The influence of seed-drill choice on soil physical properties and crop performance in a semi-arid production region of South Africa.

by

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DECLARATION

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"*Agriculture is the most healthful, most useful and most noble employment of man.*" *– George Washington*

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ABSTRACT

Producers following conservation agriculture principles rely on seed-drill equipment that place seed directly in the soil. Most producers are currently using tine openers to establish their crops but the interest in disc openers is increasing. The aim of this study was to determine the influence of the seed-drill opener on seedbed properties and crop performance. The study was conducted 35 km south of Swellendam in the Napky region of the southern Cape, South Africa in two production seasons (2018 and 2019). Barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.) and wheat *(Triticum aestivum* L.) were seeded with seed-drills mounted with either double disc, tine or a combination of tines and single disc openers. Soil bulk density, gravimetric soil water content and unsaturated hydraulic conductivity were used as an indication of the influence of the seed-drill openers on the soil physical properties. Soil bulk density and gravimetric soil water content were determined 7, 30, 60, 90 and 120 days after seeding for a depth of 100 mm on the seeding row, while unsaturated hydraulic conductivity was only determined on days 7 and 60 after seeding. Soil bulk density varied between the tested seed-drills ($p < 0.05$), especially directly following the seeding operation. A tendency was noted that a decrease in soil disturbance, at the time of seeding, conserve more gravimetric soil water in the seed-furrow. Unsaturated hydraulic conductivity showed inconsistent results over the first growing season. Various crop parameters were evaluated to draw conclusions about the influence of seed-drill choice on crop performance. Seeding depth was determined on a few sampling dates from 16 days after seeding to calculate an average seeding depth. Seedlings were counted approximately every four days to determine the rate of emergence and survival. Biomass production was measured respectively 30, 60, 90, 120 and 150 days after seeding. By the end of the growing season, yield components were used to estimate the potential yield for each of the seed-drills, except for canola. Seeding depth was most accurate where the tine seed-drill was used for seeding purposes ($p < 0.05$). However, the direct influence of seeding depth on seedling emergence is not prevalent. Barley and wheat plant populations did not differ between the different seed-drills ($p > 0.05$), but lower canola populations were established with a double disc seed-drill ($p < 0.05$). Increased biomass production ($p < 0.05$) was noted towards the end of the growing seasons, where seeding took place with less soil disturbance (i.e. double disc seed-drill). The type of seed-drill and its associated opener will influence soil physical properties and crop performance to different extents, depending on the prevailing climatic conditions and the inherent soil physical properties.

Keywords: Direct seeding, conservation agriculture, seed-drill, crop uniformity.

UITTREKSEL

Produsente wat gebruik maak van bewaringslandboutegnieke maak op planters, wat saad direk in die grond plaas, staat, sonder einge grondbewerkingspraktyke wat vooraf gedoen word. Die meerderheid produsente maak tans van tandplanters gebruik, alhoewel die belangstelling in skyfplanters is besig om te groei. Die doel van die studie was om die invloed van die tipe planter op die grondfisiese eienskappe en gewasprestasie is te bepaal. Die studie is ongeveer 35 km suid van Swellendam uitgevoer, in die Napky-streek van die Suid-Kaap, Suid-Afrika, in die 2018 en 2019 produksieseisoene. Canola (*Brassica napus* L.), gars (*Hordeum vulgare* L.) en koring (*Triticum aestivum* L.) is met drie verskillende planters gevestig. Planters was onderskeidelik met dubbelskyfoopmakers, tandoopmakers of ‘n kombinasie van enkelskyf- en tandoopmakers gemonteer, Grondbrutodigtheid, gravimetriese waterinhoud en versadigde hidroliese geleiding is bepaal om die invloed van die planter op die grondfisiese eienskappe te kwantifiseer. Grondbrutodigtheid en gravimetriese waterinhoud is onderskeidelik 7, 30, 60, 90 and 120 dae na planttyd bepaal tot op ‘n diepte van 100 mm, terwyl die hidroliese geleiding slegs 7 en 60 dae na plant bepaal is. Brutodigtheid het statisties tussen die drie planters verskil ($p < 0.05$), veral kort nadat die plantaksie plaasgevind het. ’n Neiging dat die gravimetriese waterinhoud hoër was in die saadvore waar grondversteuring minimaal was (met behulp van die dubbelskyfplanter), is waargeneem. Onversadigde hidroliese geleiding het wisselende resultate in die eerste seisoen getoon. ’n Verskeidenheid gewasfaktore is oor die loop van die groeiseisoene gemeet. Saadplasing is verskeie kere bepaal na opkoms om ‘n gemiddelde plantdiepte vir elke gewas- en planterkombinasie te kon bereken. Saailinge is ongeveer elke vier dae getel om te bepaal wat die tempo van gewasopkoms en -oorlewing is. Biomassaproduksie is onderskeidelik 30, 60, 90, 120 en 150 dae na plant bepaal. Teen die einde van die seisoen is die opbrengskomponente bepaal om ‘n potensiële opbrengs vir koring en gars te bereken. Saadplasing was die akkuraatste met die tandplanter ($p < 0.05$). Die direkte invloed van plantdiepte op saailingopkoms en -oorlewing was egter nie duidelik nie. Gars- en koringpopulasies het nie tussen die verskillende planters verskil nie ($p > 0.05$). Canola plantpopulasie was wel laer waar die dubbelskyfplanter gebruik is. Verhoogde biomassaproduksie ($p < 0.05$) is aan die einde van die groeiseisoene waargeneem waar die skyfplanter gebruik was om gewasse te vestig. Die tipe planter en die oopmaker wat daarmee geassosieer word, beinvloed grondfisiese eienskappe en gewasprestasie tot verskillende mates, afhangende van die heersende klimaatstoestande en die inherente grondfisiese eienskappe.

Sleutelwoorde: Bewaringsboerdery, minimum grondversteuring, planter, gewas eenvormigheid.

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CHAPTER 1

General Introduction

Barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.) and wheat (*Triticum aestivum* L.) are some of the most important dryland cash crops grown in the southern Cape in South Africa (ARC Economic & Biometrical Services, 2014). In this Mediterranean-type region, most producers use conservation agriculture (CA) principles to achieve moderate to good yields for the relatively dry environment (Milder et al., 2011; Smith et al., 2016). By making use of crop rotations, residue retention and no-tillage or even zero-tillage farming practices, producers have increased the quality of their soil as well as the success rate and profitability of their overall farming systems. Currently the majority of producers understand the benefits CA brings to their farms. Over the last decade conservation agriculture CA resulted in better rainfall utilisation in dryland farming systems compared to conventional agriculture (Bennie and Hensley, 2001). Research has also shown that soil water infiltration (Chang and Lindwall, 1989) and aggregate stability increase (Johansen et al., 2012) while water loss through evaporation decrease (Johansen et al., 2012). However, for producers to be more competitive in terms of yield and profitability (Milder et al., 2011; Smith et al., 2016), ways must be found to ensure a well-established, healthy crop by using the most accurate methods to complement the current understanding of CA.

With the transition from conventional agriculture to CA, it was necessary to adapt the seeding implements accordingly. The traditional high disturbance planters were modified to suite the reduced and/or no-disturbance needs. As research progress, improvements and changes are still being refined. Seed-drills are classified according to the amount of disturbance they cause to the soil profile. For a seed-drill to be classified as a CA implement, the amount of soil disturbance should be below the maximum amount of disturbance that is allowed in this farming practice. According to Kassam (2012), all soil disturbance should be avoided as much as possible, but should be confined to less than 25% of the soil surface being disturbed in bands narrower than 15 cm (Kassam et al., 2012). Different degrees of CA are practiced, varying between no-tillage and zero-tillage. No-tillage and zero-tillage eliminate all primary and secondary soil disturbance; soil disturbance occurs only during the seeding operation. No-tillage practices make use of tine seed-drills. Tine seed-drills disturb the soil by pulling tines through the soil volume while placing the seed at the desired depth. Zero-tillage disturb the soil less than no-tillage by making use of disc seed-drills. Disc seed-drills have a shallower working depth compared to tine seed-drills and creates a seed-furrow by pulling disc(s) through the surface soil layer.

One of the most critical agricultural practices is the seeding operation. The main goals of this operation are to, (1) place the seed at the recommended depth and (2) have uniform row spacing to ensure a more consistent emerging crop (Celik et al., 2007). When this operation is done with accuracy, the seed germination, plant population, plant and soil health, crop yield as well as income can be maximised. Preparation of the seedbed, residues on the surface, soil water content and environmental conditions can have both a positive and/or negative effect on crop growth and development. The choice of machinery can modify the prevailing soil conditions and determine the seed placement in the seedbed. For the duration of the growing season, the seedbed will be the growing area for the crop’s roots. The influence of seeding implements can ensure a conducive growing area where roots proliferate optimally. A well-developed root system can maximise the amount of nutrients and water extracted from the soil and are also positively correlated to the biomass of the crop (Fageria et al., 2006). The accuracy of the seed-drill will also have an influence on the uniformity of the seeding depth. Even though optimal seeding depth is crop dependant, is it still necessary to evaluate minimum disturbance seed-drills in terms of their seed placement uniformity. Uniform seed placement may result in better germination, emergence and higher yields. Performance of individual plants are determined by the competition for available resources. Uniformity of establishment lower competition between plants for nutrients, water and light (Celik et al., 2007). This uniformity will also ensure crops to have better competitiveness over possible weeds (Weiner et al., 2001). In contrast, sub-optimal seed emergence and plant establishment will have a negative effect on the yield (Nasr and Selles, 1995; Place et al., 2008).

There are various seed-drills available for producers to choose from. However, the success of the implement will largely depend on the management, type of crop, soil physical properties and the environment. For producers to make informed decisions about seed-drills, scientific research must be conducted that assess the efficiencies of the various seed-drills under variable conditions. Research done on seeding implements with winged openers, hoe openers and chisel openers illustrated the importance of the shape of the seed-drill opener on the seed-furrow (Chaudhry and Baker, 1988; Choudhary and Baker, 1980; McLeod et al., 1992). Controversy still exist about the bulk density of minimum-tilled, conservation agriculture soils. Some reports show an increase in soil bulk density in the upper layers (Mohammadi et al., 2013), while other researchers noticed a decrease in soil bulk density over the long-term (Botha, 2013). The choice of seed-drill opener can have a pronounced effect on the soil bulk density (Rainbow, 2000) and thus root development of the crop (Place et al., 2008). High soil bulk densities restrict root development and water and nutrient uptake (Khalil et al., 2014). Seed-drill opener types revealed that canola showed higher plant populations and accumulated more biomass when a tine seed-drill as oppose to a disc seed-drill was utilised for seeding purposes (Swanepoel et al., 2019).

The importance of the seeding operation on soil physical properties and the establishment of crops is clear. Focus of producers is currently on tine openers, while the interest in disc openers is increasing (Swanepoel et al., 2017). For producers to make scientifically justified decisions, knowledge must be generated concerning seed-drill openers and their influence on economical important crops. By broadening the current knowledge on reduced tillage practices and applying the suggested practices, increases in crop productivity and sustainability can be expected.

1.1 Aims and Objectives:

The aim of this study was to evaluate the seedbed properties and crop performance as influenced by different seed-drills in order to optimise crop establishment and uniformity.

Objective 1: Determine the effect of seed-drills on dynamic soil physical indicators (soil bulk density, gravimetric water content and infiltration).

Objective 2: Determine the effects of seed-drills on crop performance (seeding depth, seedling emergence and survival (plant populations), biomass production and yield).

The thesis is divided into seven chapters. The first chapter is a general introduction highlighting the importance of the seeding operation in conservation agriculture and the need for research in terms of seeding equipment. Chapter 2 review seed-drills and tillage equipment in production systems in terms of their influence on soil physical properties and crop performance. Chapter 3 elaborates on the materials used and the methods followed during the duration of the research trial. Chapter 4 describes the technical properties and working actions of the three utilised seed-drills. Chapters 5 and 6 include the results and discussions of the research trial, respectively. The results are divided into soil properties and crop performance. Finally, the conclusions, recommendations and limitations for this study are compiled in Chapter 7.

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CHAPTER 2

Literature Review

Sustainability of farming systems can be supported by adopting the three basic principles of conservation agriculture (CA) (Bennie and Hensley, 2001; Lal, 2004; Nyagumbo et al., 2017). These principles include, (1) minimum mechanical soil disturbance (hereafter referred to as no-tillage or zero-tillage); (2) a permanent organic soil cover and (3) crop diversification. When adopting CA systems all three of the abovementioned principles must be practiced in combination.

A large number of tillage systems are available for soil preparation and crop establishment. A common approach is to group these according to the amount of soil disturbance the implement(s) cause while preparing the soil for the seeding operation. Two extremes exist: (1) conventional tillage, where the soil is fully inverted and (2) no-tillage and/or zero-tillage, where soil disturbance prior to the seeding operation is eliminated. Various practices in between the two extremes are referred to as minimum-tillage. Minimum tillage includes practices where soil disturbance is reduced compared to conventional agricultural systems. However, making use of minimum soil disturbance does not always fully comply with CA standards. Within a CA system soil disturbance can be divided into different degrees (1) no-tillage includes seeding practices where tine seed-drills are used for seeding purposes and (2) zero-tillage includes seeding practices where discs are used for seeding purposes. Only no-tillage and zero-tillage used in conjunction with practices such as covering soil and crop diversity are regarded as true CA systems.

