Received: 23 July 2019 | Accepted: 24 October 2019 | Published online: 17 February 2020

DOI: 10.1002/csc2.20103

Crop Science

REVIEW AND INTERPRETATION

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

Stephanus J. Haarhoff | **Theunis N. Kotzé** | **Pieter A. Swanepoel**

Department of Agronomy, Stellenbosch University, Private Bag X1, Matieland, 7602 Stellenbosch, Western Cape, South Africa

Correspondence
Pieter A. Swanepoel, Department of Agronomy, Stellenbosch University, Private Bag X1, Matieland 7602, Stellenbosch, Western Cape, South Africa.
Email: pieterswanepoel@sun.ac.za

Assigned to Associate Editor Eric Ober

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 interseasonal 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 livestock-integrated production systems providing livestock feed 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.

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, which are common. Soil organic matter and nutrients are depleted and there is significant soil loss through wind and water erosion (Le Roux, Morgenthal, Malherbe, Pretorius, & Sumner, 2008; Mills & Fey, 2003). Although more sustainable practices have been proposed (Kassam, Mkomwa, & Friedrich, 2016; Smith, Kruger, Knot, & Blignaut, 2017; Swanepoel, Swanepoel, & Smith, 2017), adoption of management practices that limit degradation has been slow (Findlater, Kandlikar, & Satterfield, 2019).

Maize is the most widely produced crop in South Africa (FAO, 2018). During the 2016–2017 production season, ~16.7 Tg of maize grain was produced from 2.6 million

Abbreviations: CT, conventional tillage; NT, no-tillage.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.
© 2020 The Authors. *Crop Science* published by Wiley Periodicals, Inc. on behalf of Crop Science Society of America

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 ∼4.5 Tg 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, Friedrich, Kassam, & Li, 2010; Kassam, Friedrich, Derpsch, & Kienzle, 2015). By the year 2007, it was estimated that 41% of South Africa's cultivated areas were highly degraded (Bai & Dent, 2007). Despite significant soil losses as a result of degrading production practices, maize grain yields increased. 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 rainfed maize production systems is further hampered by erratic rainfall patterns and frequent drought periods. In this paper, we review the effects of current agronomic management practices followed in the South African rainfed production systems. 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 | 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 1). The Western and Eastern regions form part of the South African inland plateau with an altitude of 1500–1800 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 creating 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 semiarid (BSk)

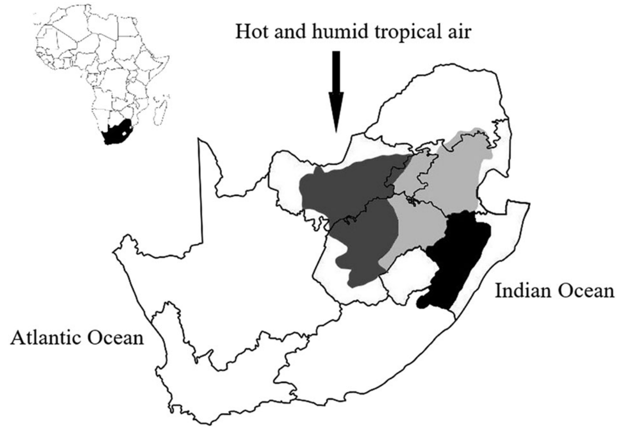

FIGURE 1 Three distinct rainfed maize production regions in South Africa—namely, Western (dark grey), Eastern (grey), and KwaZulu-Natal (black) regions. The summer rainfall pattern across the three rainfed maize production regions is induced by the southward movement of hot and humid tropical air from the equator, with the warm Indian Ocean further inducing rainfall across the KwaZulu-Natal region

according to the Köppen–Geiger climate classification system (Kottek, Grieser, Beck, Rudolf, & Rubel, 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 interannual variability. Prolonged dry spells during the rainy season is a common phenomenon (Zuma-Netshiukhwi, Stigter, & Walker, 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) climatic 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 1500–2000 mm annually, increasing to > 2500 mm per year in the Western region. Growing degree days for the period October to March gradually decreases from approximately 2011 to 1872 moving from the Western to the KwaZulu-Natal regions (Walker & 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 mo, with a more limited 7–8 mo in the Eastern and KwaZulu-Natal regions.

Variability in rainfall patterns between growing seasons affects maize grain yields in the Western and Eastern regions extensively, whereas temperature variability is more critical in the KwaZulu-Natal region (Ray, Gerber, MacDonald, & West, 2015; Walker & Schulze, 2008). Ray et al. (2015) reported that maize grain yield variability was explained by normal and

