.393^{a}$ |
| | | Season 2 | $0.220^{b}$ | $0.209^{b}$ | $0.217^{b}$ | $0.224^{b}$ |

**Table 6.6:** Analysis of variance for average lateral root length and branching angle at the tasseling (VT) growth stage measured against crop rows and between crop rows indicating *P*-values on main effects and interactions. Bold text is used to indicate *P*-values ≤ 0.05.

| Variable | Lateral root length | | Lateral root branching angle | |
|---|---|---|---|---|
| | **Against crop rows** | **Between crop rows** | **Against crop rows** | **Between crop rows** |
| Plant population (PP) | 0.300 | 0.462 | 0.871 | 0.871 |
| Soil depth (SD) | 0.063 | 0.064 | **0.013** | **0.014** |
| Season (S) | **0.031** | 0.096 | 0.200 | 0.113 |
| PP x SD | 0.491 | 0.935 | 0.641 | 0.407 |
| PP x S | 0.735 | 0.147 | 0.178 | 0.697 |
| SD x S | 0.171 | 0.238 | 0.726 | 0.720 |
| PP x SD x S | 0.981 | 0.413 | 0.483 | 0.465 |

### *6.3.3 Relationship between plant population, $RLD_v$ and maize grain yield*

A 3-D quadratic spline was used to visualize maize grain yield response to plant population and the corresponding accumulated (0-60 cm soil depth) $RLD_v$ at R5-R6 against and between the crop rows in Season 1 and 2. In Season 1 and against the crop row, a maize grain yield of 6 000 to more than 8 000 kg $ha^{-1}$ was achieved at plant populations ranging from 20 000 plants $ha^{-1}$ to 40 000 plants $ha^{-1}$ (Figure 6.5). To uphold the increase in maize grain yield as plant population increased, a higher accumulated $RLD_v$ was required. At a plant population of more than 34 000 plants $ha^{-1}$ coupled with an accumulated $RLD_v$ of less than 1.8 cm $cm^{-3}$, maize grain yield was more than 5 000 kg $ha^{-1}$. In contrast, at a plant population of less than 26 000 plants $ha^{-1}$, maize grain yield was low despite indicating a high accumulated $RLD_v$. In Season 2 and against the crop row, maize grain yield was less than 5 000 kg $ha^{-1}$ at plant populations of more than 28 000 plants $ha^{-1}$ irrespective of the accumulated $RLD_v$. The higher maize grain yields achieved at plant populations of less than 28 000 plants $ha^{-1}$ required a high $RLD_v$ of more than 2.6 cm $cm^{-3}$. In Season 1 and between the crop rows, maize grain yield was between 6 000 kg $ha^{-1}$ and 8 000 kg $ha^{-1}$ at a plant population of more than 32 000 plants $ha^{-1}$, despite the low accumulated $RLD_v$ of less than 1.2 cm $cm^{-3}$ (Figure 6.6). In contrast, in Season 2 and between the crop rows, a high accumulated $RLD_v$ of more than 1.5 cm $cm^{-3}$ was required to achieve a maize grain yield of more than 6 000 kg $ha^{-1}$. At high plant populations of more than

34 000 plants ha$^{-1}$ and an accumulated RLD$_v$ of between 1.0 to 1.2 cm cm$^{-3}$, maize grain yields in excess of 7 000 kg ha$^{-1}$ was achieved.

**Table 6.7:** The response of lateral root length at the tasseling (VT) growth stage to soil depth and season across plant population in Season 1 and 2 against and between crop rows. Treatments within the same tube placement with a different letter are significantly different at $P \leq 0.05$.

| **Tube placement** | **Season** | **Lateral root length (cm) at various soil depths** | | | |
|---|---|---|---|---|---|
| | | **0-15 cm** | **15-30 cm** | **30-45 cm** | **45-60 cm** |
| Against crop rows | Season 1 | 7.04$^{cd}$ | 9.92$^{ab}$ | 10.49$^{a}$ | 9.23$^{abc}$ |
| | Season 2 | 5.73$^{d}$ | 6.23$^{d}$ | 6.41$^{d}$ | 7.86$^{bcd}$ |
| Between crop rows | Season 1 | 7.33$^{cd}$ | 9.14$^{ab}$ | 10.17$^{a}$ | 8.67$^{abc}$ |
| | Season 2 | 6.51$^{d}$ | 7.33$^{cd}$ | 7.62$^{bcd}$ | 7.05$^{cd}$ |

**Table 6.8:** The response of lateral root branching angle at the tasseling (VT) growth stage to soil depth across plant population and season against and between crop rows. Treatments within the same tube placement with a different letter are significantly different at $P \leq 0.05$.

| **Tube placement** | **Lateral root branching angle (°) at various soil depths** | | | |
|---|---|---|---|---|
| | **0-15 cm** | **15-30 cm** | **30-45 cm** | **45-60 cm** |
| Against crop rows | 53.51$^{b}$ | 61.56$^{a}$ | 60.54$^{a}$ | 64.62$^{a}$ |
| Between crop rows | 56.30$^{b}$ | 61.34$^{a}$ | 61.91$^{a}$ | 63.54$^{a}$ |

## 6.4 Discussion

Volumetric root length density has been widely used as a root parameter to investigate the effect of crop and soil management on root growth in maize (Fiorini et al., 2018; Gao et al., 2010; Li et al., 2019a). Plant population density had no effect on RLD$_v$ and average root diameter against and between crop rows at V6 and VT (Tables 6.3 and 6.4). This is in contrast with findings of Sun et al. (2018), who reported that root diameter decreased as plant population increased.