In crop production, successful seedling establishment depends on the conditions prevailing during the seeding operation (Ahmad et al., 2008; Reis and Forcellini, 2002; Tullberg et al., 2006). During seeding operations, the opener cuts a furrow and allows the seed to be deposited directly into the soil (Altikat et al., 2013; Chaudhuri, 2001). A press-wheel moves over the furrow to ensure good contact between the seed and the soil. The main objective of the seed-drill is to place the seed uniformly according to a pre-set seeding depth in the seedbed (Karayel and Özmerzi, 2008). When uniform seeding is achieved, better germination, emergence, deep root penetration, weed control and yield increases can be expected (Altikat and Celik, 2011; Celik et al., 2007; Karayel and Özmerzi, 2008; Karayel and Özmerzi, 2002). For producers to be able to achieve a uniform crop, the choice of implements and management practices is important. Agronomical practices can change the physical, chemical and biological properties of the soil (Haruna and Nkongolo, 2015; Villalobos and Fereres, 2016). More research is therefore necessary on these soil property alterations during the cropping season.

2.1 Crop performance

Literature on the influence of specific seed-drill openers on crop performance is scant. Swanepoel et al. (2019) found that the seed-drill opener type significantly affected canola plant populations. Canola established with a tine opener resulted in 43 plants m^{-2}, while 31 plants m^{-2} established with a disc opener in the same growing conditions. The canola plant population was always among the lowest even when seeding took place in different residue loads. Canola also produced more biomass 30 and 60 days, respectively, after seeding with a tine opener. By 90 days after seeding the effect had dissipated. However, it was noted that the tine-seeded canola remained more productive until physiological maturity compared to the disc-seeded canola. No difference in grain yield was observed between the two different seed-drill openers. It is suggested that there is no major disadvantage in using either disc or tine openers due to the ability of canola to compensate for reduced plant populations. However, higher plant populations would be able to yield more in seasons where the environmental conditions are optimal. Similarly, poor wheat growth is often observed under direct drilling, compared to conventional soil tillage treatments (Chan et al., 1987). Although poor growth may persist throughout the growing season, the outcome on the grain yield is not clear (Gates et al., 1981; Reeves and Ellington, 1974).

A tillage experiment was established to look at the effects of summer fallow treatments on the growth and yield of wheat. The three treatments included, (1) conventional fallow, maintained by shallow cultivations, (2) chemical fallow, maintained by two herbicide applications and (3) a zero-fallow, where weeds were allowed to grow until one week before seeding when a single herbicide application was applied. The number of wheat plants established did not differ between the treatments. Dry matter was significantly less in the direct drilling plots compared to the conventional fallow 35 days after seeding. The dry matter production of the chemically-controlled and zero-fallow plots was 68 and 37% respectively, of the conventional treatment plots (Chan et al., 1987). Differences in the wheat vegetative growth may be due to a difference in soil physical properties like higher soil bulk density or lower soil water availability at the time of seeding. These authors highlighted the problem of poor early growth of wheat under direct drilling conditions, which can relate to the current zero-tillage or no-tillage practices.

Further research is necessary to monitor the changes in soil physical properties under direct drilling conditions in order to maintain optimal plant growth and yield (Chan et al., 1987). It would be valuable to conduct seed-drill opener trials over a longer period of time and in greater varieties of soil conditions. To our knowledge, no other work comparing the performance of seed-drill openers have been published. It is not known if similar trends would be observed in different climates and on soil types not included in their study.

2.2 Soil properties

2.2.1 Physical properties

Aggregate stability, soil water content, infiltration rate and bulk density are some of the most important physical properties of the soil. Soil structure is defined according to the form and stability of the soil (Amézketa, 1999). Soil form refers to the arrangement of the solid particles and air spaces in between, at a given time. The stability of the soil refers to the ability of the soil to maintain its structure when subjected to stress (Hillel, 2004). Soil structure is an important characteristic to gauge whether management interventions align with sustainability ideals (Amézketa, 1999). The pore spaces between the aggregates provide area for water, air and root movement. The main binding agencies of aggregate stabilisation are organic materials that include decomposing plant and animal material, as well as organic secretions or so-called exudates (Bossuyt et al., 2001). Agronomic management practices can influence the stability of the soil aggregates through mechanical soil disruption and physical aeration of decomposing residues (Acar et al., 2018).

In dryland cropping systems the moisture content is usually the most restrictive factor for crop growth. Physical disruption of the soil aggregates decreases the water holding capacity and increases evaporation from the soil surface (Johansen et al., 2012). Thus, tillage systems that conserve soil moisture are important to increase production and mitigate the negative effect of droughts (Boydaş and Turgut, 2007; Kahlon et al., 2013). The interest in reducing the number of tillage operations has grown exponentially, particularly in the rain-fed cereal production regions where reduced tillage generally increases soil water recharge and the amount of the available water for sufficient crop yields (Abdullah, 2014; Kahlon et al., 2013). Abdullah (2014) reported on average 13.5% higher soil water contents in minimum-tilled soils compared to conventionally tilled soils, over two seasons, respectively. McLeod et al. (1992) seeded wheat seeds directly into crop residues on various soil types and found that the wheat yield was the lowest where the openers were used that caused the most soil disturbance. The lower yield was due to the loss of plant-available soil water through evaporation since soil disturbance is one of the factors contributing to evaporation. Cantero-Martínez et al. (2003) also found that barley yielded more, especially during dry seasons, when no-tillage seeding practices were implemented compared to tilled treatments. The opposite is usually true in wet years, where more soil disturbance results in higher-yielding crops (Martin-Rueda et al., 2007). Limited literature is available on the amount of soil disturbance that is allowed to avoid water loss through evaporation especially within CA parameters. Generally, it is accepted that the more the seed-drill opener disturbs the soil, the higher the evaporation rate (Blanco-Canqui and Ruis, 2018; Chaudhuri, 2001). Therefore, it is anticipated that less soil disturbance in accordance with CA practices should make the farming system more resilient to climate variability and change (Haruna and Nkongolo, 2015; Lal, 2004; Nyagumbo et al., 2017) and has proven to be superior in utilising rainfall in dryland farming compared to conventional agriculture (Bennie and Hensley, 2001). However, contradictory findings have been reported. Wilkins et al. (1983) reported higher soil water content in seed-furrows where deeper soil disturbance occurred. The deep furrow openers had the ability to move moist soil up to the seed zone, which accounted for better emergence rates. It has been suggested that the design of seed-drill openers need to be amended to allow moist soil to move upwards from the deeper disturbed areas (Wilkins et al., 1983).

Soil water infiltration rate is another soil physical property that is influenced by the degree of soil disturbance (Blanco-Canqui and Ruis, 2018; de Almeida et al., 2018; Gozubuyuk et al., 2014). The infiltration rate is a description of the amount of water entering the soil per time unit (Hillel, 2004). In a study that compared the infiltration rate under different tillage practices it was shown/observed that no-tillage systems had higher infiltration rates than the minimum-tilled and conventional tilled soils (Chang and Lindwall 1989). The higher infiltration rates were attributed to, amongst other factors, the more stable soil aggregates that develop in a no-tillage or minimum tilled agricultural system (Boydaş and Turgut, 2007; Chang and Lindwall, 1989) as soil infiltration is directly proportional to the stability of the soil structure (Tisdall and Adem, 1986). Gozubuyuk et al. (2014) compared the infiltration rates for different tillage systems. The systems included the following practices: conventional tillage that included a deep tillage operation, reduced tillage with a cultivator and combined harrows, reduced tillage with a rotary harrow and a no-tillage system. The conventional tillage system and the reduced tillage system making use of a rotary harrow had the lowest infiltration rates. The reduced tillage system using a cultivator and combined harrows as well as the no-tillage systems had higher infiltration rates. Higher infiltration rates in one of the reduced tillage systems and the no-tillage system might have been facilitated through higher aggregate stability found near the soil surface. Therefore, the soil surface is more resistant to breakup of aggregates and more water can infiltrate the soil during rainfall events.

De Almeida et al. (2018) indicated that water infiltration is influenced more strongly by the canopy cover than the soil tillage system. The canopy cover greatly influence the infiltration because it has an important influence on the raindrop interception. By increasing the amount of vegetative cover, surface residues and surface roughness the infiltration at the beginning of a rainfall event will increase. Conventional tillage systems tend to increase the infiltration directly after the tillage action took place (de Almeida et al. 2018). However, after a few days, the surface tends to seal (i.e. crust formation) and water infiltration decreases because of the impact of raindrops on the soil surface. However, it is not clear if this occurrence will be true when comparing no-tillage and zero-tillage seeding methods.

Soil bulk density is one of the soil physical properties producers are most concerned about. Soil bulk density is usually higher where minimum tillage is implemented instead of conventional tillage (Huang et al., 2015; Mohammadi et al., 2013). Huang et al. (2015) measured an increase in soil bulk density in the upper layers of the soil in minimum-tillage systems. Lower down in the profile the soil bulk density was similar or lower than that of tilled soils. Altikat and Celik (2011) compared two reduced tillage seed-drills and a conventional tillage implement in terms of soil bulk density and seedling emergence. Tillage systems and intra-row soil bulk density values had significant effects on the seedbed properties and the emergence of the crop. The highest bulk density (1.14 g.cm^{-3}) was measured where one of the reduced tillage seed-drills was used. The press wheel on this specific implement exerted more pressure on the soil surface and increased the compaction in the upper layer of the seed furrow. The lowest soil bulk density (0.88 g.cm^{-3}) was measured in the upper layers of the conventional tillage system. In the deeper soil layers, the measured soil bulk densities were similar. Simultaneously, the mean emergence time of the seedlings was determined. The lowest mean emergence time was recorded where the reduced tillage seed-drills were used for seeding purposes, while the conventional tillage system had the highest mean emergence. A higher water content was recorded in the reduced tillage systems. This higher soil water content possibly led to an earlier crop emergence, even though the mean emergence was less, compared to the conventional tillage systems.

The response of barley crops was evaluated when seeding took place with seed-drills with different shapes of openers (Chaudhry and Baker, 1988). A winged opener made an inverted T-shaped furrow, whereas a triple-disc opener made a V-shaped furrow and a hoe opener made a U-shaped furrow. The winged and hoe-openers caused more soil disturbance and had better seedling emergence rates. Higher root and shoot mass was also noted where winged and hoe-openers were used for seeding purposes. Where disturbance was reduced, while using triple disc openers, fewer seedlings emerged and the root to shoot ratio was lower. Higher soil bulk densities occurred where the triple-disc opener was used for seeding purposes that might explain the difference in emergence as well as root and shoot mass.

Baker and Mai (1982) compared soil compaction as caused by different seeding implements, to the compaction of the same undisturbed soil. The triple-disc opener had a bigger effect on the soil bulk density in comparison to the chisel opener that was used. The base of the seed furrows, where the triple-disc openers were used, had a higher bulk density. The bulk density of the soil where the chisel opener was used related more to that of the undisturbed soil. Roots of lupine seedlings were also simultaneously, evaluated. In the higher soil bulk density seed furrows the roots were 23% shorter and 42% lower in mass, compared to the undisturbed soil. The lupine taproot was distorted where the base of the seed furrow was encountered. Where seeding took place with a chisel opener, the taproot showed no distortion. Evidently, the negative effect of high bulk densities are also evident in other crops, where the increase in soil bulk density usually impaired the early growth of wheat in minimum tillage systems (Rebetzke et al. 2014). No-tillage generally resulted in a higher root length density in the topsoil than deeper soil layers compared to conventional tillage treatments (Rebetzke et al., 2014). The difference between no-tillage and conventional tillage treatments increased with prolonged tillage management (Qin et al., 2004). Over time, the soil layer that contained more roots in the no-tillage treatments became thicker. Guan et al. (2015) concluded that no-tillage significantly increased soil bulk density compared to ploughed and reduced tillage treatments. This increased soil bulk density influenced the spatial and temporal pattern of winter wheat root mass density. Root mass was higher in the ploughed and reduced tillage treatments compared to the no-tillage treatments, especially in the early growth stages. However, no-tillage treatments showed higher root mass densities in the later growth stages (Guan et al., 2015). Munkholm et al. (2008) investigated the effect of tillage intensities on the soil structure and winter wheat root and shoot growth. A reduction in early growth and root clustering was noted where soil disturbance was limited while using direct drilling equipment (Munkholm et al., 2008). Even though this specific article did not contain positive feedback in terms of reduced soil disturbance and root growth, possible long-term benefits were highlighted. Below the tillage depth, an extensive system of bio-pores produced by earthworms and actively growing roots were noted. Over the long-term it is possible that improvements in the upper layers could also be expected (Horn, 2004; Munkholm et al., 2008). In a long-term trial conducted in the Swartland region of South Africa, Botha (2013) confirmed that minimum tilled soils with high initial soil bulk densities tended to regenerate over time. At the beginning of the trial, the conventional tillage systems resulted in the lowest soil bulk densities. Yet, over time the no-tillage treatments had lower soil bulk density values (Botha, 2013). The more stable soil aggregates and the higher organic matter in the no-tillage systems partly explained the phenomenon of decreased soil bulk densities. Nonetheless, different regions and different soil types will react differently. Therefore it should be taken into consideration that there are various soil and climatic factors that contribute to the success of a reduced tillage system (Soane et al., 2012).

Successful quantification of soil physical properties remains complicated since various factors like surface residues, crop growth, organic matter, temperature, rainfall, soil quality and soil types have interacting effects. Swanepoel et al. (2017) compared seed-drill openers on soil with high and low qualities. Both tine and disc openers were considered suitable for CA systems even though tine openers disturb the soil more than disc openers. Seeding with disc openers resulted in higher-yielding crops compared to tine openers, even when seeding in low quality soils. The lowest yield was obtained on low quality soils where seeding took place with tine openers, which caused more soil disturbance. Generally, it is assumed that high quality soils automatically provide a more suitable seedbed and that a certain degree of soil disturbance is necessary to improve the seedbed of low quality soils. Conversely, it was illustrated that crops performed better with less soil disturbance, even when seeded in low quality soils (Swanepoel et al., 2017).