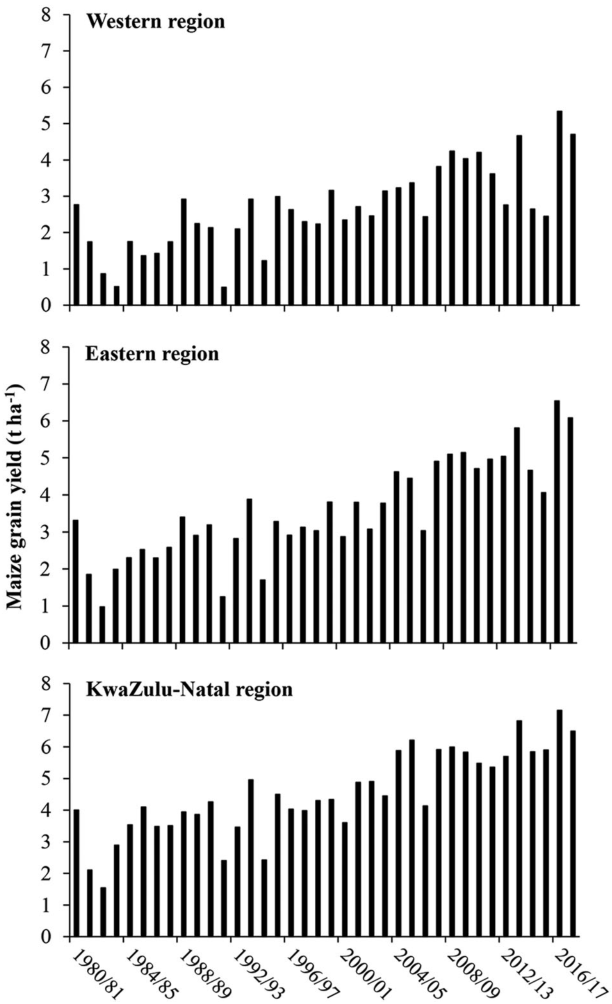

FIGURE 2 Long-term maize grain yields achieved in the Western (36 districts), Eastern (46 districts), and KwaZulu-Natal (14 districts) for production seasons 1980–1981 to 2017–2018. Source: South African Department of Agriculture, Forestry and Fisheries (R. Beukes, personal communication, 2019)

extreme rainfall inconsistency related to the El Niño Southern Oscillation in the Western and Eastern production regions. The interseasonal rainfall variability explained > 60% of maize grain yield variability in the drier 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 (Figure 2) (R. Beukes, personal communication, 2019). Data show high interannual maize grain yield variability during the 1980–1981 to 1999–2000 period, especially in the Western and Eastern regions, with lower variability in the KwaZulu-Natal region (Table 1). High variability in maize grain yields is not solely experienced in the South African semiarid maize production regions, but also in a global context (Haarhoff & Swanepoel, 2018). The lower variability in maize grain yield during the 2000–2001 to 2017–2018 period in all three production regions is attributed

TABLE 1 The CV of maize grain yield for periods 1980–1981 to 1999–2000 and 2000–2001 to 2017–2018 in the Western, Eastern, and KwaZulu-Natal regions

Production region	CV	
	1980–1981 to 1999–2000	2000–2001 to 2017–2018
	%	
Western	39.9	25.7
Eastern	29.1	20.4
KwaZulu-Natal	24.9	13.7

to improved crop breeding (Gouse, Pray, Kirsten, & Schimmelpfennig, 2005) where plants became more drought and disease tolerant. Also, the release of effective herbicides may have also contributed towards the decreased 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 & 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 climatic 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.

3 | RAINFED MAIZE PRODUCTION SYSTEMS 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 3a). After harvest in winter, a 3- to 4-mo 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 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

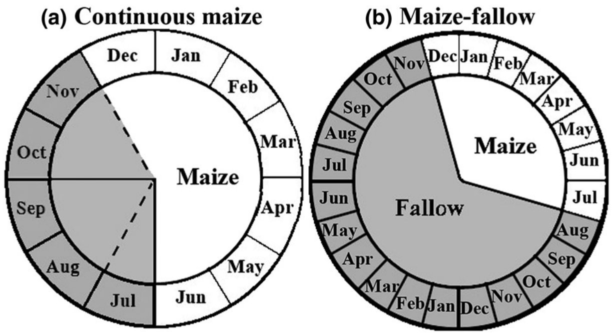

FIGURE 3 The (a) continuous maize and (b) maize–fallow production sequences followed across the rainfed maize production systems in South Africa presented as 1- and 2-yr cycles with production seasons lasting from September to June in the Eastern and KwaZulu-Natal regions (solid lines) and from November to July in the Western region (dotted lines) in the continuous maize production system

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 maize density stands and yields in the continuous maize production system. Consequently, a maize–fallow production system was introduced, adding a further 11–12 mo 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 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 & Hensley, 2001; Bennie, Hoffman, & Coetzee, 1995; De Bruyn, 1974) and were established as principal practice on the sandy soils in the Western region during the 20th century. Optimal maize planting date is from mid-November to mid-December in the Western region and from mid-October to mid-November in the Eastern and KwaZulu-Natal regions.

4 | SOIL MANAGEMENT FOR IMPROVED AND SUSTAINABLE RAINFED MAIZE PRODUCTION

4.1 | Soil tillage systems

Conventional tillage (CT) is traditional practice in the continuous maize and maize–fallow production systems. No-tillage (NT) or other forms of reduced tillage 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 plows in combination with pre- and postemergence herbicides. During early maize growth stages, interrow cultivation is done 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 & Krynauw, 1985). Consequently, in-row deep ripping (500- to 750-mm soil depth) is performed prior to maize planting to alleviate compaction and plow pans caused by machinery wheel pressure and previous tillage operations. Chisel and disc plows are used for seedbed preparation and alleviation of cattle-induced compaction at shallow soil depths. Moldboard plows 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 & 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 moldboard plows include incorporation of crop residues and soil amendments such as gypsum or limestone. Weed control in NT depends entirely on chemical control, altering 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 ~75% in the 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). At various locations in the KwaZulu-Natal region, the response of maize grain yield to soil tillage practice was mainly influenced by growing season rainfall and poor crop establishment. Mallett, Lang, and Arathoon (1987) reported maize grain yields of between 5000 and 9400 kg ha^{-1} under NT, whereas maize grain yields of 4200–9300 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 ($p < .05$) compared with CT. During the latter 4 yr of the trial, average and above-average rainfall was received, resulting in no maize grain yield differences ($p > .05$). Berry, Mallett, and Greenfield (1987) found maize grain yield 13% higher under NT compared with CT, with maize grain yields of 7600 and 6700 kg ha^{-1}, respectively. Maize grain yield achieved under reduced tillage was ~7000 kg ha^{-1}. The reason for the increased maize grain yield was improved soil water conservation, with more water held at plant-available soil water tensions during critical growth stages. The NT plots had 79% more soil cover by maize residues than