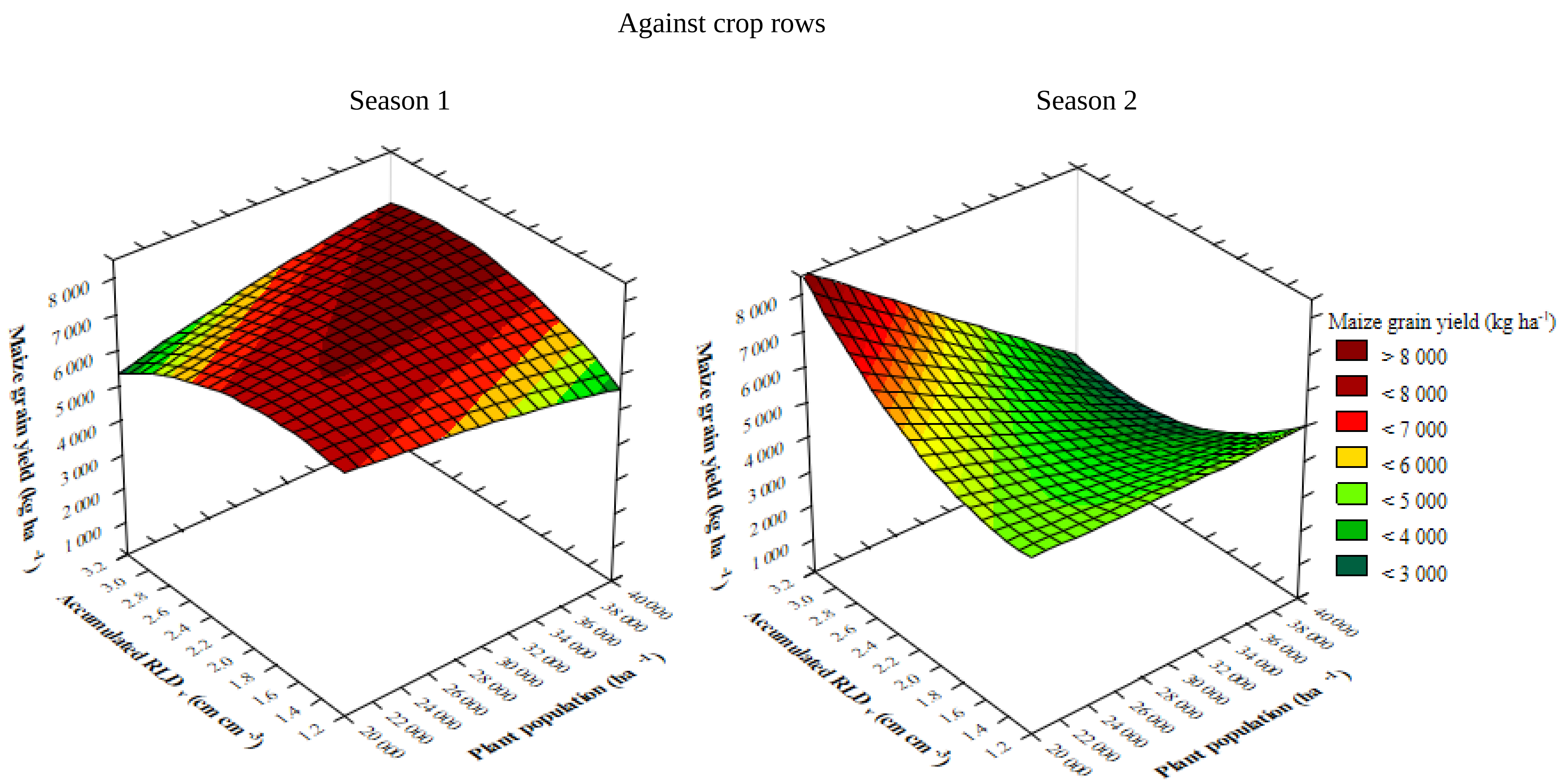


**Figure 6.5:** The relationship between maize grain yield, accumulated volumetric root length density ($RLD_v$) and plant population against the crop rows in Season 1 (left) and Season 2 (right).