Quantifying the influence of farming equipment especially seed-drill openers, on the soil physical properties are important. The majority of research related to soil disturbance during the seeding operation date back years and is not applicable to the current commercial seed-drills. There is thus a need for research quantifying influences of modern seeding equipment on soil physical properties and crop performance.

2.2.2 Chemical properties

The long-term sustainability of dryland farming depends on soil quality and fertility. Soil disturbance and the seeding operations can alter both of these soil properties to a certain extent. The choice of seed-drill will determine where the fertiliser will be placed in relation to the seed (Figure 1). Seed-drills with disc openers (Figure 1A) place the seed and the fertiliser in the same furrow, while tine openers (Figure 1B) ensure placement of fertiliser, specified distances below the seed. The double chute opener (Figure 1C) place the seed into the sidewalls of the seed-furrow while the fertiliser is distributed at the bottom-middle of the seed-furrow.

One of the major considerations for fertiliser placement is the possibility of toxicity to the seed and emerging seedlings (Kushwaha et al., 1999). Fertiliser placement plays an important role in efficient crop management. Placing the fertiliser in the correct area for root uptake, can increase the efficiency of nutrient uptake and possibly the crop yield (Mahler, 2001). Subsurface placement of fertilisers, close to the seed or the plant roots, leads to higher nutrient uptake and yield, compared to broadcasting of fertilisers (Nkebiwe et al., 2016). Placing the fertiliser in close proximity to the seed, resulted in a yield increase of 3.7% when compared to soil surface broadcasting.

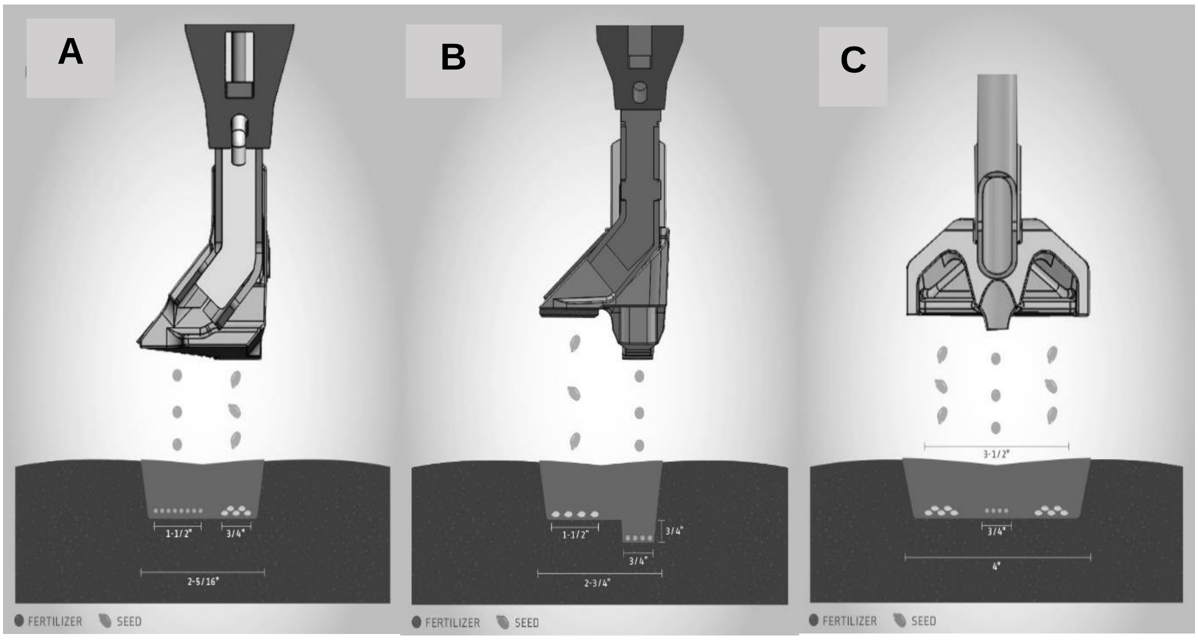

Figure 1. Illustration of seed and fertiliser distribution in the seed-furrow. Distribution for a disc opener (A), tine opener (B) and double chute (C). Images are for only for illustrative purposes, opener composition will differ between producers. Source: Unknown.

Xie et al. (1998) investigated optimal row spacing and seed-fertiliser placement. Paired-row seed-fertiliser placement was compared to wide-row and narrow-row placement. In the paired-row placement, the seed-drill placed two seed rows (2 cm wide and 6.6 cm apart) with a urea band below the seed rows and midway between the paired seed rows. The wide-row placement consisted of a wide seed row (12.5 cm) with urea placed together with the seed. The narrow-row placement was done with a narrow knifepoint opener, which resulted in a narrow seed row (2.5 cm) with side-banded urea. The paired-row seed and fertiliser placement outperformed the narrow-row placement in both the canola and wheat trials. There was an average yield increase of 20% for wheat and 8% for canola. Where the seed and fertiliser were placed in narrow-rows, the seed density was higher. This resulted in stronger interplant competition, which decreased the yield. With the wide-row seed-fertiliser placement, urea caused damage to the emerging seedlings and led to a decrease in yield decrease. The degree of seedling damage would be greater where wider row spacing (>38 cm) was used because of higher fertiliser concentrations within the seed row as the row space increased (Xie et al., 1998).

The influence of soil moisture should be taken into consideration. Seeding in dry soil tends to result in more fertiliser damage compared to seeding in moist soils (Kushwaha et al., 1999). Under dry conditions, it will be beneficial to separate the seed further from the fertiliser or to decrease to amount of fertiliser applied during the seeding operation. Baker and Afzal (1986) determined rape seedling emergence under different fertiliser placement distances. After 37 days, the non-fertiliser treatments had a higher seedling emergence (88.3%) than treatments where fertiliser was used. When the fertiliser was placed 10 and 20 mm away from the seed, the seedling emergence was 73.3 and 68.3%, respectively. When a seed-fertiliser spacing of 20 mm was used, or when fertiliser was eliminated, the crop was taller and had higher biomass. Rape growth was effected negatively by the 10 mm separation of seed and fertiliser (Baker and Afzal, 1986).

Fertiliser placement in relation to the seed is therefore an important factor to consider when choosing the best-suited seed-drill. This will have a direct influence on the amount and type of fertiliser that can be placed at the time of seeding.

2.2.3 Biological properties

Organic matter influences the physical, chemical and biological properties of the soil and has a major impact on soil productivity and sustainability (Mathew et al., 2012; Rasmussen, 1999). Soil organic matter has an influence on the number of macro aggregates in the soil. The development of macro pores is important in maintaining moisture and air in the soil. These factors are critical for the metabolism and survival of organisms in the soil. In general, crop production and tillage decrease the amount of organic matter in the soil. Conventional agriculture adversely affect long-term soil productivity due to erosion and loss of organic matter (Acar et al., 2018; Mathew et al., 2012). The conversion to CA might be a possible sustainable solution to the declining soil organic matter values.

Soils in the Free State province of South Africa, has already lost 68% of the organic matter due to vigorous soil tillage processes (Prinsloo et al., 1990). The reason for this decline in organic matter is the mixing and aeration of the soil particles and the organic matter that occur during tillage practices. Aerating the soil frequently increases the oxidation process of organic matter. Research done by Cooper (2017) showed that no-tillage systems contained more carbon than both minimum tillage and conventional tillage systems. Similarly, Balota et al. (2003) found that a no-tillage system contained more carbon than a conventional production system, even when a wheat monoculture system was followed. The reduction in tillage had a greater impact on the microbial biomass, particularly in the 0 to 5 cm soil layer, compared to crop rotations.

Over the years researchers noticed the accumulation of organic matter in minimum tillage systems occurs mainly in the topsoil (0-5 cm) and the carbon content decrease with soil depth. The 20 to 40 cm layer had between 22 and 77% lower carbon than the 0 to 5 cm layer (Mathew et al., 2012). The no-tillage system had the highest amount of carbon in the topsoil. The minimum tillage system followed next, while the conventional tillage system had the least carbon in the topsoil. Below the tillage zone (>30 cm) there was no difference between the three treatments. This stratification of soil organic matter and nutrient distribution in CA systems create different habitats for microorganisms and results in shifts of microbial community structures (Mathew et al., 2012). Generally, conventional tillage leads to soil microbial communities dominated by aerobic microorganisms, while CA systems contain higher microbial activity and microbial biomass (Balota et al., 2003).

Soil organic matter is a key factor in determining the soil biological activity since organic matter is the main carbon source for these microorganisms (Mohammadi et al., 2011; Powlson et al., 2001). Various types of bacterial and fungal organisms are beneficial for soil quality and crop health (Acosta-Martinez and Cotton, 2017). Fungi usually dominate in minimum disturbed soils (Mathew et al., 2012), while the increase in bacteria numbers are not that drastic. It should be taken into consideration that, not only the amount but also the type of microorganism play an important role in the soil quality (Villalobos and Fereres, 2016).

Microorganisms contribute to soil quality in various ways. Arbuscular mycorrhizal fungi that live in the root area contribute to the production of a glue-like substance called glomalin (Vamerali et al., 2006; Wright and Upadhyaya, 1998). Glomalin is a glycoprotein with nitrogen-linked oligosaccharides produced by fungal organisms through their actively growing hyphae. This small protein is insoluble and has hydrophobic characteristics. Abundant production of this protein might be involved in the stabilisation of soil aggregates allowing better aeration and water drainage. The relationship between glomalin and the stability of soil aggregates should be researched further. According to the current understanding, this type of aggregate stability can lead to more sustainable agricultural systems (Taylor and Amézketa, 1999). Bacteria and some fungal organisms can contribute to nutrient bioavailability, which may improve degraded soils over the long-term (Imtiaz et al., 2016). Different types of bacteria increase the availability of different crop nutrients. Some benefits of bacteria include nitrogen fixation, phosphorus solubilisation and/or mineralisation, potassium solubilisation, iron chelation as well as decomposition of organic material (Imtiaz et al., 2016).

One of the advantages of plant residues retained on the soil surface, in CA, is the continuous supply of organic matter and carbon compounds during the off-season. In conventional farming systems, the soil surface would have been left bare; however, this practice is deemed unsustainable with regards to soil quality and crop production. In minimally disturbed soils, the accumulation of crop residues on the soil surface leads to enrichment of soil organic matter, and as a consequence to an increase in microorganisms. The amounts of fungi, bacteria, arbuscular mycorrhizal fungi and actinobacteria increase in the upper layers of CA soils. The reason for this increase is linked to the increased organic material as well as the decrease in disturbance (Wright and Upadhyaya, 1998). Understanding the contributions of soil microorganisms to soil stabilisation at molecular level should lead to ways to enhance inputs for sustainable agricultural systems (Wright and Upadhyaya, 1998). Currently, it is not known if soil disturbance through different seed-drill openers will have an influence on the biological properties under CA practices over the long-term.

2.3 Synopsis

Several producers are converting from conventional agriculture to minimum tillage, no-tillage or even zero-tillage practices. In some cases, the implication is that sub-surface soil disturbance is eliminated and only a slight amount of soil disturbance takes place during the seeding operation. Currently, the effect of limited soil disturbance on soil properties is a debatable issue (Anghinoni et al., 2017).

The importance of the seeding operation is thus increasing when other soil disturbance practices are limited or eliminated. Limited literature is available on the influence of seed-drill openers on crop performance like biomass production, seedling emergence, plant populations, growth and yield. Nonetheless, it is believed that early emergence is important since seedlings that emerge earlier contribute more to yield than those that emerge later (Gan et al., 1992). Thus, desirable crop yields may be achieved by providing seeds with an environment that encourages early germination (Boydaş and Turgut, 2007). Various producers noted a difference in the emergence and establishment rate when comparing disc and tine openers (Berry et al., 1987; Swanepoel and Strauss, personal communication, 2019). Producers currently hypothesise that tine openers prepare a better seedbed for the germinating seeds, which then leads to a quicker emergence rate. When seeding with a seed-drill equipped with disc openers, the seedlings do not emerge as early, whereas later in the season the growth rate of seedlings shown with a tine opener plateaus. More research is needed to understand the early growth responses of crops established with different seed-drills.

The preceding literature review illustrates the importance of the choice of implements and agronomic management practices. The method and degree of mechanical soil disturbance by virtue of producer choice influence the physical, chemical and biological soil properties (Blanco-Canqui and Ruis, 2018; Villalobos and Fereres, 2016) and consequently the crop performance. The seed-drill choice must therefore be scientifically justified to ensure sustainable farming practices without compromising yield.

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CHAPTER 3

Materials and Methods

3.1 Site description

The study was conducted approximately 35 km south of Swellendam (34° 16′ 30.17″ S; 20° 27′ 10.8″ E) in the Napky region, southern Cape, South Africa in the 2018 and 2019 production seasons. The trial site was located on a farm where no-tillage practices were implemented for four years prior to the onset of the trial (2014 to 2017). The Napky region is a rain-fed winter cereal producing area and generally drier than the surrounding production areas. The region has a Mediterranean-type climate, with more than 60% of the annual rainfall received between April and September. Summer months are usually hot and dry.

Rainfall distribution was erratic in the 2018 production season with daily maximum temperatures well over 30°C during the first few weeks after seeding. The first four months had average daily maximum temperatures above 20°C (Table 1). A total of 149.60 mm of rain was received during the months April to September in 2019, compared to 111.40 mm in 2019 for the same months. However, only 136 mm rain was received from the date of seeding up to the date of crop termination in the 2018 production season, with only five rainfall events greater than 7 mm per day. The 2019 production season commenced with slightly more rainfall during the first part of the season together with cooler temperatures. However, rainfall decreased as temperatures increased towards August. A total of 62.10 mm was received during the duration of the 2019 growing season from the date of seeding up to the date of crop termination. Both of the production seasons were slightly drier compared to the long-term average rainfall for the region (Table 1) which average approximately 157.60 mm for the months April to September. Refer to appendix A for the daily rainfall and minimum and maximum temperatures for both of the production seasons.