TABLE 2 Previous research that evaluated the response of maize grain yield to various soil tillage practices across the three distinct South African rainfed maize production regions

Reference	Production region	Duration of trial yr	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 4 yr NT outyielded CT
Lawrance et al. (1999)	KwaZulu-Natal	13	CT (3), NT (83), RT (28)	Clay loam	Continuous maize	No differences between tillage systems
Bennie et al. (1995)	Western	3	CT, NT, RT	Sand	Continuous maize or wheat; maize–fallow–wheat	CT outyielded NT and RT all years
Swanepoel et al. (2018)	Eastern	6–8	CT, RT	Sandy loam, clay	Continuous maize	RT outyielded CT in 4 yr, other 4 yr no difference
Berry et al. (1987)	KwaZulu-Natal	1	CT (4), RT (18), NT (83)	Loam	Continuous maize	NT outyielded 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 outyielded NT and RT

†If no value is given, the soil cover percentage was not reported in the paper; CT, conventional tillage; NT, no-tillage; RT, reduced tillage (defined as shallow chisel and disc tillage).
‡Outyielded significantly at $p < .05$.

the CT plots, which possibly explains the improved soil water-holding capacity. Although not reported, the 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 ($p > .05$) on mean maize grain yield in research by Lawrance, Prinsloo, and Berry (1999) and Berry and Mallett (1988) on finer textured soils in the KwaZulu-Natal region. However, in three seasons, NT had higher ($p < .05$) maize grain yields than CT (two of these years had below-average rainfall). In seasons with above-average rainfall, CT had higher ($p < .05$) maize grain yields than NT (Lawrance et al., 1999). Overall, the mean maize grain yields for NT, reduced tillage, and CT were 6736, 6748, and 6631 kg ha^{-1}, respectively. Despite no significant differences between soil tillage treatments over the 13-yr experiment, final plant population was lower ($p < .05$) in the NT treatment in six trial years. Similarly, Berry and Mallett (1988) reported no difference ($p > .05$) in maize grain yield between soil tillage practices, which ranged from 7500–8200 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 9410 kg ha^{-1} for CT, reduced tillage, and NT, respectively. Again, plant population was lower ($p < .05$) in both the NT and reduced tillage plots, resulting in higher ($p < .05$) maize grain yields in the CT treatment.

In the Western region, Bennie et al. (1995) found higher ($p < .05$) maize grain yields under CT (1600 kg ha^{-1}) in a maize–fallow production system compared with NT (1200 kg ha^{-1}) in a continuous maize production system. Overall, the lowest mean maize grain yield was 1400 kg ha^{-1} under reduced tillage. The longer fallow period associated with the maize–fallow production system was attributed to the higher yield. 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 systems 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, labor, and effects across the rotation through time is required.

The results reported by studies in Table 2 indicate that NT, in combination with high crop residue cover, is an alternative soil tillage system 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 systems 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 specialized planter equipment to achieve maximal maize establishment.

Utilization of maize residues by cattle and rigorous soil disturbance 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 oxidation of maize residues. Maize residues are of high value in mixed crop–livestock production systems. After grazing of maize residues by cattle, bare fields are moldboard or chisel plowed 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 utilization is needed alongside less intensive soil disturbance 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 & 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 precipitation 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 below.

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, Drijber, & Franti, 2010). In-row deep ripping improves root growth by alleviation of compacted soil layers and results in higher maize grain yields (Bennie & 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 minimizing 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.

4.2 | Fallow and rainfall use efficiency

Research conducted across the rainfed maize production regions have 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 mo, maize grain yield increased by 26% over four production years (De Bruyn, 1974). In an extremely dry year with only 189 mm of rainfall received during the growing season, the maize–fallow rotation produced 629–789 kg ha^{-1} of maize grain with total crop failure in the continuous maize production system (Hensley, Botha, Anderson, Van Staden, & Du Toit, 1999). Increased available soil water at planting after fallow was responsible for the increased maize grain yields in the maize–fallow production system (Bennie & Hensley, 2001) despite reports of pre-plant rainfall storage efficiencies of between 2 and 37% for soils in the Western region (Bennie, Hoffman, Coetzee, & Very, 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 above-mentioned 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 under local semiarid 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 after a winter fallow period.

Maize planting after the 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-mo 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 deeper to obtain adequate seed germination. Deeper seed placement delays seedling emergence (Alessi & Power, 1971). Moreover, later emerging maize seedlings are confronted with surface crusts, which are common across all maize production regions. Surface crusts are problematic when formed after planting but before seedling emergence, thereby impeding maize seedling emergence (Parker & 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 growth conditions early in the growing season.

Alternative production systems need to be recognized in the maize–fallow 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, Poggio, Ermácora, & Satorre, 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 maximize production per unit soil water available.