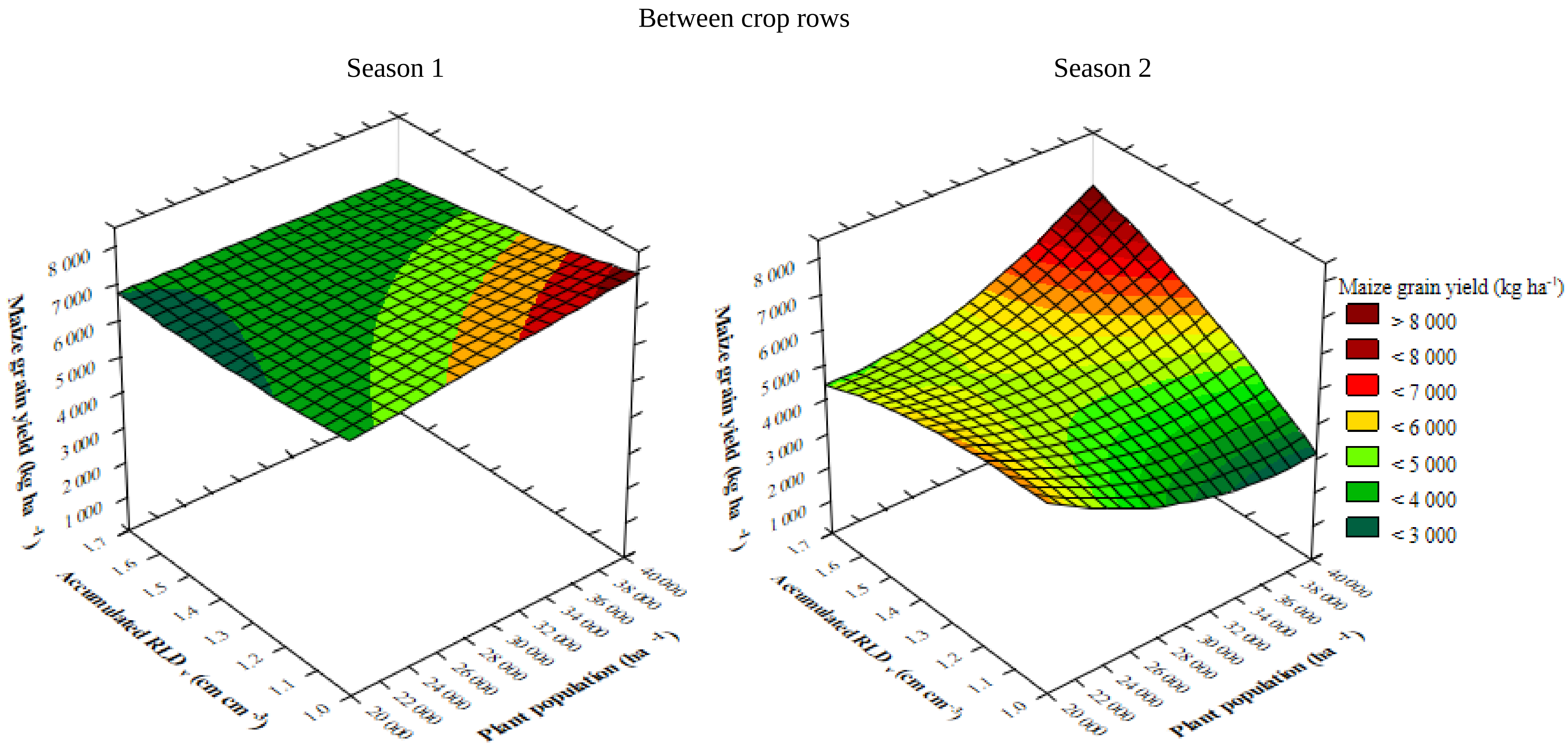


**Figure 6.6:** The relationship between maize grain yield, accumulated volumetric root length density ($RLD_v$) and plant population between crop rows in Season 1 (left) and Season 2 (right).

Generally, maize roots are confined to shallow soil depths (0-15 cm) due to breeding, the stratification of nutrients (Lynch, 2011) and the higher bulk density of deeper soil layers (Buczko et al., 2009). These soil physical characteristics have previously been associated with soils under several years of NT (Dam et al., 2005). However, in contrast to previous studies (Grabarnik, 1998; Guan et al., 2014), in this study, $RLD_v$ was lower for all plant populations at the 0-15 cm soil depth compared to the deeper soil depths in Season 1 at V6 and VT against the crop row (Figure 6.2). Due to low rainfall frequency in Season 1, drying of the top 0-15 cm soil depth resulted in poor root growth at this soil layer. To overcome prevailing soil and climate constraints, maize plants may increase $RLD_v$ to explore a greater soil volume and increase the uptake of soil resources (Kristian, 2006). In semi-arid environments, where dry spells are common and limits rainfed maize production (Rotili et al., 2019), increased $RLD_v$ in deeper soil depths may sustain aboveground growth and development during water stress periods resulting in adequate maize grain yields (Figure 6.5). However, prolonged water stress periods negatively affect maize root growth, limiting soil resource uptake and overall aboveground production (Li et al., 2015). The results obtained in our study indicated that, in the season with low and erratic rainfall occurrence (Season 2), $RLD_v$, average root diameter and lateral root length was lower compared to Season 1 with a more optimal rainfall distribution (Figures 6.2 to 6.4). This explains the low maize grain yields at high plant populations in Season 2, despite the presence of a high accumulated $RLD_v$. Similarly, Jiang et al. (2012) and Li et al. (2019a) reported lower maize root growth where maize plants underwent severe water stress conditions. As photosynthesis is negatively affected when maize plants undergo water stress, photosynthate storage in the roots is reduced and ultimately leads to poor $RLD_v$, lower root diameter and root length (Liu et al., 2012; Shao et al., 2018) (Figure 6.2; Tables 6.5 and 6.7).

Lateral root length and branching angle is fundamental in maize root system spatial distribution and functioning (Atkinson, 2014) and accounts for the majority of soil water and nutrient uptake (Varney and Canny, 1993; Wang et al., 1994). This role of lateral roots is attributed to the high surface area and the length of the lateral roots contribute towards the total surface area and length of the root system (Lynch, 2013; Yu et al., 2019), explaining the importance of finer roots for soil water uptake (Ahmed et al., 2016). Reduced lateral root branching angles improve soil resource uptake (Zhan and Lynch, 2015) and is of great advantage in rainfed maize production systems. In our study, average lateral root length and branching angle was only affected by season and soil depth, respectively (Table 6.6). The low soil water levels throughout the growing season in Season 1 and 2 due to low rainfall may have impeded plant population treatment effect on lateral root growth and development. Zhan et al. (2015) reported that maize genotypes with reduced lateral root branching have shown more tolerance to drought under field conditions. Also, the possibility exist that soil cracks and fissures along the minirhizotron tubes may have altered lateral root growth, especially in Season 2 with dry soil leading to poor soil-tube contact.

## 6.5 Conclusion

Plant population did not affect $RLD_v$ and average root diameter against and between rows at V6 and VT, while only soil depth and season affecting these maize root parameters. Volumetric root length density was lower for all plant populations at the 0-15 cm soil depth compared to the deeper soil depths in Season 1 at V6 and VT against the crop row. Due to low rainfall frequency in Season 1, drying of the top 0-15 cm soil depth resulted in poor root growth at this soil layer. In the season with low and erratic rainfall occurrence (Season 2), $RLD_v$, average root diameter and lateral root length was lower compared to Season 1 with more optimal rainfall distribution. This explains the low maize grain yields at high plant populations in Season 2, despite the presence of a high accumulated $RLD_v$. Average lateral root length and branching angle was only affected by season and soil depth, respectively. The low soil water levels during the growing season due to low rainfall might have impeded any plant population treatment effects on maize root growth and development.