Table 1. Climate data for the Napky region for the 2018 and 2019 production seasons as well as the average long-term rainfall data from April to September.

Month	Average minimum temperature (°C)	Average maximum temperature (°C)	Total rainfall (mm)
		2018	
April	9.83	22.93	8.40
May	11.71	23.98	9.90
June	8.60	20.66	22.70
July	8.24	21.15	28.00
August	6.79	18.13	28.10
September	8.62	19.91	44.80
Total			**149.60**
		2019	
April	13.57	23.42	19.30
May	11.07	22.70	14.50
June	8.04	20.55	8.60
July	8.48	19.73	29.70
August	7.42	21.65	8.60
September	10.66	25.27	30.70
Total			**111.40**
		Long-term rainfall (mm) ***Average 2007 - 2019***	
April		21.80	
May		21.00	
June		31.30	
July		32.40	
August		32.70	
September		18.40	
Total		**157.60**	

Soils in the southern Cape are highly variable over short distances. Oxidic and Lithic soil groups are common in this region (Fey et al., 2010). Soils of the trial site contained a high stone fraction (>50%). The stone-free soil texture comprises 54% sand, 25% silt and 20% clay, and had an organic carbon content of 1.65%. Refer to appendix B for an illustration of the amount of stones on the soil surface at the time of the seeding operation.

3.2 Experimental design

Three experiments on three crops were conducted, each involving three seed-drills as treatments, replicated three times in a completely randomised design. Appendix C include a diagram with the experimental layout. Crops that were seeded included barley (*Hordeum vulgare* L. *cv.* Hessekwa), canola (*Brassica napus* L. *cv.* Alpha TT) and wheat (*Triticum aestivum* L. *cv.* SST0127). The first seed-drill had double disc openers (X-Farm, Albertinia, South Africa; www.xfarm.co.za). Seeding units are hydraulically controlled and had a mass between 150 to 300 kg each. Double disc openers on the X-Farm seed-drill penetrated the soil up to a depth of 25 mm. Discs were tilted by 30° with the vertical and 11° between grouped discs. The second seed-drill had tine openers (Rovic Leers, Cape Town, South Africa; www.rovicleers.co.za). The working depth for the tine seed-drill ranged between 50 and 150 mm and each individual seeding unit had a mass of 14 kg. The third seed-drill had a combination of tine and single-disc openers (Rovic Leers, Cape Town, South Africa; www.rovicleers.co.za). The tine openers on the combination seed-drill resulted in most of the soil disturbance to a depth of 50 to 150 mm. However, seed placement occurred with a single disc angled vertically at 5°. Each unit of the combination seed-drill had a mass of 66 kg. Seed-drills complied with CA standards in terms of degree of soil disturbance (double disc openers < tine openers ≤ combination of tine and single-disc openers). A detailed description of the three seed-drills is presented in Chapter 4. Plot dimensions were 25 x 100 m and buffer strips (1 m) were left bare between the adjacent plots to simplify movement between the plots. Sufficient area for tractors to turn was left bare between adjacent rows (10 m strips).

3.3 Trial management

Seeding took place on 27 April 2018 in the first production season with all three of the seed-drills being tested. In the second production season, seeding took place on two different seeding dates; i.e., the double-disc seed-drill and the tine seed-drill seeded crops on 3 May 2019 and the combination seed-drill seeded crops on 9 May 2019 due to technical problems. Nevertheless, these dates fall within the acceptable seeding window for this region. Prior to the onset of the trial (2017 production season) the trial site was seeded with oats (*Avena sativa* L.) that was baled for animal feed. A crop rotation that included canola, wheat, barley and a mixed species cover crop (peas (*Pisum sativum* L.), oats (*Avena sativa* L.), vetch (*Vicia sativa L.*) and triticale (*Triticale hexaploide* L.)) was followed on the trial site (Appendix D). Seed-drills did not rotate between the different plots. Plots with mixed species cover crops were not included in the sampling. Weeds, pests and diseases were controlled chemically using appropriate pesticides.

In the 2018 production season, canola was seeded at a rate of 3 kg ha^{-1}, while barley and wheat were seeded at a rate of 65 kg ha^{-1} each. All crops were fertilised with 60 kg ha^{-1} mono-ammoniumphosphate (MAP) (6.6 kg N ha^{-1} and 13.2 kg P ha^{-1}). In the 2019 production season, canola was seeded at a rate of 3.2 kg ha^{-1}, barley was seeded at a rate of 50 kg ha^{-1} and wheat was seeded at a rate of 60 kg ha^{-1}. All crops were fertilised at a rate of 175 kg ha^{-1} with 2:1:2 mix organic fertiliser (3.85 kg N ha^{-1}, 1.93 kg P ha^{-1} and 3.85 kg K ha^{-1}). No additional fertilisers were applied as topdressing due to the dry climatic conditions that prevailed throughout both production seasons.

The seeding rate was adapted between the first and the second season according to general practice for the region after consulting with local agronomists, while the fertiliser sources were adapted according to availability at the time of seeding.

In both years, barley and wheat were seeded at a depth of 2.5 cm while canola was seeded at a depth of 2.0 cm. No yield data was collected since crops were chemically terminated prior to harvest in both production seasons. A combination of low rainfall, economic feasibility and weeds led to the decision. Good weed control was not achieved during the first growing season because of the low amount of rainfall and a final decision was made to terminate the crop chemically to prevent weeds from being problematic in the future. In 2019, the crops were terminated to be baled for animal feed to help the farmer in the severe drought. The crops were terminated on 26 September 2018 and 11 September 2019.

3.4 Soil parameters

Soil sampling was done before the crops were seeded to determine baseline soil fertility status in both production seasons. Four representative soil samples were taken to a depth of 150 mm and the results were used to correct any nutrient deficiencies prior to seeding in 2018. Prior to the 2019 production season, two representative soil samples were collected on each of the plots that were used for analyses (Table 2).

Table 2. Average values for soil analyses results of the 2018 and 2019 production seasons prior to seeding and fertilisation. Analyses were conducted by the Elsenburg laboratory using standard soil analyses methods.

Soil property	**2018**	**2019**
pH (*KCl*)	6.10	6.08
Resistance (*ohm*)	315.00	377.78
Exchangeable Ca, *mg kg^{-1}*	1 556.00	1 573.10
Exchangeable Mg, *mg kg^{-1}*	276.33	242.34
Exchangeable Na, *mg kg^{-1}*	96.50	117.00
Exchangeable K, *mg kg^{-1}*	237.00	203.42
Cation exchange capacity, *cmol kg^{-1}*	11.08	10.89
Extractable P, *mg kg^{-1}*	61.75	65.56
Organic C (%)	1.65	1.644
Clay, %	20	20
Silt, %	26	26
Sand, %	54	54
Soil texture	Loam	Loam

3.4.1 Soil bulk density

Soil bulk density was determined using the excavation method, which is suited for soils with a high portion of coarse fragments (Al-Shammary et al., 2018). Soil was removed with a steel ring directly on the furrow, to a depth of 100 mm and replicated twice per plot. Deeper bulk density determination was not possible because of the inability to remove an undisturbed soil sample with all the stones present in the soil volume. The volume of the soil sample was determined by lining the excavated hole carefully with a plastic bag and filling it with sand of which the density was known (1.52 g cm^{-3}). The mass of the sand was determined to enable calculation of the volume of the soil sample. Soil samples were oven-dried at 105 ˚C for 72 hours. Soil bulk density was calculated by dividing the oven-dried soil mass by the sample volume (g cm^{-3}).

Samples for soil bulk density and gravimetric soil water content were taken approximately 7, 30, 60, 90 and 120 days after seeding in both production seasons.

3.4.2 Gravimetric soil water content

Gravimetric soil water content was determined from the same soil samples collected for the bulk density determination in both production seasons, to limit the amount of destructive soil samples that was taken. The mass of soil samples were determined before and after oven drying at 105˚C for 48 h. Gravimetric soil water content was determined based on the difference in mass between the wet soil sample and the dry sample.

Two bulk density soil samples and gravimetric soil water content samples were taken per plot. Therefore, eighteen soil samples were statistically analysed per seed-drill, irrespective of the crop present on the plot, to ensure enough data for statistical analysis.

3.4.3 Infiltration rate (unsaturated hydraulic conductivity)

A minidisk infiltrometer (Model S; Decagon Devices, Inc.) was used to measure the unsaturated hydraulic conductivity directly on the seeding row, at 7 and 60 days after seeding in the 2018 production season only. The infiltrometer was filled with water and placed upright on the seed-furrow surface. The infiltrating volume was recorded at 30 s intervals until consecutive volumes differed less than 5%. A suction rate of 0.5 kPa was used, which eliminated water movement in macropores with a smaller air entry value than the suction set on the infiltrometer.

Measurements were omitted in the second season because of the variable and inconsistent results found in the first season together with the time consuming nature of this specific measurement.

3.5 Crop parameters

3.5.1 Seeding depth

Ten fully emerged seedlings were excavated from the soil, root intact, on different sampling dates. The coleoptile and chlorophyll-free length of the stem was measured to indicate the depth at which the seed was placed. Sampling took place 25, 35, 42 and 46 days after seeding in the 2018 production season. Sampling took place 16, 27 and 35 days after seeding in the 2019 production season with the double-disc and tine seed-drills. These measurements coincided with 10, 21 and 29 days after seeding with the combination seed-drill.

3.5.2 Emergence and survival

The number of emerged seedlings were counted in five 1 m rows, randomly selected within each plot and remained set through the growing season. Counts were done approximately every four days during the first few weeks of the growing seasons, thereafter the counting dates were spaced further apart. Counting commenced 21 days after seeding in 2018 and 10 days after seeding in 2019. Counting stopped when individual plants could not be distinguished anymore. Counting of the individual plants continued for such a long period to be able to compare the changes in the plant populations between the three different seed-drills over the first part of the growing season. Data are expressed as plant population (m^{-2}).

3.5.3 Biomass production

Biomass production was determined by randomly selecting five 1 m rows per plot. Plants in these randomly selected rows were cut at ground level and oven-dried at 60°C for 72 h to determine aboveground biomass production per square meter. Due to uneven emergence, the first measurement in both production seasons were conducted by randomly selecting ten seedlings per plot. The seedlings were oven-dried and the biomass per seedling was converted to biomass per square meter by using the number of plants counted per square meter. In the 2018 production season, sampling was done approximately 30, 60, 90, 120 and 150 days after seeding. In the 2019 production season, biomass was sampled on 35, 60, 90 and 120 days after seeding with the double-disc and tine seed-drills. These measurement dates coincided with 29, 54, 84 and 114 days after seeding with the combination seed-drill.

3.5.4 Yield

Crops were chemically terminated prior to harvest in both production seasons. Crops were terminated on 26 September 2018 in the first production season and 11 September 2019 in the second production season. Yield components were used to estimate potential yield. Ten randomly selected 1 m rows were cut at ground level to determine the number of ears m^{-2}. Thereafter, a random sample of approximately 30 wheat and 30 barley ears per plot, were used to determine the average number of kernels per ear. The kernels per ear and ears m^{-2} were used to estimate a potential yield. A thousand kernel mass of 36 g were used in the calculations (Le Roux, 2015) (Equation 1).

$$Yield\ (kg\ ha^{-1}) = Kernels\ per\ ear\ \times Ears\ per\ ha^{-1}\ \times TKM\ (kg)\ \div 1000$$

(Equation 1)

No canola yield was estimated for the 2018 or 2019 production season, as plants were still too premature at the time of termination.

3.6 Statistical analyses

Mixed model procedures using restricted maximum likelihood (REML) were followed to test for the treatment effects. The Variance Estimation and Precision (VEPAC) package of Statistica Version 13.3 (TIBCO Software Inc. 2018) was used. For repeated measures, fixed effects were specified as seed-drill and date, and their interaction. Random effects were specified as seed-drill nested within date. Repeated measures included bulk density, gravimetric soil water content, crop emergence and biomass production. For samples taken only once during the season (unsaturated hydraulic conductivity; seeding depth; yield components), generalised linear regressions were used to conduct an Analysis of variance (ANOVA). The crop was not considered a factor when soil parameters were analysed, and one dataset for the entire trial was used. Therefore, soil parameters had nine replicates, which was permitted because it was a completely randomised design. For all other parameters, crops were not compared to each other, and therefore analysed separately ($n = 3$). Probability values for significance at a 5% level of each variable were calculated using type III decomposition. Post-hoc pairwise comparisons were calculated using the Bonferroni test at a 5% significance level.

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CHAPTER 4

Seed-drills

The basic objective of seeding equipment is to place the seed and fertiliser uniformly in rows at a specific depth, cover the seeds with soil and provide sufficient seed-soil contact to ensure good germination. When uniform seeding is achieved better germination, emergence and yield increases are likely (Celik et al., 2007; Karayel and Özmerzi, 2002). Current no- and zero-tillage practices consist of direct seeding without prior soil preparation. This practice was developed, in conjunction with other CA principles, in order to improve soil management and increase the sustainability of agriculture (Bennie and Hensley, 2001; Lal, 2004; Nyagumbo et al., 2017). In the absence of tillage and the presence of crop residue on the soil surface, erosive processes are reduced and numerous soil attributes are improved (Altikat and Celik, 2011; Conte et al., 2011; Haruna and Nkongolo, 2015).