4.3 | Runoff losses and soil erosion

More than 70% of South Africa's land surface is affected by erosion (Hoffman & Todd, 2000), with soil tillage and poor land management as the major causes (Borrelli et al., 2017; Mills & Fey, 2003). Topsoils 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 & 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 conventionally tilled continuous maize and permanent fallow (Du Plessis & 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 yr, ∼2700 mm of rainfall was lost as runoff (Figure 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 followed. In contrast, Gibbs, Russel, and Kloppers (1993) reported a weak correlation (r^2 = .44) between annual runoff and annual rainfall from fallow plots over 10 yr at a trial site in the KwaZulu-Natal region. Only 15% of the mean annual rainfall was lost as runoff. The trial site was characterized 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 h 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 ($p < .05$) with increasing crop residue cover (Table 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 field trials were conducted several decades ago, the data produced from these trials are still relevant in present times, as similar growth and climatic conditions are currently faced in the rainfed maize production systems.

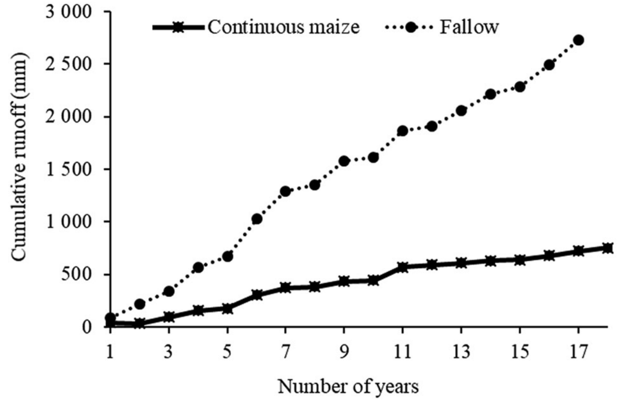

FIGURE 4 Cumulative runoff measured at a trial site in the Western region for plots under continuous maize and permanent fallow for 18 yr. Source: adapted from Du Plessis and Mostert (1965)

Although rainfall is the main agent 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.,

TABLE 3 The effect of crop residues on 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	Soil erosion	Sediment concentration
%		mm h^{-1}	kg ha^{-1}	kg m^{-3}
0	31	19.8	5989	13.7
10	37	23.1	3761	9.6
20	39	24.6	2812	7.4
30	41	26.6	1999	5.3
45	48	30.7	1501	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

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 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 moldboard-plowed, fallow soil in the Western region from late winter to spring. Soil dust deposition was at a maximum during October (spring) at ~1.923 g m^{-2} d^{-1}. Overall, soil dust deposition equaled an average of 0.48 g m^{-2} d^{-1} over 3 mo.

Producers opt to use moldboard or chisel plows to roughen the soil surface prior to fallow in winter or the lengthy 15- to 17-mo 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 semiarid 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 for producers to lower runoff losses and erosion rates. To promote the mind shift change needed among producers, further research is needed to investigate and facilitate the function of less intensive soil tillage practices and alternative crop sequences in current 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, Loveridge, & Fairweather, 1995; Sithole, Magwaza, & Mafongoya, 2016).

5 | CROP MANAGEMENT IN RAINFED MAIZE PRODUCTION SYSTEMS

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 skeptical 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 reevaluate optimal plant densities in the South African rainfed maize production regions.

Plant density directly influence maize grain yield (Ciampitti & Vyn, 2012). Adjusting plant density according to soil fertility, soil water-holding capacity, 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, McLean, Doherty, Hammer, & Robertson, 2008). However, these wide row spacings (> 0.91 m) used in the Western region are not optimized 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} at 0.76- to 1.2-m row spacing, respectively.

Maize grain yield variability obtained in the Western region is directly linked to erratic rainfall patterns between production seasons (Figure 2). Plant density has been increasing in major maize producing countries such as the United States, 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 fertilizers all contributed towards improved maize grain yields. The introduction of NT and increased crop residue retention lead to the redesign of production systems in the semiarid US Great Plains (Hansen, Allen, Baumhardt, & Lyon, 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 water-holding capacity and infiltration rate (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 of leaf canopy cover, plant density, and available modern hybrids. Modern maize hybrids in the United States 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 maximize modern maize hybrid potential and improving soil resource use efficiency in the rainfed maize production systems.

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 of South Africa and improve the management of available soil water and nutrients, particularly N. The continuous maize and maize–fallow production systems accelerate soil losses (Du Plooy, 1968), with the latter practice associated with low water and N 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 & 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 production systems, 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 tradeoffs for diversifying the maize monoculture crop sequence with legumes or sunflower is the low soil water and crop residue levels present after 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 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-mo 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 N for the subsequent maize crops. Despite an urgent call from Nel (2005) to quantify the contribution of fixed N to

TABLE 4 Annual maize residue cover required to maintain soil organic C 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	
	Conventional tillage	No-tillage
	kg ha^{-1}	
Western	4400–5800	3800–5000
Eastern	4100–4400	3300–3800
KwaZulu-Natal	4200–4700	3600–3800

subsequent crops in various crop sequence rotations, there is still a paucity of scientific data reporting on this matter in the 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 utilization 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 limit runoff and soil losses during rainfall events. 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 utilization 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 utilized 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.

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 use 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 utilization by livestock with increasing stock density on natural vegetation.