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# CHAPTER 7

# Summary and recommendations

## 7.1 Rationale and research themes

Plant population and row spacing are principal agronomic management practices influencing maize growth, development and grain yield. Both plant population and row spacing directly influence the rate and efficiency of soil resource use and rainfall. With the introduction of alternative soil and crop management practices [no-tillage (NT) and conservation agriculture (CA)] in rainfed maize production systems which significantly change soil quality, there was a need to re-evaluate plant population and row spacing guidelines. This study investigated the following five critical research themes:

1. A review of the effects of current agronomic management practices followed in the South African rainfed maize production systems on the soil-plant environment. Sustainable and alternative agronomic management approaches were highlighted. Future research options were explored, expanding our knowledge of proposed approaches in local soil and climate conditions.

2. A global systematic review of published data reporting on the effects of plant population on rainfed maize grain yield under different climate and agronomic conditions, and the influence of mean annual rainfall, soil tillage and nitrogen application on the relationship between plant population and maize grain yield.

3. The effects of varying plant population and row spacing configurations on rainfed maize grain yield, soil temperature and soil water content under CA in a subtropical environment.

4. The effects of plant population and row spacing on aboveground rainfed maize growth, grain yield, water use efficiency and soil β-glucosidase activity under NT in a semi-arid environment.

5. The response of rainfed maize root morphology to varying levels of plant population under NT in a semi-arid environment.

## 7.2 Synthesis of empirical findings

The findings are chapter specific and were summarised within the respective research themes, correlating to the respective chapters in this thesis:

The first research theme (Chapter 2) was focussed on evaluating the current agronomic management practices followed in the rainfed maize production systems of South Africa. Each production region offers a diverse set of challenges and advantages for rainfed maize grain production. Maize producers are mainly profit-driven with an important management goal of maximising maize grain yields. However, short-term profit should not be the only goal, as it may lead to severe soil losses and depletes soils from organic matter and nutrients (Bai and Dent, 2007; Mills and Fey, 2003). Currently, most maize producers in South Africa follow rigorous soil tillage practices, prolonged fallow periods and maize monoculture which increase the rainfed maize production systems'sensitivity for poor growing conditions such as low rainfall and high temperatures (Sithole et al., 2016). Over the long term, maize grain yields are highly variable between seasons and results in the continuous loss of fertile soil and nutrients. Coupled with inconsistent rainfall patterns, the variable yields and soil losses highlights the need for changes in the agronomic management practices currently followed in the South African rainfed maize production regions. Alternative soil and crop management practices, such as no- or minimum tillage, crop intensification and diversification, maintenance of crop residues to cover soil, and livestock integration may provide pathways to increase the sustainability of the rainfed maize production systems. Through these pathways, the water content of soils could be improved and sustain increased plant populations. The recent introduction of NT and CA across the rainfed maize production regions of South Africa may provide an approach to facilitate sustainable intensification of maize grain production. It should, however, be stressed that practicing NT as a sole practice may not be sufficient in achieving the desired soil conservation goals (Pittelkow et al., 2015; Verhulst et al., 2010). Conventional tillage (CT) practices, such as deep in-row ripping, may still be needed to address soil compaction challenges until alternative methods are identified. It is still not well understood whether NT or CA are the best approach to facilitate sustainable intensification of maize production in South Africa. There is a paucity of published information on the performance of rainfed maize and other crops in rotation with maize within CT, NT and/or CA systems. Studies that evaluated the effects of soil and crop management practices (CT, NT and CA) on maize grain yield outside South Africa often reported highly variable yield responses.

Results originating from the major maize production regions, such as the USA, China, Argentina and Brazil, were highly seasonal- and site-specific (Amelong et al., 2017; Blumenthal et al., 2003; Cox and Cherney, 2012; Hörbe et al., 2013; Jin et al., 2012). Since yield responses are context-specific, producers are exposed to a plethora of information, not necessarily relevant, which leads to confusion among producers. Maize plant population and row spacing should be adapted alongside the changes in soil and crop practices (Barbieri et al., 2012; Pedersen and Lauer, 2003; Ruffo et al., 2015).

In this context, and following an evaluation of the current agronomic management practices followed in the rainfed maize production systems of South Africa, the second research theme was formulated (Chapter 3): A global systematic review of published data reporting on the effects of plant population on rainfed maize grain yield under different climate and agronomic conditions, and the influence of mean annual rainfall, soil tillage and nitrogen application on the relationship between plant population and maize grain yield. By collating a large set of maize grain yield data, obtained from various climates and systems with diverse sets of agronomic management across the world, it became evident that it is not only plant population that affects maize grain yield, but the relationship between plant population and rainfall is of high significance. In environments with a high rainfall (more than 600 mm per annum), maize grain yield responded positively with increased plant population. The risk for crop failure in these environments are low due to the more evenly distributed rainfall throughout the growing season. Even distribution of rainfall enables maize plants to take advantage of the available soil water and reach maturity in relatively stress-free conditions. This makes plant populations in excess of 60 000 plants $ha^{-1}$ at 0.76 m or narrower row spacing a viable option for producers to achieve high and stable maize grain yields.

In contrast, dry spells during the growing season and prolonged droughts is common in semi-arid and arid environments receiving less than 600 mm of rainfall annually, explaining the high variability of maize grain yield in these environments. Soil-water deficits during the critical reproductive growth stages constrain maize grain yield. With no assurance that a good economic return is possible with the establishment of plant populations in excess of 40 000 plants $ha^{-1}$, producers resort to lower plant populations in low rainfall environments. However, inconsistent maize grain yield responses to plant population and row spacing in low rainfall areas were mainly obtained from field trials characterised by CT. There are not enough rigorous evidence that a change in soil and crop management requires changes in plant population and row spacing.

The influence of soil tillage practice on the relationship between maize grain yield and plant population was evaluated using a systematically compiled dataset (Chapter 3), ensuring a sufficient number of maize grain yield data points represent CT and NT systems. The optimum plant population for NT was lower than that of CT. However, at a given plant population, maize grain yield under NT outperformed yields under CT. The yield response to soil tillage practice is attributed to soil and climate-related challenges, rather than the effect of plant population and/or row spacing. For example, soils sensitive to compaction or poor drainage limited maize grain yield (Van den Putte et al., 2010), where in these cases, tillage would have mitigated yield constraining factors. The trade-offs for using a once-off or strategic tillage action are the destruction of soil aggregates and the loss of soil cover (Grandy et al., 2006). Maintaining a soil cover under NT is vital, since this is the interface supporting water infiltration during rainfall events and the lowering of soil water evaporation induced by direct sunlight (Rusinamhodzi et al., 2011). Improved soil water storage, infiltration rate and organic matter content are among the most important characteristics of soils managed under NT and CA. It can be argued that the potential exist to increase plant population at a narrower row spacing when NT or CA are performed, provided that NT and CA are performed using a system-based approach, thereby including the relationships among sound agronomic management practices.