With the transition from conventional agriculture to CA, it was necessary to adapt the seeding equipment to be able to seed in untilled soil. Former seeding equipment was adapted to suit the minimum and/or no-disturbance needs and were replaced with direct drilling implements known as seed-drills. Modern seed-drills contain distinct structural characteristics compared to the ones previously used in conventional farming practices. These adaptations allow seed-drills to cut through surface residues that cover the soil surface at the time of seeding.

Seed-drills are classified according to the amount of disturbance they cause in the seed-furrow. For a seed-drill to be classified as a CA implement, the amount of soil disturbance should be less than the maximum amount of disturbance that is allowed in this farming system. According to Kassam et al. (2012), soil disturbance should be avoided as much as possible. Disturbance is only allowed if less than 25% of the soil surface is disturbed in bands narrower than 150 mm (Kassam et al., 2012). Within these CA parameters, tillage intensities vary between minimum tillage, no-tillage and zero-tillage. Minimum tillage is a broad concept that describe farming practices with reduced amounts of soil disturbance compared to conventional tillage, while no-tillage and zero-tillage eliminate soil disturbance to varying degrees. Soil disturbance only occur during the seeding operation and thus the type of seed-drill opener used, quantify the amount of soil disturbance. No-tillage practices make use of seed-drills with tine (knifepoint or shank) openers while zero-tillage make use of disc openers.

In South Africa, especially the Western Cape, farmers are converting to CA systems and there are a variety of seed-drills available on the market. When producers are considering new seed-drills, they must take several environmental, soil and crop factors into consideration. This research project analysed three different seed-drill openers in order to validate the choice taken by producers. Two commercially available seed-drills as well as one seed-drill that is currently in the testing phase, was used for the research project. Technical properties (Table 3), illustrations and descriptions for each seed-drill follow below.

Table 3. Technical properties of the double disc, tine and combination seed-drills.

Technical property	Double disc seed-drill[4.1]	Tine opener seed-drill[4.2]	Combination seed-drill[4.3]
Furrow opener type	Double discs	Tines	Tines and single discs
Number of openers	14 rows	43 rows	11 rows in pairs
Width of openers (mm)	*Not applicable*	2 x 16 mm per row	2 x discs per row
Inter-row distance (mm)	175	285	285
Seed metering unit	Piket metering units; electrically controlled	Air-seeder	Air-seeder
Tilt and disc angle	Tilt: 8° with the vertical Disc: 11° between discs	*Not applicable*	Tilt: 0° Angle: 5°
Total mass (kg)	4 000	12 300	4 100
Mass per furrow opener	Hydraulically controlled between 150 and 300 kg	14 kg per row	66 kg per pair
Attachment to tractor	Trailed	Trailed	Trailed
Manufacturer	X-Farm	Rovic Leers	Rovic Leers

4.1 Double disc seed-drill

The X-farm NTX disc seed-drill was developed, designed and manufactured at Albertinia in the southern Cape, South Africa. This seed-drill consists of 14 individual seeding units, each with a set of double discs. A hydraulic ram fitted to each individual seeding unit, allows vertical movement for the seeding unit to follow the natural undulation of the soil as well as accommodating stone and other physical barriers. The disc sets are tilted 8° with the vertical with 11° between discs of the same set. Disc blades are robust and manufactured to be able to cut through soil surface residues while opening a seed-furrow for seed placement. To ensure a successful cutting action, the total mass of the implement is designed for 300 kg downforce on each seeding disc pair. This high force exerted on the soil volume, ensure successful residue cutting and penetration of the soil for proper seed placement. Due to the shallower working depth and decreased amount of soil disturbance, classification of this seed-drill falls in the zero-till category of conservation agriculture. The shallower working depth also results in less draught force necessary, typically 3-4 kW per disc set, to pull the discs through the soil, compared to tine implements.

Seed is delivered to the furrow under gravity. Fertiliser are placed simultaneously in the seed-furrow at a depth between 20 and 25 mm while the double discs are cutting through the soil (Figure 2 A and B). Thereafter a rounded press-wheel moves over the newly formed seed-furrow to ensure sufficient seed-soil contact. The seeding depth is controlled and maintained by the press wheel, which can be adjusted to obtain the desired seeding depth. Before seeding takes place, fertiliser quantities must be taken into consideration. High quantities of fertiliser in the direct proximity of the seed can lead to seed scorching, which may decrease germination and emergence percentages.

Each double disc-unit will establish a single row of crops, 175 mm from the adjacent row (Figure 2 C). In row crops, the seeding rate is determined according to the final plant population requirement and based on thousand kernel mass. This plant population is crop specific and the seeding rate can be adjusted accordingly. This seeding rate will influence the distance between the adjacent plants in the same row while the row spacing of 175 mm will remain the same.

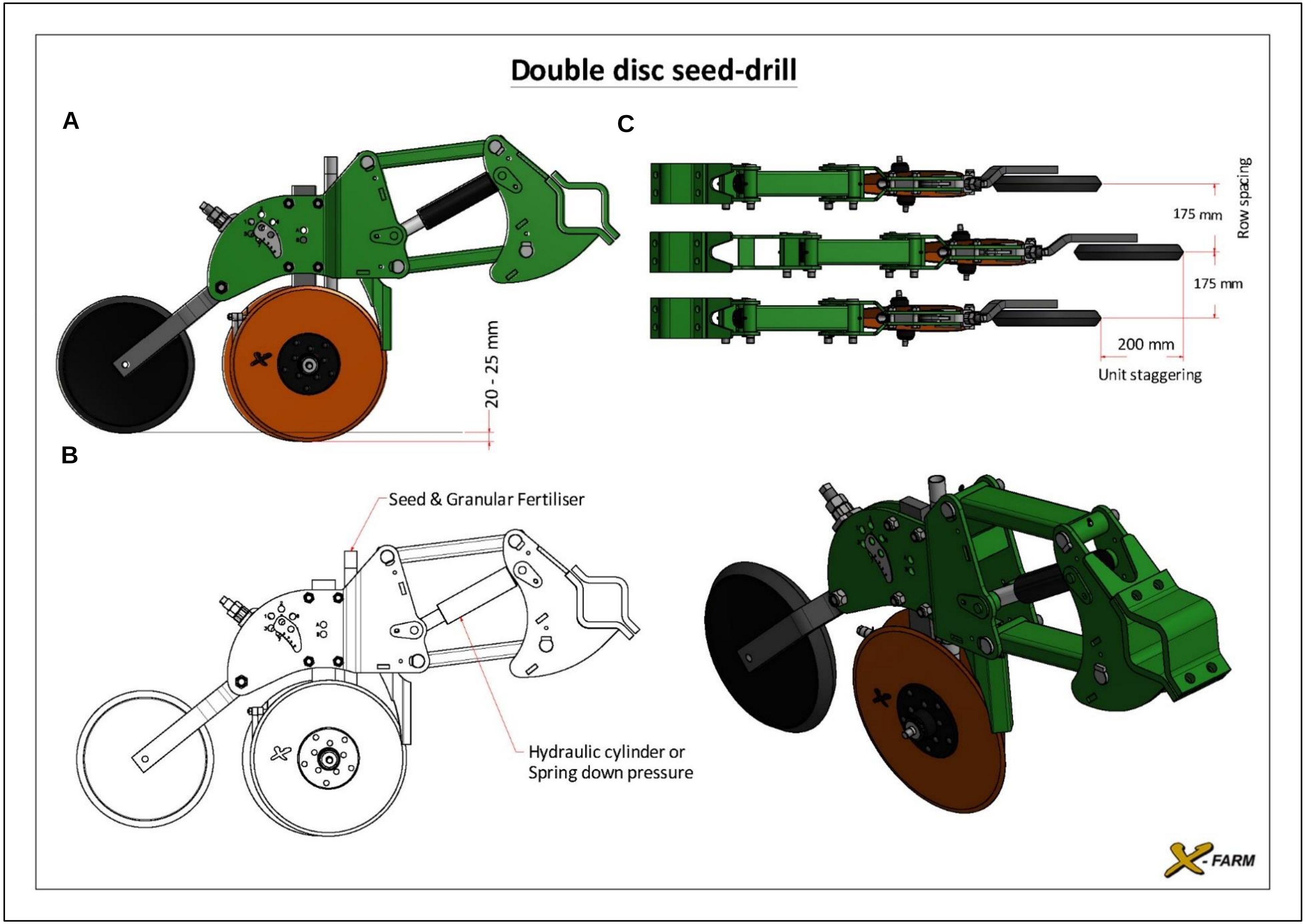

Figure 2. Side view of the double disc seed-drill, illustrating the working action depth (A) together with the seeding unit individually fitted hydraulic arm (B). Top view of the X-farm double disc seed-drill illustrating the spatial distribution of the individual seeding units in relation to one another (C). Source: Rinus Willemse; X Farm

4.2 Tine seed-drill

The Rovic Leers tine seed-drill was developed, designed and manufactured locally. This seed-drill contains tungsten-covered tines on a three-beam design that offer working widths ranging from 4.2 to 15.1 m. Each tine has its own hydraulic arm, which enable the tines to move individually. A theoretical power requirement ranging between 5 and 8 kW per tine is necessary for horizontal movement through the soil volume. A trip height of 385 mm allows vertical movement when physical soil parameters (stones etc.) hinder the forward movement. Soil disturbance occurs within the expectable parameters of CA and this seed-drill falls in the no-till category. The optimal working depth of each tine is between 50 and 150 mm. Seed placement usually occurs at a depth ranging between 20 and 30 mm while fertiliser placement can occur up to a depth of 150 mm (Figure 3 A). Adjustments can alter the seed placement depth according to the specific needs of the crop.

Spatial separation between the seed and the fertiliser allows fertiliser applications at relatively high rates simultaneously with seeding. Even though there is a seed and fertiliser separation, the crop’s sensitivity must still be taken into consideration to prevent seed scorching when applying high rates of fertiliser.

A rubber moulded V-shaped press wheel (45 mm width) moves over the seed furrow, directly behind the seed and fertiliser placement units. This ensures sufficient contact between the seed and the soil. Crops established with this type of tine seed-drill will emerge in 50 mm banded rows that are 285 mm apart (Figure 3 B).

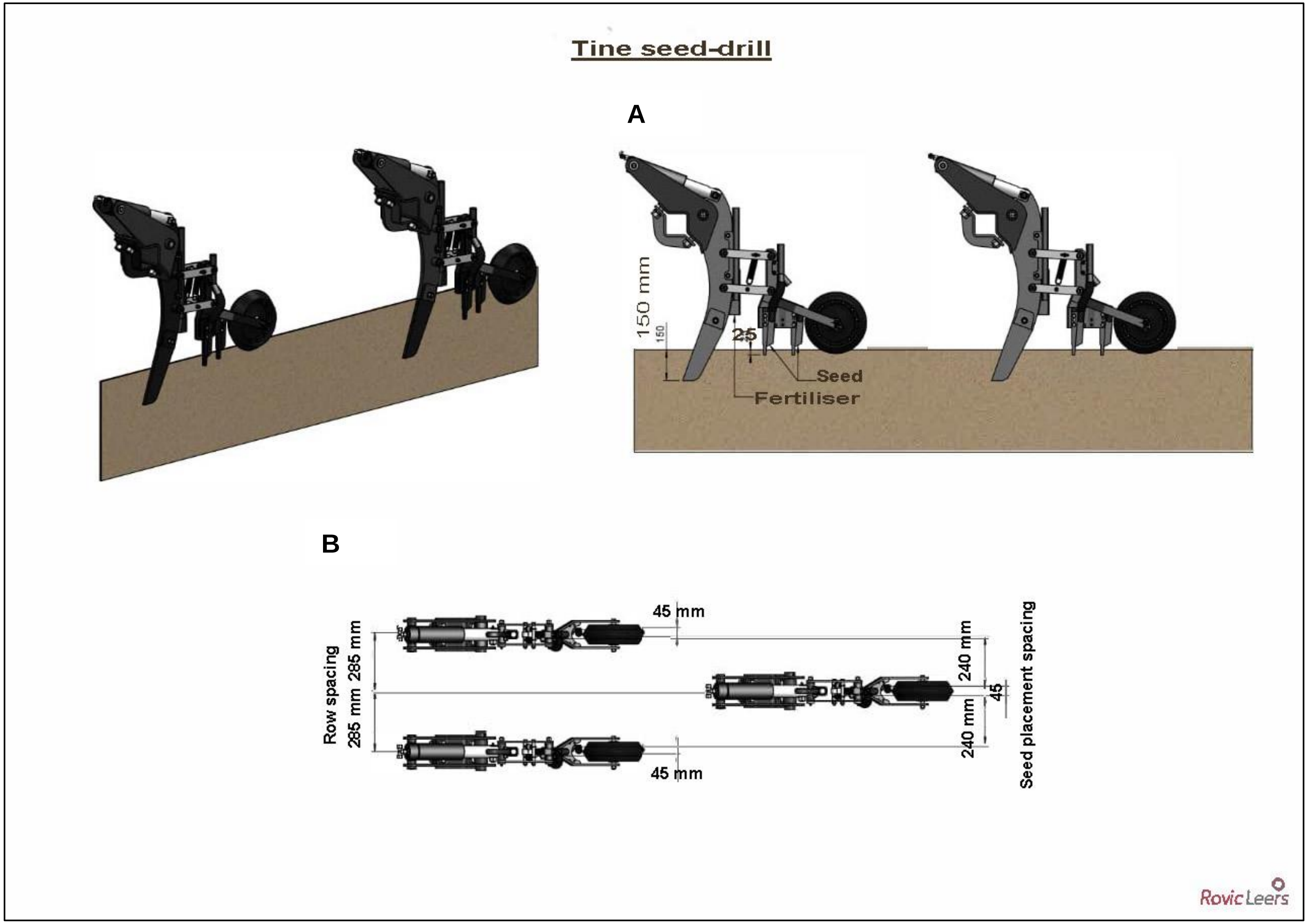

Figure 3. Spatial separation of seed and fertiliser at the time of seeding, illustrated as a side-view of the Rovic Leers no-tillage seed-drill, with tine openers (A). Top-view illustration of the spatial distribution of the seeding units and press wheels on the Rovic Leers no-tillage tine seed-drill (mm units) (B). Source: Rovic Leers.