During the 20th century, producers in the Western region followed a winter-sown 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-sown wheat, allowing grain harvest early in summer. Winter-sown 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 (× *Triticosecale* Wittm. ex A. Camus) and oat (*Avena strigosa* Schreb.) and summer-grown forage sorghum increased to assist forage needs.

Potential tradeoffs 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 C. 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 water 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 plows to alleviate shallow soil compaction, combat wind erosion, and eliminate winter weeds. These management practices result in a soil cover of < 5%. The quantity of soil water loss caused by these soil tillage actions is unknown, which may contribute to the fact

TABLE 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	Weed control challenges	Maintain high soil cover
	Delayed planting date	Nutrient-depleted soils	Diverse crop sequence
	High crop residue volumes	High disease pressure	Mixed crop–livestock system
	Grain easily marketed	Inconsistent yields	Intercropping
		Inconsistent grain markets	Integrated weed management
Maize–fallow	Lower risk for crop failure	One harvest in 2 yr	Increase crop frequency
	Planting date more optimal	Bare soil for long period	Increase crop diversity
	Planting depth more optimal	Low rainfall use efficiency	Cover crops
		Increased weed control costs	Maintain crop residues
		Enhance soil erosion and degradation	
		Nutrient leaching	
		Low livestock feed levels	
Diverse crop rotations	High rainfall use efficiency	Inconsistent grain markets	Include cover or forage crops
	Lowers disease pressure	Low soil water levels following cash crop	Integrate livestock
	Improved weed control		Maintain high soil cover
	Utilization of crop residues or cover crops		
	Increased annual biomass production		
	Increased production intensity		
	High livestock feed levels		
	Crop diversity		
Mixed crop–livestock	Stable cash flow throughout year	Shallow soil compaction	Strategic tillage
	Risk better managed	Soil cover loss	Establish cover or forage crops
	Improved biomass utilization	Low soil water levels after cash crop	Improve biomass management
	Crop diversity		Short-duration, high-intensity grazing
	Improved weed control		

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 C levels at 2.0% in the various rainfed maize production regions in a continuous maize production system (Table 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 semiarid Western region.

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 agronomic management practice (Tables 5 and 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

TABLE 6 A summary of advantages, disadvantages, and possible tools to overcome the disadvantages of some 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 system	Conventional tillage	Short-term weed control	Enhance soil erosion and degradation	Lower soil disturbance
		Alleviate soil compaction	No soil cover	Maintain soil cover
		Uniform seedbed	High production costs	Diversify crop sequence
		Soil amendment incorporation	Inconsistent yields	
			Enhance soil organic matter loss	
	No-tillage	Low production costs	Soil compaction	Controlled traffic farming
		Good soil cover	Inconsistent yields	Strategic tillage
		Lower erosion	Costly planter equipment	Cover crops
		Improved soil organic matter	Higher herbicide use	Integrated weed management
		Improved soil water holding capacity	Nutrient stratification	
		Lower runoff losses		
Plant density	Low plant density	Less risk for crop failure	Yield penalty in good rainfall seasons	Optimize row spacing and plant population for available soil resources
		Low seed costs	Poor sunlight use efficiency	Maintain soil cover
			Poor weed suppression	
			High soil evaporation losses	
			Low biomass production	
	High plant density	High yields in good rainfall seasons	High risk for crop failure	Maintain soil cover
		Improve soil resource use	High seed costs	Less soil disturbance
		Improve sunlight interception		Diversify crop sequence
		High biomass production		
		Suppress weeds more easily		

maize–fallow systems. As demonstrated for the small grain crop rotation systems produced in the Western Cape of South Africa (MacLaren, Storkey, Strauss, Swanepoel, & Dehnen-Schmutz, 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 semiarid 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 minimize 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 tradeoffs associated with crop residue utilization 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, Bristow, Stirzaker, & Annandale, 2017), whereby all aspects regarding in-field activities are taken into consideration, resulting in a wide spectrum of agronomic management options. Unfavorable climatic conditions, such as prolonged droughts and damaging winds, across the South African maize production regions inherently call for such adaptable approach.

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 the 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 systems (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 systems should follow a farming system analysis, considering economics (potential savings in fuel and labor) 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.
- Reevaluation of optimal plant densities (plant population and row spacing) entailing an integrated approach including crop residue retention, diverse crop sequences, and various levels of soil disturbance using newly released hybrids. To optimize resource use efficiency, row spacings should be optimized for the balance between narrower row spacings that would limit soil surface evaporation, and plant populations that can be supported by the available soil water and nutrients.
- Incorporation of cover or forage crops (leguminous and nonleguminous) 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 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.
- Investigation of the effects of livestock-induced soil compaction, and providing pathways to limit the effects of livestock on soil structure and subsequent crop yields.
- Quantification of the contribution of fixed N to subsequent crops in various crop sequence rotations.