From above research findings, it was evident that manipulating plant population and row spacing, coupled with changes in soil and crop management practices, are important considerations for producers to increase maize grain yield. Alternatively, these changes to soil and crop management can be used to stabilise variability in maize grain yield over the long term. The research findings in Chapter 3 also indicated a lack of plant population and row spacing field trial studies conducted under CA in any rainfall environment, and under NT in water limited semi-arid environments. No published data reporting on the effects of plant population and row spacing on maize grain yield was found in the rainfed maize production regions of South Africa. Also, no scientific data was available explaining possible yield advantages provided by the plant populations and row spacings currently followed by producers. Two multiple-year field trials were conducted in different climate zones in South Africa to address the paucity on information regarding the effects of plant population and row spacing on *inter alia* maize grain yield and growth in local soil and climate conditions (Chapters 4, 5 and 6).

In the first rainfed field trial, which was conducted in a high rainfall environment, plant available water, daily average soil temperature and maize grain yield response to plant population and row spacing was evaluated over three production seasons under CA (Chapter 4). Increased plant population (more than 50 000 plants $ha^{-1}$) at any row spacing (0.5 - 1.0 m) proved to be advantageous in the season with low rainfall and in the season with well-distributed near average rainfall, suggesting increased plant populations are favourable under CA. Row spacing had no effect on maize grain yield in any production season. The improved soil water capacity and present soil cover may have led to adequate soil water content during the critical reproductive growth stages in the dry season, enabling the higher plant populations to produce good yields. Higher plant populations also resulted in quicker leaf canopy closure, maximising sunlight interception and limiting water losses through evaporation from soil. A plant population and row spacing configuration of 28 000 plants $ha^{-1}$ at 1.0 m showed ineffective use of soil water and was reflected by a low maize grain yield. There exist a need to increase plant population and decrease row spacing in subtropical environments where CA is performed. In this way, producers can adequately utilise the soil related benefits.

In the second field trial, which was conducted in a low rainfall environment, soil water content and aboveground maize growth and development was evaluated in response to varying plant population and row spacing (Chapter 5). Over two production seasons, rainfall distribution throughout the growing season had a major impact on research findings. In the season with very low rainfall, adequate soil water levels during the reproductive growth stages was vital, with poor yields achieved when plant population reached more than 25 000 plants $ha^{-1}$ at a 0.52 m row spacing. A row spacing of 0.76 m was advantageous in the drier season, where all plant populations (20 000 to 50 000 plants $ha^{-1}$) out yielded any given plant population more than 25 000 plants $ha^{-1}$ at 0.52 m row spacing. The effect of increased interplant competition with increased plant population was highlighted when soil water was limited. The importance of optimising plant population and row spacing in a water-limited environment is underscored. Despite the more effective sunlight interception and higher leaf area index at higher plant populations, a lack in soil water inhibited the physiological processes, photosynthesis and carbohydrate assimilation, and maize plants were unable to produce adequate grain. In the season with more uniform rainfall distribution, increased plant population offered no maize grain yield benefits at neither 0.52 nor 0.76 m row spacings, except where 50 000 plants were established per hectare at 0.76 m row spacing.

Cautious consideration must be given to plant population and row spacing under NT in a water limited environment. Increased maize grain yield are possible with a plant population of more than 40 000 plants $ha^{-1}$ at 0.76 m row spacing in a season with adequate rainfall amount and uniform distribution, however, in seasons with poor rainfall, poor yields are highly likely. The success and profitability of increased plant population at a given row spacing in a semi-arid environment will ultimately be determined by the rainfall amount and distribution throughout the growing season, with emphasis on the soil water levels during the critical reproductive growth stages.

Research theme five (Chapter 6) was addressed by exploring belowground maize growth in response to plant population. Rainfed maize root morphology in response to plant population, ranging from low to high at 0.76 m row spacing, was evaluated *in situ* throughout the growing seasons of the two-year field trial. Rainfall significantly affected maize root morphology. Poor root growth and development was observed when rainfall is low during the initial vegetative growth stages. Overall, plant population had a small effect on maize root length density, average root diameter, lateral root branching angle and lateral root length. The low soil water content throughout the growing season in Season 1 and 2 may have impeded plant population treatment effects on lateral root growth and development. Across the 0-60 cm soil depth, the majority of the root system was located at the 15 to 60 cm soil layer against crop rows, regardless of the plant population. Between crop rows, the maize root system was more evenly distributed throughout the 0 to 60 cm soil layer for all plant populations. These observations highlights the importance of fertiliser application and placement for maize under NT. Stratification of nutrients in the upper part of the soil profile is a well-known characteristic of soils under several years of NT (López-Fando and Pardo, 2009). Nutrient management should not be primarily limited to the upper 15 cm of the soil profile. Care should be given to the presence of physical soil restriction layers (compaction) which may potentially impede the movement of soil water and nutrients to deeper soil layers.

## 7.3 Theoretical implication

Using plant population and row spacing to optimise maize grain yield has been recommended for a variety of different climate environments over several decades (Alessi and Power, 1974;

Begna et al., 1997; Duvick, 2005; Jones, 1985; Rotili et al., 2019). However, the complexity of the relationship between maize density stands and additional factors such as genetics, environmental factors and agronomic management practices results in seasonal- and site-specific conclusions. This leads to uncertainty among researchers and producers regarding the most appropriate agronomic management practices to optimise maize grain yield in a specific rainfall region and farming system. Moreover, the current scientific knowledge on plant population and row spacing in the rainfed maize production regions of South Africa has been absent for several decades, as well as the synergy between accompanying agronomic management practices (Sithole et al., 2016; Van der Laan et al., 2017). This study contributes towards understanding the underlying concepts of interplant competition and the functioning of the rainfed maize production systems in South Africa, ultimately aimed at optimising maize grain production on a global and local scale.