In row crops, the seeding rate is determined according to the final plant population requirement and based on thousand kernel mass. This plant population is crop specific and the seeding rate can be adjusted accordingly. The chosen seeding rate will influence the distance between the adjacent plants, in the same row, while the row spacing remains the same.

4.3 Combination seed-drill

The Rovic Leers combination seed-drill is a local design, which constitutes a combination of a tine and a disc seed-drill. This specific seed-drill is a new innovative design that is in the testing phase and not yet commercially available. Soil disturbance occurs with a deep working tine, while shallower seed placement is achieved through single disc openers angled at 5° with the vertical (Figure 4). This seed-drill is also categorised as a no-tillage implement because of the presence of tines that disturb the soil volume in accordance with CA practices. Tungsten covered tines on this innovative seed-drill, are equipped with hydraulic arms to allow vertical movement over stones and other physical barriers. This vertical movement is based on the same concept as mentioned previously with the Rovic Leers tine seed-drill.

Moving through the soil, the tractor will firstly drag the tines through the soil volume, thereafter a small cage roller and double chute single disc openers follow. The tines will allow deeper soil disturbance to take place compared to an implement with only disc seeding units. The small cage roller passes over the soil surface where the tines disturbed the soil, to prepare the soil for the working action of the single discs. Seed placement then occurs in the newly created seed-furrow by the means of double chute single discs, as described above. The final part of the implement to pass over the soil surface is a flat rubber press wheel to ensure sufficient seed-soil contact.

Placement of fertiliser and seed occurs at different depths (Figure 4 A). Fertiliser placement occurs through tine openers while seed placement occurs through tandem single discs. Separation of the fertiliser and seed allows for higher fertiliser rates without increasing the risk for seed scorching. Double chute single discs ensure a dual seed placement, which allows better seed distribution and wider seed spacing in the row, resulting in less interplant competition. The seed, which arrives at each seeding unit, is shared between two tandem discs by means of an air source that splits the seeds with dual crop rows the result. Crop establishment will thus result in two seedling lines per row (also referred to as twin rows). The main seed rows will be 285 mm apart, directly where the tine worked (Figure 4 B). Seed placement will then be 40.5 mm off-centre, on each side of the main row. This will allow seedling establishment with a final row spacing of 204 mm between main rows and 81 mm between adjacent rows.

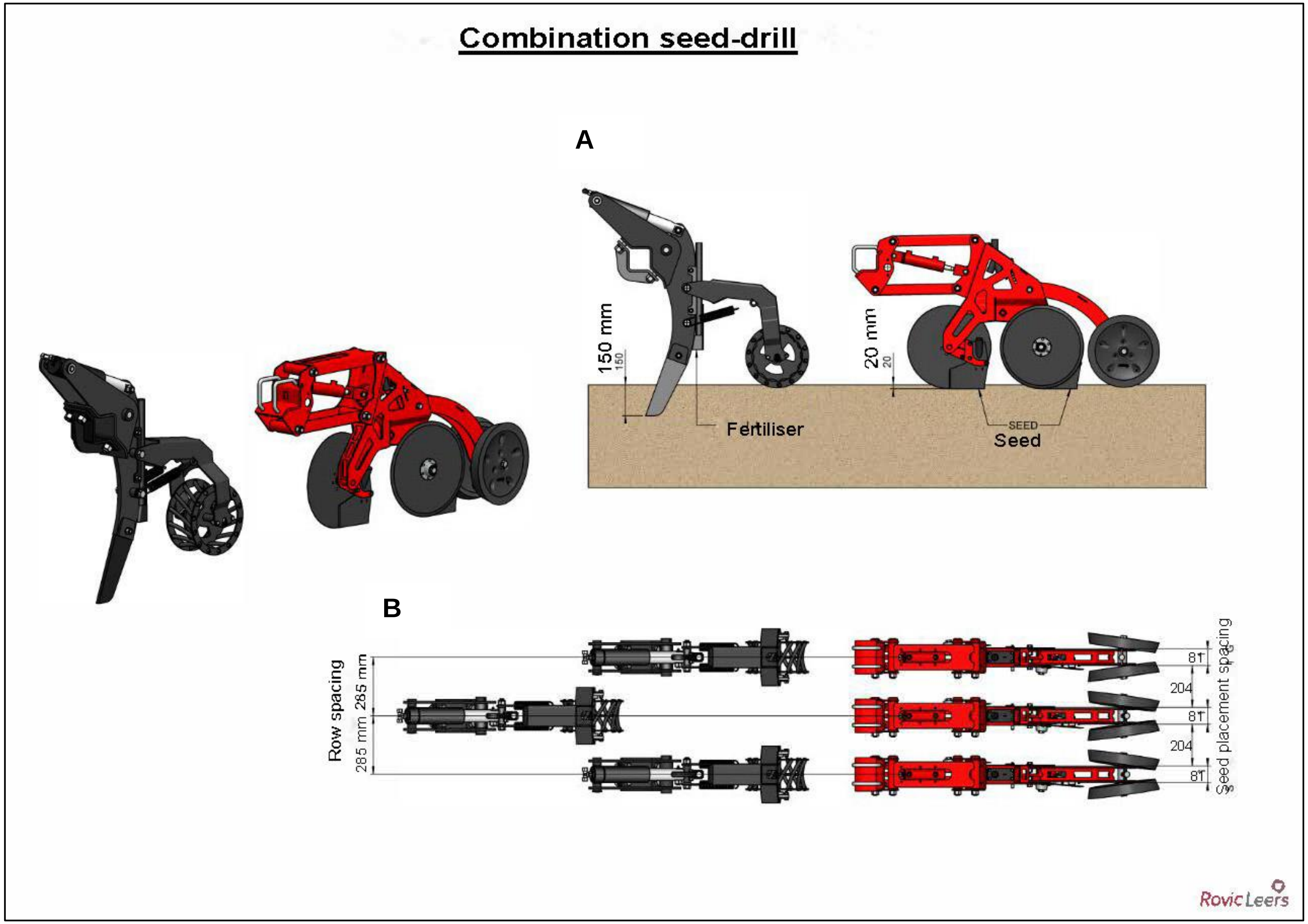

Figure 4. Side view of the Rovic Leers no-tillage seed-drill containing both tines and tandem discs together with an illustration of the spatial separation of seed and fertiliser placement (A). Top view of the combination seed-drill containing tine opener-fertiliser units (black) and seed units with double chute single disc openers (red). Spatial distribution of the different components are illustrated (mm units) (B). Source: Rovic Leers.

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CHAPTER 5

Influence of Seed-Drills on Soil Physical Properties

5.1 Abstract

Producers following conservation agriculture (CA) principles rely on seed-drill equipment that place seed directly in the soil. Soil disturbance influences soil physical properties, but knowledge about specific seed-drill openers is limited. The aim of this study was to quantify the influence of three types of seed-drills on soil bulk density, gravimetric soil water content and unsaturated hydraulic conductivity at various times during the growing season in the southern Cape, South Africa. Soil bulk density was influenced ($p < 0.05$) early in the growing season, but he effect dissipated gradually. In terms of gravimetric soil water content, only three out of the eleven measurements showed significant differences for water contained in the topsoil. Unsaturated hydraulic conductivity varied ($p < 0.05$) across treatments, but values remained low throughout the growing season. Even though seed-drills changed soil physical factors, particularly shortly after seeding, the magnitude of change was not big enough that one can expect significant influence on plant production. Combined principles of CA, not merely a reduction in soil disturbance, will likely contribute to changes in soil physical properties. Various factors, including soil physical conditions, environmental conditions and practical applications, must be taken into consideration when selecting a seed-drill.

5.2 Introduction

Conservation agriculture promote soil and water conservation and reduce input costs (Tejero et al., 2013). Since minimum-tillage forms part of CA, producers rely on seed-drill equipment that place seed directly in the soil. Various types of furrow openers are commercially available. The type of opener will determine the amount of soil disturbance that occurs in proximity to the seed. Although previous research showed that mechanical soil disturbance influences soil physical properties, there is still a lack of knowledge in terms of the influence of seed-drill openers on the soil properties in the seed-furrow (Boydaş and Turgut, 2007).

To sustain crop production, it is important that soil physical conditions allow rapid entry and movement of water and gases, and do not physically restrict seedling emergence or root development. Soil disturbance generally loosens the soil surface, decreases bulk density (Steyn et al., 1995), increases porosity (Bronick and Lal, 2005) and often increases the soil hydraulic conductivity (Haruna et al., 2018). However, this effect declined over time as the soil particles reconsolidated (Sauer et al., 1990). Soil bulk density in the direct proximity of the seed, and later in the season in the rooting zone, is an important physical property that influences crop establishment and productivity. Increased soil bulk density (i.e. soil compaction) is associated with a loss of air-filled pore volume (Gozubuyuk et al., 2014). This loss can have various consequences, which include decreased oxygen, water and nutrient supply to plant roots and soil organisms (Hillel, 2004). Mechanical soil disturbance not only alters the bulk density and pore geometry, but also soil hydraulic conductivity. Understanding the impact of soil disturbance on soil hydraulic conductivity or water flow is necessary to conserve and manage soil water under different management regimes (Blanco-Canqui et al., 2017). Water flow is mainly driven by hydraulic potential gradients, but it is also affected by the geometry of the pore system (Hillel, 2004). Inconsistent results have been reported on the influence of tillage practices on soil hydraulic properties (Blanco-Canqui et al., 2017). Quantification of the unsaturated water flow state is necessary for realistic comparisons, because water flow rarely occurs in a saturated state in rain-fed agricultural systems. Not only is it important to quantify the rate of water movement in soil, but also the amount of water retained in the seed-furrow. The degree of soil disturbance and the shape of the furrow caused by the seed-drill opener, influence water retention or losses through evaporation (Blanco-Canqui et al., 2017). Quantification of the soil water content in the seed-furrow may help with comparisons between seed-drill openers especially in semi-arid rain-fed production regions where water conservation is important. It was hypothesised that an increase in soil disturbance during the seeding operation will decrease the soil water content and soil bulk density of the seed-furrow, while increasing infiltration rate in the disturbed area. This study aimed to quantify the influence of three seed-drills on soil bulk density, gravimetric soil water content and unsaturated hydraulic conductivity at various points during the production season of crops in the Napky region, southern Cape, South Africa.

5.3 Results and discussion

5.3.1 Soil bulk density

For the 2018 production season, seed-furrow soil bulk densities differed ($p < 0.05$) across treatments up to 60 days after seeding, thereafter no differences ($p > 0.05$) were recorded (Figure 5)***.*** Treatment effects ($p < 0.05$) coincided with the degree of soil disturbance caused by the seed-drills (i.e. double disc openers < tine openers ≤

combination of tine and single disc openers). The degree of soil disturbance was not quantified directly, but depth of soil disturbance was used as an indication of this parameter. Both the tine and combination seed-drills disturbed the soil to a depth of 150 mm, while the double disc seed-drill only disturbed the soil in direct proximity of the placed seed (20 to 25 mm).

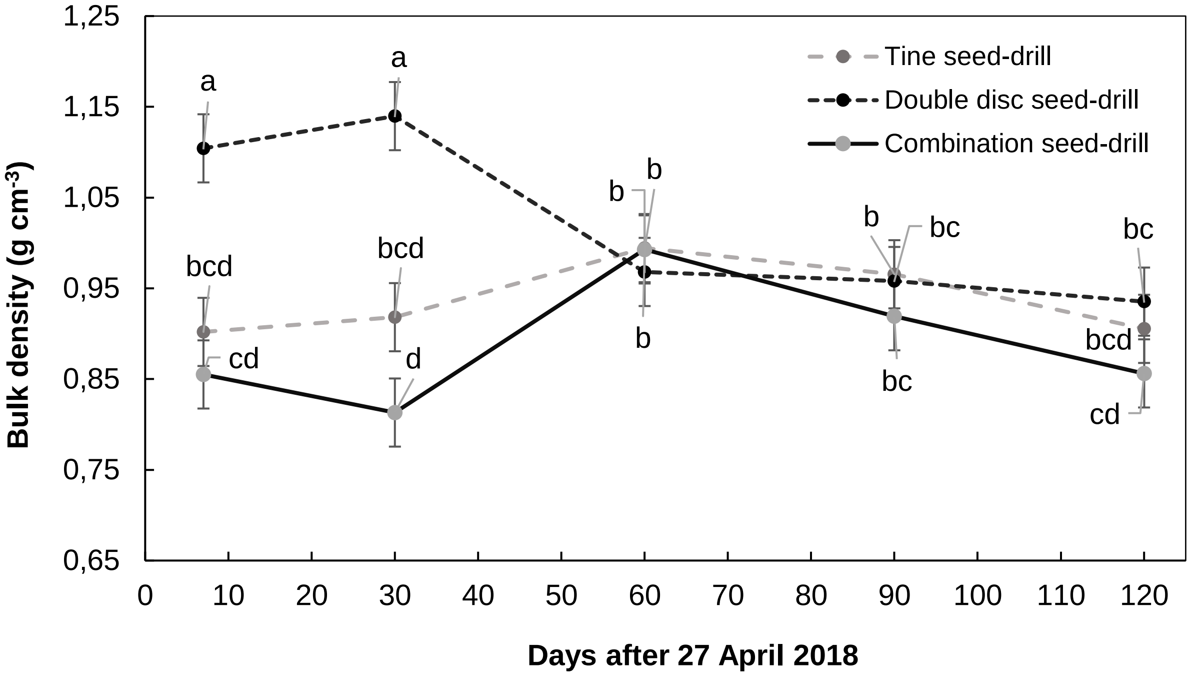

Figure 5. Soil bulk density (g cm^{-3}) measured in seed-furrows for the top 100 mm where seeding took place with seed-drills with either double disc openers, tine openers or a combination of tine and single disc openers in 2018. Error bars indicate the SE. Different letters indicate a significant difference at p = 0.05.