ACKNOWLEDGMENTS

The Maize Trust, AgriSETA, and South African Society of Crop Production are acknowledged for providing funding to complete this work under respective Ph.D. bursary programs.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ORCID

Stephanus J. Haarhoff
https://orcid.org/0000-0001-7768-2845
Pieter A. Swanepoel
https://orcid.org/0000-0002-6481-0673

REFERENCES

AFMA. (2017). Prospectus on the South African maize industry. *Animal Feed Manufacturers Association*. Retrieved from https://www.afma.co.za/prospectus-south-african-maize-industry/

Alessi, J., & Power, J. F. (1971). Corn emergence in relation to soil temperature and seeding depth. *Agronomy Journal 63*, 717–719. https://doi.org/10.2134/agronj1971.00021962006300050018x

Andrade, J. F., Poggio, S. L., Ermácora, M., & Satorre, E. H. (2015). Productivity and resource use in intensified cropping systems in the Rolling Pampa, *Argentina. European Journal of Agronomy*, *67*, 37–51. https://doi.org/10.1016/j.eja.2015.03.001

Andrade, J. F., Poggio, S. L., Ermácora, M., & Satorre, E. H. (2017). Land use intensification in the Rolling Pampa, Argentina: Diversifying crop sequences to increase yields and resource use. *European Journal of Agronomy*, *82*, 1–10. https://doi.org/10.1016/j.eja.2016.09.013

Bai, Z. G., & Dent, D. L. (2007). *Land degradation and improvement in South Africa*. Wageningen, the Netherlands: International Soil Reference and Information Centre (ISRIC)-World Soil Information.

Batidzirai, B., Valk, M., Wicke, B., Junginger, M., Daioglou, V., Euler, W., & Faaij, A. P. C. (2016). Current and future technical, economic and environmental feasibility of maize and wheat residues supply for biomass energy application: Illustrated for South Africa. *Biomass Bioenergy*, *92*, 106–129. https://doi.org/10.1016/j.biombioe.2016.06.010

Bennie, A. T. P., & Botha, F. J. P. (1986). Effect of deep tillage and controlled traffic on root growth, water-use efficiency and yield of irrigated maize and wheat. *Soil and Tillage Research*, *7*, 85–95. https://doi.org/10.1016/0167-1987(86)90010-3

Bennie, A. T. P., & Hensley, M. (2001). Maximizing precipitation utilization in dryland agriculture in South Africa: A review. *Journal of Hydrology*, *241*, 124–139. https://doi.org/10.1016/S0022-1694(00)00377-2

Bennie, A. T. P., Hoffman, J. E., & Coetzee, M. J. (1995). Sustainable crop production on aeolian sandy semi-arid soils in South Africa. *African Crop Science Journal*, *3*, 67–72. http://doi.org/10.4314/acsj.v3i1.54567

Bennie, A. T. P., Hoffman, J. E., Coetzee, M. J., & Very, H. S. (1994). *Storage and utilization of rain water in soils for stabilizing crop production in semi-arid areas*. Report 227/1. Pretoria, South Africa: Water Research Commission.

Bennie, A. T. P., & Krynauw, G. N. (1985). Causes, adverse effects and control of soil compaction. *South African Journal of Plant and Soil*, *2*, 109–114. https://doi.org/10.1080/02571862.1985.10634148

Berry, W. A. J., & Mallett, J. B. (1988). The effect of tillage: Maize residue interactions upon soil water storage. *South African Journal of Plant and Soil*, *5*, 57–64. https://doi.org/10.1080/02571862.1988.10634253

Berry, W. A. J., Mallett, J. B., & Greenfield, P. L. (1987). Water storage, soil temperatures and maize (*Zea mays* L.) growth for various tillage practices. *South African Journal of Plant and Soil*, *4*, 26–30.

Birch, C. J., McLean, G., Doherty, A., Hammer, G. L., & Robertson, M. J. (2008). Reliability of production of quick to medium maturity maize in areas of variable rainfall in north-east Australia. *Australian Journal of Experimental Agriculture*, *48*, 326–334. https://doi.org/10.1071/EA06104

Bloem, A. A., & Barnard, R. O. (2001). Effect of annual legumes on soil nitrogen and on the subsequent yield of maize and grain sorghum. *South African Journal of Plant and Soil*, *18*, 56–61. https://doi.org/10.1080/02571862.2001.10634404

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., & Panagos, P. (2017). An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications*, *8*, 2013. https://doi.org/10.1038/s41467-017-02142-7

Caviglia, O. P., & Andrade, F. H. (2010). Sustainable intensification of agriculture in the Argentinean pampas: Capture and use efficiency environmental resources. *The Americas Journal of Plant Science and Biotechnology*, *3*, 1–8.

Chamen, T. (2015). Controlled traffic farming: From worldwide research to adoption in Europe and its future prospects. *Acta Technologica Agriculturae*, *18*, 64–73.

Ciampitti, I. A., & Vyn, T. J. (2012). Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: A review. *Field Crops Research*, *133*, 48–67. https://doi.org/10.1016/j.fcr.2012.03.008

De Bruyn, L. P. (1974). *The effect of cultivation techniques, water use and internal plant water stress on growth and production of Zea mays in marginal areas (Doctoral dissertation)*. (In Afrikaans, with English abstract.) Bloemfontein, South Africa: University of Orange Free State.

Derpsch, R., Friedrich, T., Kassam, A., & Li, H. (2010). Current status of adoption of no-till farming in the world and some of its main benefits. *International Journal of Agricultural and Biological Engineering*, *3*, 1–25.

Du Plessis, M. C., & Mostert, J. W. C. (1965). Runoff and soil losses at the Agricultural Research Centre, Glen. (In Afrikaans, with English abstract.) *South African Journal of Agricultural Science*, *8*,1051–1061.

Du Plooy, J. (1968). The aim and function of crop rotation systems with maize. (In Afrikaans.) In *Symposium on Maize*. Pretoria, South Africa. 13–15 Aug 1968. Potchefstroom, South Africa: Agricultural Research Institute, Highveld region, Department of Agriculture.