Optimising maize grain yield using plant population and row spacing requires a system-based and adaptable approach offering a wide spectrum of agronomic management options, while acknowledging the context-specific limitations for maize grain production. Firstly, this study provides novel information on the association between agronomic management practices and the soil-crop system on a global and local scale, which establishes the platform to optimise maize grain yield in South African and foreign rainfed maize production systems. Secondly, information regarding the response of maize grain yield and growth under newly introduced soil and crop management (CA and NT) was needed. This study provided evidence that increased plant populations (more than 50 000 plants $ha^{-1}$) can be used to increase maize grain yield under CA in a high rainfall environment. In an environment where low rainfall and dry spells are common, increased plant population at a row spacing of 0.76 m is a lower risk option compared to a row spacing of 0.52 m, while rainfall amount and distribution throughout the growing season ultimately determine the possibility of any yield benefits when producers establish a high plant population of more than 40 000 plants $ha^{-1}$.

## 7.4 Recommendation for future research

The synergetic interactions among plant population, row spacing, and the applied soil and crop management practices are extensive and multifaceted. It is proposed that strategies for sustainable and more cost-effective rainfed maize grain production in South Africa include the intensification and diversification of the maize-dominated cropping systems, less soil disturbance, and the limitation of fallow periods. Accompanying these changes in soil and crop management with a permanent soil cover using crop residues or living crops, soils may restore organic matter and nutrients following multiple decades of soil degradation, especially soil erosion (Serraj and Siddique, 2012). In turn, the water content of soils can be increased offering the opportunity to increase plant population and narrowing row spacing with a lower risk of crop failure when rains fail. To generate a further understanding regarding the interlinked components influencing the optimal plant population and row spacing in rainfed maize production systems, long-term assessments should include economic, production and agroecological evaluations. Exploring the following as future research strategies can facilitate the attainment of these aspects:

- The incorporation of more diverse cropping sequences in the maize-dominated cropping systems using alternative cash crops and cover/forage crops (leguminous and non-leguminous). Such studies should follow a farming system analysis, considering economics (with and without livestock integration), crop residue cover management, the influence of each crop within the crop sequence rotation on the growth of the subsequent crops, and the contribution of fixed nitrogen to subsequent crops in various crop sequence rotations.
- Because of uncertain climate conditions leading to variable maize grain yields and grain prices, a farming systems budget analysis is needed to quantify the profitability of different plant populations under various soil and crop management practices (CT, NT as a sole practices and in the context of CA). Such studies should be conducted at various localities in each of the South African rainfed maize production regions. The research findings obtained from budget analyses can be used by producers to estimate the change in annual profit in an average season for plant populations in each region.
- Because this study stressed the importance of soil water-use efficiency, row spacing guidelines currently used in the South African rainfed maize grain production regions should be revisited to clarify the optimal point between narrower row spacing that limit soil surface evaporation and plant population which can be supported by the available soil water.
- The direct effects of plant population and row spacing on soil nutrient withdrawal and how fertiliser management should be adapted accordingly for different plant populations, especially coupled with the adoption of NT and/or CA.

- Future research should include studies on methods to reduce soil compaction. This study showed that one of the major constraints for adopting lower soil disturbance practices, particularly in regions characterised by easily compactable fine-sandy soil, are due to the lack of recent and relatable research. In order for producers to address the extreme soil erosion and degradation in their farming systems, alternative management practices to alleviate or bypass severe soil compaction sustainably should be identified. This will require farm-level research to establish the reasons for compaction (tillage actions and timing, machinery wheel pressure, livestock-induced) and how it can be dealt with, for example, using strategic tillage or a controlled traffic farming system.
- The maize grain yield and growth response of a wide range of current commercially available hybrids should be tested, each offering a different set of benefits and disadvantages associated with drought and soil resource use efficiency. The agronomic performance of hybrids differing in morphological above- and belowground characteristics should be further explored. Understanding how each hybrid flexes its ear size and change its leaf orientation based on interplant competition and growing conditions will aid producers and researchers to identify the optimal plant population, row spacing and fertiliser management to achieve optimal maize grain yields.

### 7.5 Study limitations

The study has offered perspectives on interplant competition of maize as influenced by a wide range of crop, soil and climate factors. As a direct consequence of the methodology followed in the two multiple-year field trials, a number of challenges were encountered, which needs to be considered:

- Due to a limited number of available soil water probes (Chapter 4), the evaluation of soil water level and temperature was restricted to only two plant population treatments in each production season. This methodology did not allow the evaluation of soil water and temperature across a wide range of plant population and row spacings thereby limiting gained information about the optimal plant population and row spacing configuration to optimise soil water use.
- The monitoring of soil water content throughout the growing seasons of the field trial discussed in Chapter 5 was restricted to the availability of the neutron soil water probe. As a result, rainfall events between soil water measurements might have concealed the effects

of plant population and row spacing on soil water levels, as the soil profile was wetted to close to equal soil water contents before measurements. In future, continuous logging soil water probes should be used across all plant population and treatments to provide soil water data continuously over a set time frame.

- A single cultivar was used in both field trials (Chapters 4, 5 and 6) over all production seasons. Different maize cultivars offer different sets of benefits and disadvantages to maize. Therefore, using a diverse set of cultivars when plant population and row spacing is evaluated, is recommended. This approach will provide information on the best suited cultivars for each plant population and row spacing configuration in a specific environment and season.
- The root quantification process (Chapter 6) is an extremely time consuming process when using the *RootSnap!* image analysis software to analyse obtained digital images. As a result, maize root digital images were only collected at four measurement dates throughout the growing season, consequently lowering the image collection frequency. In future research, a higher frequency of digital image collection throughout the growing season is needed to improve the tracking of temporal and spatial changes in maize root morphology.