Early in the season, double disc openers led to the highest ($p < 0.05$) soil bulk densities, while lower ($p < 0.05$) soil bulk densities were recorded where seeding took place with seed-drills equipped with tine openers. A reduction in the degree of soil disturbance while using double disc openers, could account for the transient increase in soil bulk density (Haruna et al., 2018). The mass of the individual seeding units mounted on the double disc seed-drill could also account for the higher measured soil bulk density. A heavier seeding unit (150-300 kg) would exert a greater force on the seed-furrow, which might account for the increased soil bulk density. Similar results were obtained by Altikat et al. (2012, 2013) who evaluated disc and hoe seed-drill openers, which are in the current study comparable to the double disc openers and tine type-openers, respectively (Altikat et al., 2012, 2013).

Between 30 and 60 days after seeding, soil bulk density decreased markedly ($p < 0.05$) where double disc openers were used. The soil bulk density increased ($p < 0.05$) where the combination seed-drill was used, while the seed-drill equipped with tine openers did not result in any changes in bulk density ($p > 0.05$). A possible explanation for the decrease in soil bulk density while utilising a double disc seed-drill may be the soil loosening action of actively growing roots (Haruna et al., 2018; Ruiz et al., 2015) or an increase in soil stability because of a reduction in the degree of soil disturbance (Botha, 2013). Actively growing roots can contribute to a decrease in soil bulk density through physical movement of soil particles, thus increasing the volume of soil pores (Haruna et al., 2018; Ruiz et al., 2015). Soil stability typically improves with a reduction in soil disturbance and increased soil aggregate stability due to organic carbon sequestration (Kahlon et al., 2013; Sundermeier et al., 2011). However, these reasons are more likely to be true over the long-term (Botha, 2013; Sundermeier et al., 2011).

For the 2019 production season, seed-furrow soil bulk densities differed ($p < 0.05$) between the treatments of the tine seed-drill and the combination seed-drill seven days after seeding; thereafter no differences ($p > 0.05$) were recorded (Figure 6). The observed amount of soil disturbance did not result in a similar trend as observed in

2018. The lowest amount of soil disturbance resulted in a higher soil bulk density compared to the combination seed-drill; however, the soil bulk density with the tine seed-drill was comparable to that of the double disc seed-drill ($p > 0.05$) seven days after the seeding operation. The highest amount of soil disturbance again resulted in the lowest soil bulk density ($p < 0.05$) at the commencement of the season. All of the treatments resulted in a significant ($p < 0.05$) increase in soil bulk density with time from seven days after seeding to 120 days after seeding. Utilisation of the tine seed-drill led to a reduction in soil density between 90 and 120 days after seeding ($p < 0.05$). The soil loosening action of the actively growing roots (Haruna et al., 2018; Ruiz et al., 2015) may be a possible explanation for this occurrence.

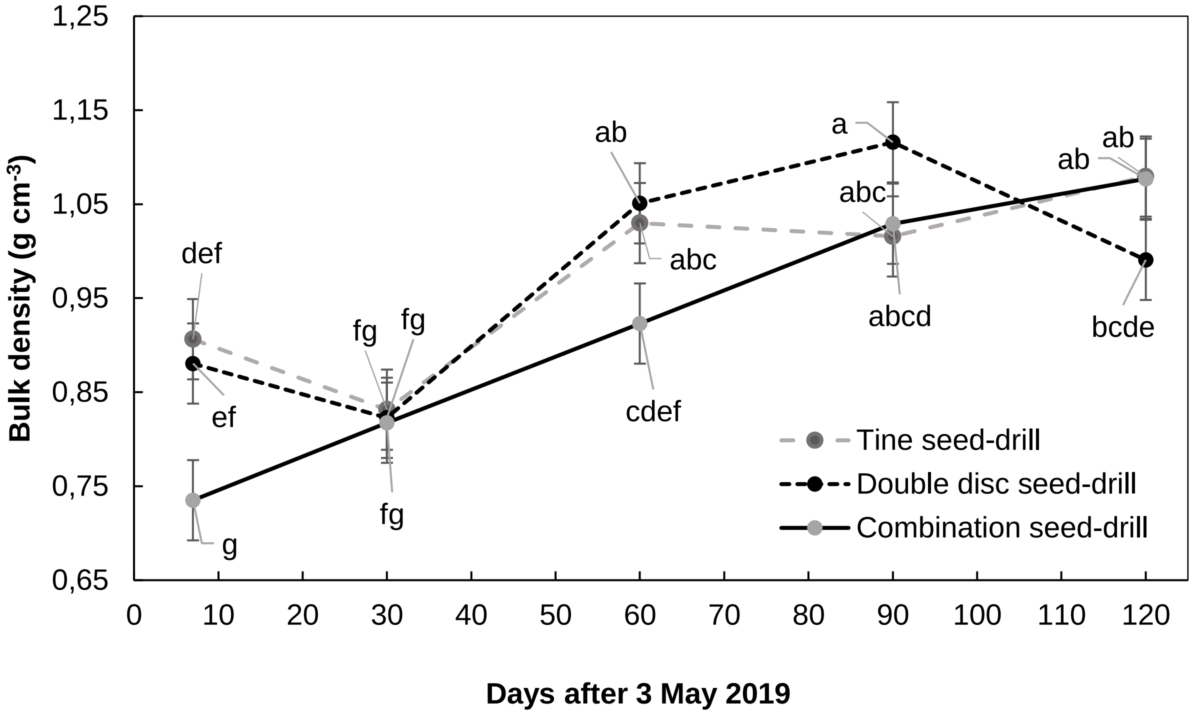

Figure 6. Soil bulk density (g cm^{-3}) measured in seed-furrows for the top 100 mm where seeding took place with seed-drills with either double disc openers, tine openers or a combination of tine and single disc openers in 2019. Error bars indicate the SE. No common letter indicates a significant difference at p = 0.05.

Previous research indicated that soils tend to compact or consolidate over the duration of the season (Halloran, 1993), which might be attributed to soil type, tillage method and fertiliser treatments (Chen et al., 1994). The rainfall amounts differed over the two seasons the trial was conducted. Therefore, the reduced amount of rainfall towards the end of the 2019 season could have influenced this soil property to a certain extent. However, it is not known if the influence of the climate could have such a prevalent influence.

Soil bulk density values obtained in the 2018 and 2019 production seasons ranged between 0.75 and 1.15 g cm^{-3}. Even though soil bulk density responded ($p < 0.05$) to seed-drills early in both seasons, all soil bulk densities that were recorded were within an acceptable range for crop production, therefore bulk density is not expected to restrict seedling emergence or root growth (Baker and Mai, 1982; Chaudhuri, 2001).

5.3.2 Gravimetric soil water content

The 2018 production season was very dry with only 98.9 mm of rainfall received over the soil-sampling period. No differences ($p > 0.05$) in soil water content in response to seed-drills were recorded early in the growing season (Figure 7). Less than 0.50 mm of precipitation was received 48 h prior to each sampling, except for sampling at 120 days, where 7.40 mm was received prior to sampling. Throughout the growing season, a tendency was noted that less soil disturbance conserved more soil water. Although soil water content did not differ ($p > 0.05$) between the double disc- and tine openers at 120 days after seeding, the soil water content in the seed-furrows of the combination seed-drill was lower ($p < 0.05$). Taking into consideration that all of the measured soil water content values were very low, indicating the dryness of the top soil on this specific site.

During the 2019 production season more daily rainfall events were observed compared to the 2018 production season; nonetheless, only 60.2 mm of rainfall was received over the soil-sampling period. No differences ($p > 0.05$) in soil water content in response to seed-drills were recorded 10, 60 and 120 days after seeding (Figure 8). Similarly, to the 2018 season, less than 1 mm of precipitation was received 48 h prior to sampling, except for sampling at 35 days, where 11.10 mm was received during the 48 h prior to sampling. Throughout the growing season, a tendency was noticed that less soil disturbance conserved more soil water. The double disc seed-drill retained more soil water in the seed-furrows 35 days after seeding ($p < 0.05$) compared to both the tine and the combination seed-drills. Ninety days after seeding the double disc seed-drill and the tine seed-drill resulted in higher seed-furrow water contents ($p < 0.05$) compared to the combination seed-drill.

Data indicated on Figure 8 for the 90 days after seeding measurement is questionable. The soil water content was expected to be much lower, given the fact that almost no rainfall was received for 10 days prior to the measuring date. Soil samples might have been contaminated with dew on the soil surface or from the crops as a result of taking this measurement earlier in the morning compared to the rest of the measurements.

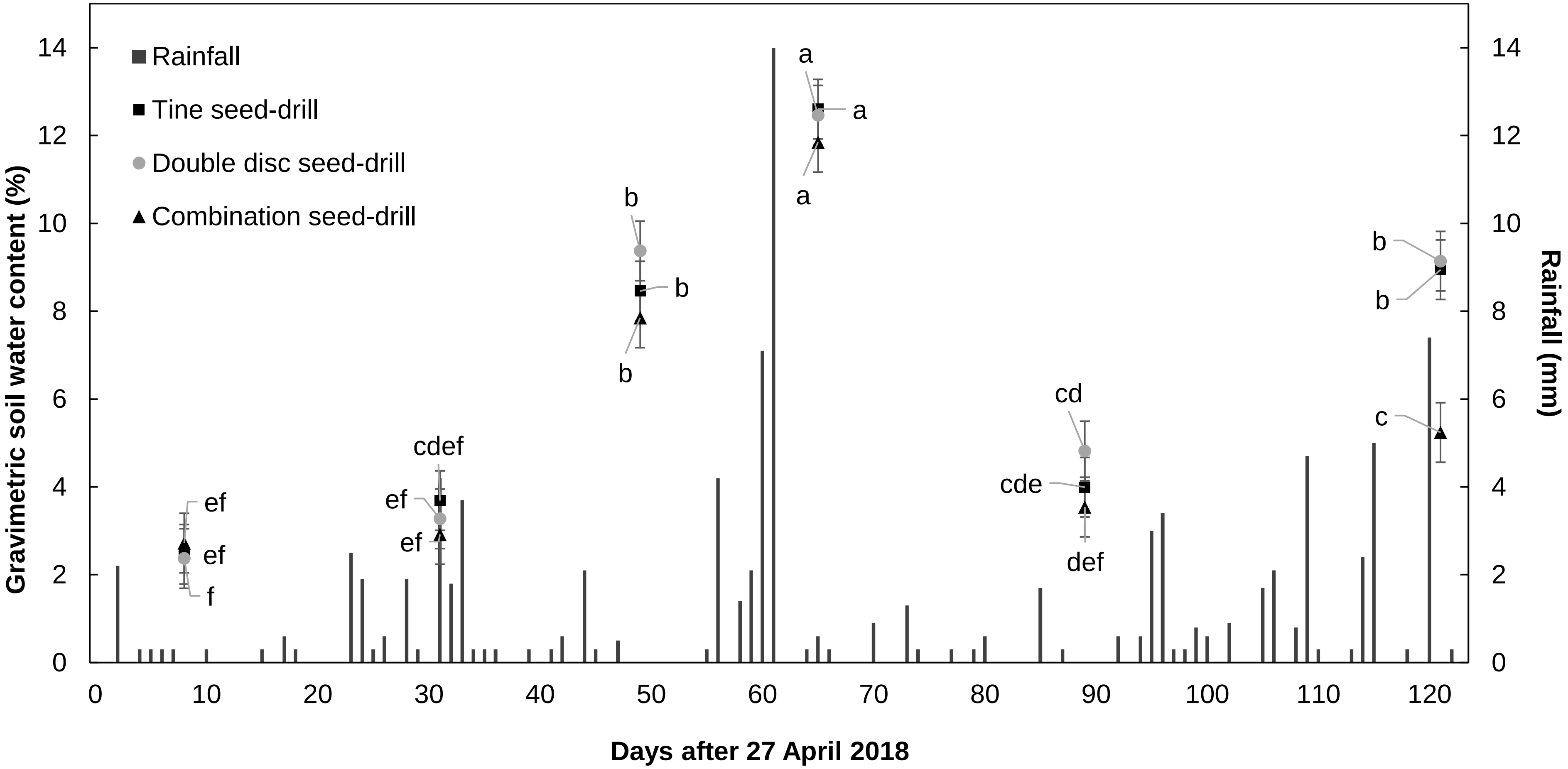

Figure 7. Daily rainfall (mm) and gravimetric soil water content (%) as measured in the seed-furrows for the top 100 mm where seeding took place with seed-drills with either double disc openers, tine openers or a combination of tine and single disc openers in 2018. Error bars indicate the SE. No common letter indicates a significant difference at $p = 0.05$.