Duvick, D. N. (2005). The contribution of breeding to yield advances in maize (*Zea mays* L.). *Advances in Agronomy*, *86*, 83–145. https://doi.org/10.1016/S0065-2113(05)86002-X

Echarte, L., Luque, S., Andrade, F. H., Sadras, V. O., Cirilo, A., Otegui, M. E., & Vega, C. R. C. (2000). Response of maize kernel number to plant density in Argentinean hybrids released between 1965 and 1993. *Field Crops Research*, *68*, 1–8. https://doi.org/10.1016/S0378-4290(00)00101-5

FAO. (2018). *FAOSTAT database*. Rome: FAO. Retrieved from http://www.fao.org/faostat/en/#data

Fey, M. V. (2010). *Soils of South Africa*. Cambridge, UK: Cambridge University Press. https://doi.org/10.1017/CBO9780511782183

Findlater, K. M., Kandlikar, M., & Satterfield, T. (2019). Misunderstanding conservation agriculture: Challenges in promoting, monitoring and evaluating sustainable farming. *Environmental Science & Policy*, *100*, 47–54. https://doi.org/10.1016/j.envsci.2019.05.027

Gibbs, M. D., Russel, W. B., & Kloppers, P. P. (1993). *Erosion studies using natural runoff plots*. Annual Report on Research Facet number N5711/38/1/1 to the Department of Agriculture, Republic of South Africa. Pretoria, South Africa: SciELO SA.

Giller, K. E., Andersson, J. A., Corbeels, M., Kirkegaard, J., Mortensen, D., Erenstein, O., & Vanlauwe, B. (2015). Beyond conservation agriculture. *Frontiers in Plant Science*, *6*, 870. https://doi.org/10.3389/fpls.2015.00870

Gouse, M., Pray, C. E., Kirsten, J., & Schimmelpfennig, D. (2005). A GM subsistence crop in Africa: The case of Bt white maize in South Africa. *International Journal of Biotechnology*, *7*, 84–94. https://doi.org/10.1504/IJBT.2005.006447

Haarhoff, S. J., & Swanepoel, P. A. (2018). Plant population and maize grain yield: A global systematic review of rainfed trials. *Crop Science*, *58*, 1819–1829. https://doi.org/10.2135/cropsci2018.01.0003

Hansen, N. C., Allen, B. L., Baumhardt, R. L., & Lyon, D. J. (2012). Research achievements and adoption of no-till, dryland cropping in the semi-arid US Great Plains. *Field Crops Research*, *132*, 196–203. https://doi.org/10.1016/j.fcr.2012.02.021

Hensley, M., Botha, J. J., Anderson, J. J., Van Staden, P. P., & Du Toit, A. (1999). *Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water*. Report 878/1/00. Pretoria, South Africa: Water Research Commission.

Hoffman, M. T., & Todd, S. (2000). A national review of land degradation in South Africa: The influence of biophysical and socio-economic factors. *Journal of Southern African Studies*, *26*, 743–758. https://doi.org/10.1080/713683611

Kassam, A., Friedrich, T., Derpsch, R., & Kienzle, J. (2015). Overview of the worldwide spread of conservation agriculture. *Field Actions Science Reports*, *8*. Retrieved from http://journals.openedition.org/factsreports/3966

Kassam, A., Mkomwa, S., & Friedrich, T. (Eds). (2016). *Conservation agriculture for Africa: Building resilient farming systems in a changing climate*. Wallingford, UK: CAB International.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*, 259–263. https://doi.org/10.1127/0941-2948/2006/0130

Lang, P. M., & Mallett, J. B. (1984). Effect of the amount of surface maize residue on infiltration and soil loss from a clay loam soil. *South African Journal of Plant and Soil*, *1*, 97–98. https://doi.org/10.1080/02571862.1984.10634119

Lang, P. M., & Mallett, J. B. (1987). The effect of tillage system and rate and time of nitrogen application on maize performance on a sandy Avalon soil. *South African Journal of Plant and Soil*, *4*, 127–130. https://doi.org/10.1080/02571862.1987.10634958

Lawrance, K. F., Prinsloo, M. A., & Berry, W. A. J. (1999). Long and short term effects of tillage systems on grain yield, the incidence of diseases and production costs for maize. *South African Journal of Plant and Soil*, *16*, 85–91. https://doi.org/10.1080/02571862.1999.10634852

Le Roux, J. J., Morgenthal, T. L., Malherbe, J., Pretorius, D. J., & Sumner, P. D. (2008). Water erosion prediction at a national scale for South Africa. *Water SA*, *34*, 305–314. https://doi.org/10.4314/wsa.v34i3.180623

Li, Y., Ma, X., Wang, T., Li, Y., Liu, C., Liu, Z., … Smith, S. (2011). Increasing maize productivity in China by planting hybrids with germplasm that responds favorably to higher planting densities. *Crop Science*, *51*, 2391–2400. https://doi.org/10.2135/cropsci2011.03.0148

Loubser, H. L., & Nel, A. A. (2004). Productivity and stability of grain yield in maize and sorghum as affected by rotational cropping systems in the north western Free State. *South African Journal of Plant and Soil*, *21*, 80–84. https://doi.org/10.1080/02571862.2004.10635027

MacLaren, C., Storkey, J., Strauss, J., Swanepoel, P., & Dehnen-Schmutz, K. (2019). Livestock in diverse cropping systems improve weed management and sustain yields whilst reducing inputs. *Journal of Applied Ecology*, *56*, 144–156. https://doi.org/10.1111/1365-2664.13239

Mallett, J. B., Lang, P. M., & Arathoon, A. J. (1987). Changes in a Doveton clay loam after 12 years of direct-drill maize production. *South African Journal of Plant and Soil*, *4*, 188–192.