## 7.5 Closing remarks

This study offers novel perspectives on the complex concept of interplant competition of rainfed maize under various soil and crop management practices and climate conditions. The system-based approach can serve as a platform for adaptive management in the South African rainfed maize production systems. Increased understanding of rainfed maize plant population and row spacing and the effects of agronomic management practices on rainfed maize growth and yield is critical to local and global challenges on how to optimise rainfed maize grain production in a sustainable way.

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# Appendix A: Supplemental material 1 (Chapter 3)

**Table A1:** References for the articles representing various rainfall groups included in the systematic review. A, arid; SA, semi-arid; SH, sub-humid; H, humid; SuH, super-humid.

| Reference | Country | Rainfall group |
|---|---|---|
| Acciaresi and Zuluaga (2006) | Argentina | H |
| Allen (2012) | USA | SA |
| Alessi and Power (1974) | USA | SA |
| Amelong et al. (2017) | Argentina | H |
| Anderson (2000) | USA | SA |
| Balkcom et al. (2011) | USA | SuH |
| Bavec and Bavec (2001) | Slovenia | H |
| Begna et al. (1997a) | Canada | H |
| Begna et al. (1997b) | Canada | H |
| Blumenthal et al. (2003) | USA | SA |
| Boomsma et al. (2009) | USA | H |
| Cheng et al. (2015) | China | SH; SuH |
| Ciampitti and Vyn (2011) | USA | H |
| Coulter et al. (2010) | USA | H |
| Cox (1997) | USA | H |
| Cox and Cherney (2012) | USA | H |
| DeBruin et al. (2017) | USA | H |
| Farnham (2001) | USA | SH; H |
| Glenn and Daynard (1973) | Canada | H |
| Haegele et al. (2014) | USA | H; SuH |
| Hammer et al. (2009) | USA | H |
| Hashemi et al. (2005) | USA | SuH |
| Hicks and Stucker (1972) | USA | SH |
| Hörbe et al. (2013) | Brazil | SuH |
| Jampatong et al. (2000) | USA | H |
| Jin et al. (2012) | China | SH |
| Jones (1986) | Botswana | SA |
| Lente (2009) | Hungary | SA |
| Li et al. (2011) | China | SA; SH; H |
| Liang et al. (1991) | Canada | H |
| Lutz et al. (1971) | USA | H |

| | | |
|---|---|---|
| Major et al. (1991) | Canada | A |
| Mashingaidze et al. (2009) | Zimbabwe | H |
| Modarres et al. (1998) | Canada | H |
| Murphy et al. (1996) | Canada | H |
| Nafziger (1996) | USA | H |
| Nowatzki et al. (2002) | USA | H |
| Portes and Melo (2014) | Brazil | SuH |
| Qian et al. (2016) | China | SA; SH; H |
| Raymond et al. (2009) | USA | H; SuH |
| Reeves and Cox (2013) | USA | H |
| Robles et al. (2012) | USA | H |
| Roth et al. (2013) | USA | H |
| Ruffo et al. (2015) | USA | H; SuH |
| Sárvári and Pepó (2014) | Hungary | SA |
| Shafi et al. (2012) | Pakistan | A |
| Shrestha et al. (2001) | Canada | H |
| Simić et al. (2012) | Serbia | SH |
| Sönmez (2002) | Turkey | SA |
| Sotomayor et al. (1980) | Puerto Rico | SuH |
| Stanger and Lauer (2006) | USA | SH; H |
| Subedi et al. (2006) | Canada | H |
| Teasdale (1995) | USA | H |
| Teasdale (1998) | USA | H |
| Teymoori et al. (2013) | Iran | H |
| Tharp and Kells (2001) | USA | SH |
| Van Roekel and Coulter (2011) | USA | SH; H |
| Van Roekel and Coulter (2012) | USA | SH |
| Wang et al. (2011) | China | SA; SH; H |
| Wang et al. (2017a) | China | SA |
| Wang et al. (2017b) | China | SA |
| Westgate et al. (1997) | USA | SA |
| Widdicombe and Thelen (2002) | USA | H |
| Zhang et al. (2014) | China | SA |