Mills, A. J., & Fey, M. V. (2003). Declining soil quality in South Africa: Effects of land use on soil organic matter and surface crusting. *South African Journal of Science*, *99*, 429–436.

Morris, C., Loveridge, A., & Fairweather, J. R. (1995). *Understanding why farmers change their farming practices: The role of orienting principles in technology transfer*. Research Report 232. Canterbury, New Zealand: Agribusiness & Economics Research Unit, Lincoln University.

Nel, A. A. (2005). *Comparison of integrated crop rotation, tillage systems and fertiliser application on economic and sustainable crop production on the Highveld*. Project MI05/10. Potchefstroom, South Africa: Agricultural Research Council, Grain Crops Institute.

Parker, J. J., & Taylor, H. M. (1965). Soil strength and seedling emergence relations: I. Soil type, moisture tension, temperature and planting depth effect. *Agronomy Journal*, *57*, 289–291. https://doi.org/10.2134/agronj1965.00021962005700030021x

Pittelkow, C. M., Linquist, B. A., Lundy, M. E., Liang, X., Van Groenigen, K. J., Lee, J., … van Kessel, C. (2015). When does no-till yield more? A global meta-analysis. *Field Crops Research*, *183*, 156–168. https://doi.org/10.1016/j.fcr.2015.07.020

Ray, D. K., Gerber, J. S., MacDonald, G. K., & West, P. C. (2015). Climate variation explains a third of global crop yield variability. *Nature Communications*, *6*, 5989. https://doi.org/10.1038/ncomms6989

Sithole, N. J., Magwaza, L. S., & Mafongoya, P. L. (2016). Conservation agriculture and its impact on soil quality and maize yield: A South African perspective. *Soil and Tillage Research*, *162*, 55–67. https://doi.org/10.1016/j.still.2016.04.014

Smith, H. J., Kruger, E., Knot, J., & Blignaut, J. N. (2017). Conservation agriculture in South Africa: Lessons from case studies. In A. Kassam, S. Mkomwa, & T. Friedrich (Eds.), *Conservation agriculture for Africa: Building resilient farming systems in a changing climate* (pp. 214–245). Wallingford, UK: CAB International. https://doi.org/10.1079/9781780645681.0214

Swanepoel, C. M., Rötter, R. P., Van der Laan, M., Annandale, J. G., Beukes, D. J., du Preez, C. C., … Hoffmann, M. P. (2018). The benefits of conservation agriculture on soil organic carbon and yield in southern Africa are site-specific. *Soil and Tillage Research*, *183*, 72–82. https://doi.org/10.1016/j.still.2018.05.016

Swanepoel, C. M., Swanepoel, L. H., & Smith, H. J. (2017). A review of conservation agriculture research in South Africa. *South African Journal of Science*, *35*, 297–306.

Turner, D. P. (2000). *Soils of KwaZulu-Natal and Mpumalanga: Recognition of natural soil bodies (Doctoral dissertation)*. Pretoria, South Africa: University of Pretoria.

Valk, M. (2013). *Availability and cost of agricultural residues for bioenergy generation. international literature review and a case study for South Africa (Master's thesis)*. Utrecht, the Netherlands: Utrecht University.

van der Laan, M., Bristow, K. L., Stirzaker, R. J., & Annandale, J. G. (2017). Towards ecologically sustainable crop production: A South African perspective *Agriculture, Ecosystems & Environment*, *236*, 108–119. https://doi.org/10.1016/j.agee.2016.11.014

Verhulst, N., Govaerts, B., Verachtert, E., Castellanos-Navarrete, A., Mezzalama, M., Wall, P. C., … Sayre, K. D. (2010). Conservation agriculture, improving soil quality for sustainable production systems? In R. Lal & B. A. Steward (Eds.), *Advances in soil science: Food security and soil quality* (pp. 137–208). Boca Raton, FL: CRC Press. https://doi.org/10.1201/EBK1439800577-7

Walker, N. J., & Schulze, R. E. (2008). Climate change impacts on agro-ecosystem sustainability across three climate regions in the maize belt of South Africa. *Agriculture, Ecosystems & Environment*, *124*, 114–124. https://doi.org/10.1016/j.agee.2007.09.001

Wiggs, G., & Holmes, P. (2011). Dynamic controls on wind erosion and dust generation on west-central Free State agricultural land, South Africa. *Earth Surface Processes and Landforms*, *36*, 827–838. https://doi.org/10.1002/esp.2110

Wortmann, C. S., Drijber, R. A., & Franti, T. G. (2010). One-time tillage of no-till crop land five years post-tillage. *Agronomy Journal*, *102*, 1302–1307. https://doi.org/10.2134/agronj2010.0051

Zuma-Netshiukhwi, G., Stigter, K., & Walker, S. (2013). Use of traditional weather/climate knowledge by farmers in the south-western Free State of South Africa: Agrometeorological learning by scientists. *Atmosphere*, *4*, 383–410. https://doi.org/10.3390/atmos4040383

How to cite this article: Haarhoff SJ, Kotzé TN, Swanepoel PA. A prospectus for sustainability of rainfed maize production systems in South Africa. *Crop Science*. 2020;60:14–28. https://doi.org/10.1002/csc2.20103