# Appendix B: Supplemental material 2 (Chapter 3)

**Reference list of articles included in the systematic review (refer to Table A1)**

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# Appendix C

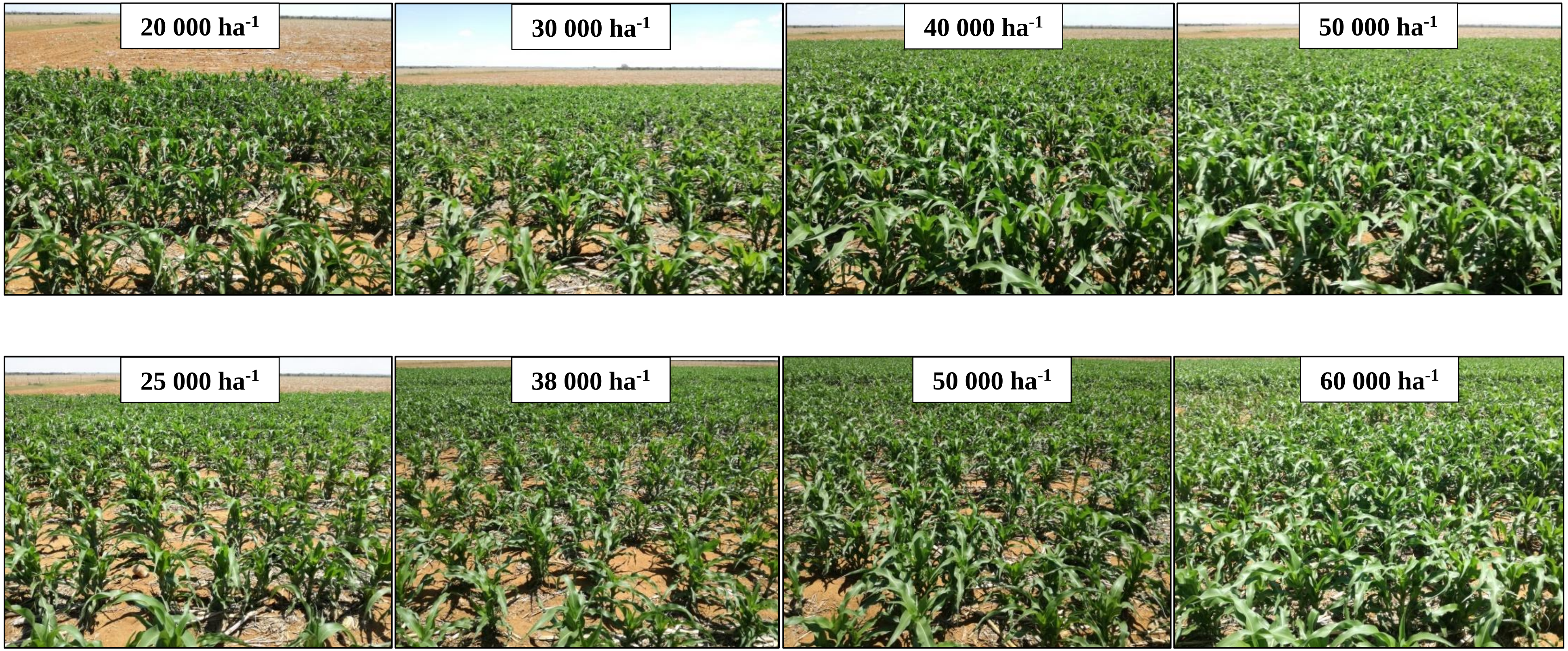


**Figure A1:** Visual presentation of the field trial plots established with varying levels of maize plant population at 0.76 m (top row) and 0.52 m (bottom row) row spacing at the sixth-leaf collar (V6) growth stage near Ottosdal, North West Province, South Africa (Chapter 5).

# Appendix D

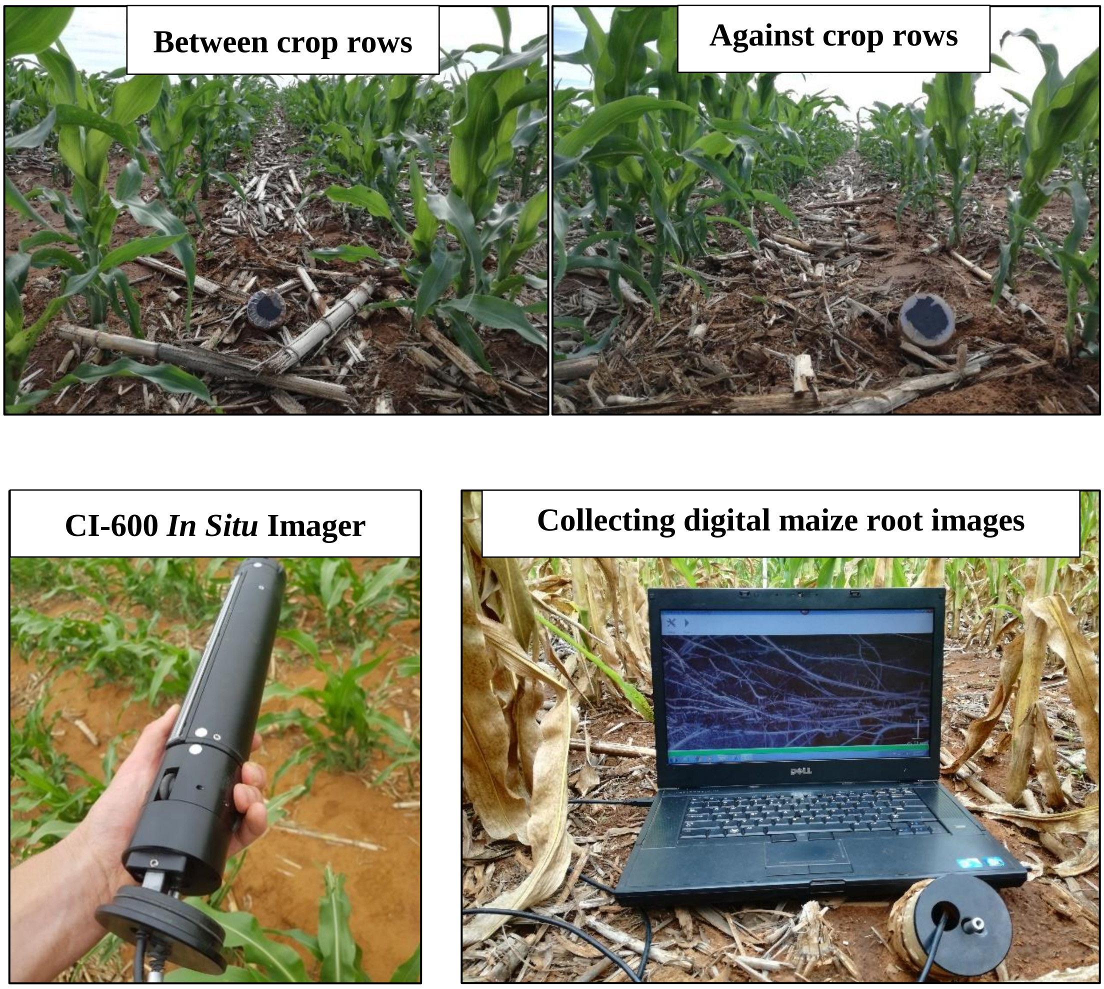


**Figure D1:** Minirhizotron tube placement for maize root observations between and against crop rows (top row). The CI-600 *In Situ* imager (bottom row, left) used to collect digital maize root images (bottom row, right) to quantify maize root morphology at the field trial near Ottosdal, North West Province, South Africa (Chapter 6).