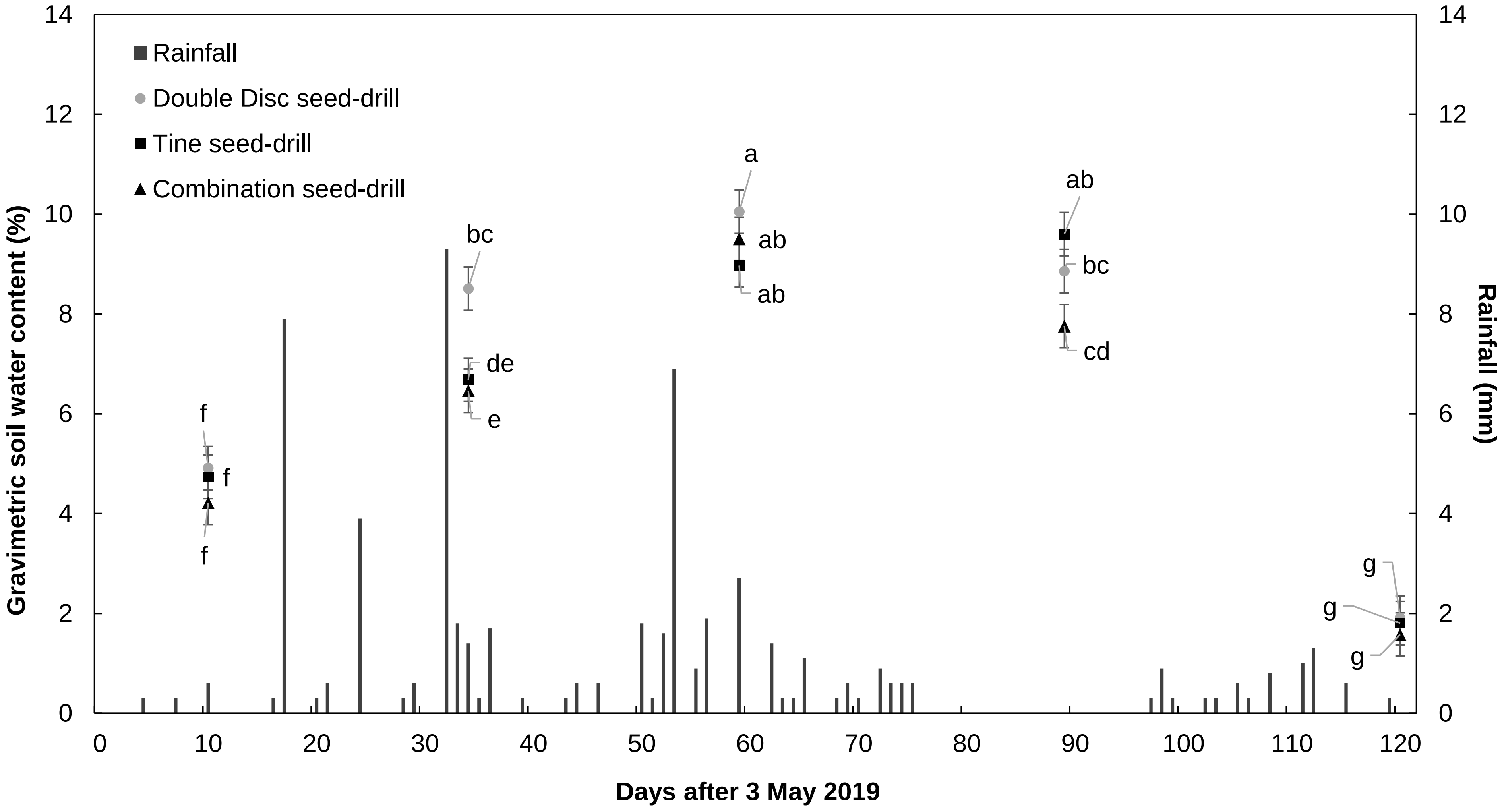

Figure 8. Daily rainfall (mm) and gravimetric soil water content (%) as measured in the seed-furrows for the top 100 mm where seeding took place with seed-drills with either double disc openers, tine openers or a combination of tine and single disc openers in 2019. Error bars indicate the SE. No common letter indicates a significant difference at $p = 0.05$.

Increasing the amount of soil disturbance generally result in higher evaporation rates. Abdullah (2014) noted that one of the reasons for the interest in reduced tillage operations are because of the increase in plant available soil water. Haruna and Nkongolo (2015) reported 8% higher gravimetric soil water content in no-tillage treatments compared to conventionally tilled treatments. Tessier et al. (1991) noted that excessive soil disturbance would allow the soil to dry more readily after the seeding operation. However, the movement of the moist soil from deeper soil layers may counter this drying effect of the excessive soil disturbance. In contrast, Chaudhuri (2001) reported higher soil water content in seed-furrows where soil disturbance occurred as a result of moist soil being brought upwards toward the seeding zone. When crop production is of interest, a certain degree of soil disturbance may thus be beneficial to allow water to move upwards from the deeper disturbed areas. However, increasing the upward movement too much might increase water loss through evaporation. However, quantification of the amount of evaporation was not possible and gravimetric water content was used as the only indication of seed-furrow water content to allow comparisons.

5.3.3 Unsaturated hydraulic conductivity

Over time, a decrease ($p < 0.05$) in unsaturated hydraulic conductivity was noted where the double disc and combination seed-drills were used (Table 4), but not where the tine seed-drill was used ($p > 0.05$).

Table 4. Unsaturated hydraulic conductivity (mm h^{-1}) as measured on the seed-furrows with a minidisk Infiltrometer at a suction rate of 0.5 kPa. No common letter indicates a significant difference at $p = 0.05$. SE = 0.13.

Days after seeding	Combination seed-drill	Double disc seed-drill	Tine seed-drill
7	14.70^a	7.08^b	3.23^c
60	4.15^d	3.81^d	5.51^c

Although inconsistent changes in unsaturated hydraulic conductivity occurred during the growing season, all values remained low. Changes in hydraulic conductivity may relate to soil and crop interactions (Chang and Lindwall, 1989), bulk density, soil water content (de Almeida et al., 2018) and/or to the alteration of pore continuity (Lipiec et al., 2006). The benefits associated with improved infiltration rates in CA systems are possibly due to the contribution of various factors, like surface residues or cover crops, and not merely because of a reduction in the soil disturbance intensity (Haruna et al., 2018). More research to quantify the effect of soil disturbance on short and long-term unsaturated hydraulic conductivity is necessary.

5.4 Conclusion

Seed-drill openers have varying influences on soil physical properties. Even though seed-drills changed soil physical properties, particularly shortly after seeding, the magnitude of change was seemingly not big to expect significant influence on crop production. Quantification of soil physical properties remain complicated since various factors like surface residues, crop growth, organic matter, temperature, rainfall and inherent physical properties have interacting effects. Positive attributes like water conservation, because of less soil disturbance, is important in semi-arid rain-fed production regions where water conservation is essential. Furthermore, lower soil bulk densities as a consequence of soil disturbance is necessary where compaction-sensitive crops are seeded. More research on unsaturated hydraulic conductivity is needed to understand the effects of CA on water infiltration. Various factors, including soil physical conditions environmental conditions and crop factors, as well as economic factors, must be taken into consideration when selecting a seed-drill (Swanepoel et al., 2019). In this research project, the effects of the various seed-drill openers were inconclusive. Furthermore, results might vary over the long-term as seed-drill openers and CA practices alter landscape properties.

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CHAPTER 6

Seed-Drill Choice and Crop Performance

6.1 Abstract

A seed-drill should facilitate seed placement in an environment conducive to uniform seedling emergence. In semi-arid rain-fed production regions, low rainfall intensity and inconsistent rainfall events can result in non-uniform emergence. Evaluation of seed-drills is necessary to supply dryland small grain producers with potential solutions to combat non-uniform seedling emergence. The aim of this study was to investigate the influence of three seed-drills on seeding depth, crop emergence, biomass production, and yield over the duration of two growing seasons. Barley, canola and wheat were established with three seed-drills, each equipped with a different opener, in a semi-arid production region of the southern Cape. Seed-drills contained either double disc openers, tine openers or a combination of both tines and single discs. Crops responded variably to seeding equipment under different climatic conditions ($p > 0.05$). For instance, accuracy of seeding depth varied between the three utilised seed-drills ($p > 0.05$). Seed-drills, together with their associated seed placement characteristics, influenced crop emergence ($p > 0.05$). Biomass production was variable over the course of the growing season ($p > 0.05$). Biomass production of crops established with the double disc seed-drill tended to be higher than that of crops established with tine seed-drills. Additional research about adaptions of agronomic practices and seed-drill openers may increase resilience to adverse climatic conditions in semi-arid small grain production regions. Various factors, including soil physical conditions, environmental

conditions, economic feasibility and practical applications, must be taken into consideration when selecting a seed-drill.

6.2 Introduction

The role of seed-drills is important in CA systems where direct seeding practices are utilised without prior soil preparation. Seed-drills should be able to place seeds in a soil environment that is conducive to successful germination and emergence (Karayel and Özmerzi, 2002, 2008). Literature report contradictory results about the outcome of direct seeding on soil properties and crop performance (Haruna and Nkongolo, 2015; McLeod et al., 1992; Mohammadi et al., 2013; Pittelkow et al., 2015; Swanepoel et al., 2017, 2019). However, it is evident that the type of seeding implement and its operating characteristics to create a seed-furrow, play an important role in the success of germination and seedling emergence (Chaudhry and Baker, 1988; Chaudhuri, 2001; Choudhary and Baker, 1980; Tessier et al., 1991).

Barley (*Hordeum vulgare* L.*)*, wheat *(Triticum aestivum* L.*)* and canola (*Brassica napus* L.*)* are important crops grown within cereal- and oilseed production regions worldwide. While seed and input costs to establish crops are constantly rising, rainfall patterns seem more unpredictable and erratic, while temperatures are increasing (Landman et al., 2018; Tibesigwa et al., 2017). Failing to provide an early and uniform crop emergence leads to more problems than simple agronomic threats to quality and yield (Harker et al., 2012). Insufficient coverage of the soil surface at the beginning of the season may increase weed germination and subsequently more herbicide applications (Harker et al., 2012). These economic and environmental concerns greatly affect producers in semi-arid rain-fed regions. Over the past few years, research and implementation of CA principles decreased input costs marginally, while overall sustainability and profitability of farming systems were increased. However, for producers to increase productivity further, more research is necessary to broaden the current knowledge of CA, especially in terms of seed placement and soil disturbance during the seeding operation.

The seeding operation is the main determining factor of uniformity and establishment of the crop (Ahmad et al., 2008; Liu et al., 2004) and to increase the effectiveness of this operation, research must focus on seed-drill openers and their influence on the seed-furrow. While the focus is mostly on emergence and establishment, only the seedlings that survive until the end of the season will contribute to the final yield. A void in available knowledge exists on crop performance when seeding occurs with different seed-drill openers (Swanepoel et al., 2019). This study aimed to evaluate the performance of three seed-drills in terms of crop parameters such as seeding depth, crop emergence, biomass production and yield.

6.3 Results and discussion

6.3.1 Seeding depth

The tine seed-drill had most constant seeding depths in both production seasons, with no difference over years for all three crops ($p > 0.05$; Table 5). In both seasons, the tine seed-drill placed the barley and wheat seed close to the target depth of 2.5 cm, despite the high amount of stones in the soil profile.

Barley seeding depth differed between the three seed-drills ($p < 0.05$; Table 5). In the 2018 production season, the double disc seed-drill placed the seed the deepest, while the combination seed-drill placed the seed shallowest. In the 2019 production season this trend was reversed with the combination seed-drill placing the seed the deepest, while the double disc seed-drill placed the seed the shallowest.

Table 5. Average seeding depth (cm) of barley, wheat and canola of the three tested seed-drills in 2018 and 2019. No common letter indicates a significant difference at p = 0.05 for a crop.

Seed-drill	**2018**	**2019**	**SE**
	Barley seeding depth (cm)		**Barley**
Double disc seed-drill	3.11^a	1.99^c	0.13
Tine seed-drill	2.61^b	2.48^b	
Combination seed-drill	1.97^c	3.12^a	
	Wheat seeding depth (cm)		**Wheat**
Double disc seed-drill	2.85^{ab}	2.29^{cd}	0.16
Tine seed-drill	2.68^{abc}	2.65^{bcd}	
Combination seed-drill	2.19^d	3.14^a	
	Canola seeding depth (cm)		**Canola**
Double disc seed-drill	2.27^a	1.73^b	0.13
Tine seed-drill	1.85^{ab}	1.67^b	
Combination seed-drill	1.75^b	1.64^b	

Wheat seeding depths differed ($p < 0.05$; Table 5) between the different seed-drills when the two production seasons are compared with the exception of the tine seed-drill ($p > 0.05$). Variation was seen between the seeding depths of the double disc seed-drill and the combination seed-drill when the 2018 and 2019 production seasons are compared. Within years, the double disc seed-drill and the tine seed-drill was comparable, while the combination seed-drill placed the seeds either shallower (2018) or deeper (2019), compared to the previously mentioned seed-drills.

Canola was placed slightly shallower than the target of 2.0 cm, but the consistency of placement was similar in both production seasons ($p > 0.05$; Table 5). Canola seeding depth differed ($p < 0.05$) between the seed-drills in 2018, but no difference was found in 2019 ($p > 0.05$). In the 2018 production season, the double disc seed-drill placed the seed deeper than the combination seed-drill; both were similar to the tine seed-drill. During the seeding operation in the 2018 season problems were observed with the press wheel of the double disc seed-drill, which might have accounted for the slightly deeper placement of the seeds. In the 2019 production season, all three seed-drills placed the seeds at a comparable depth. When comparing years and consistency of seeding depth, the tine seed-drill and the combination seed-drill did not show differences over the two production seasons ($p > 0.05$).

There is ongoing dispute regarding the optimum seedling depth by these implements. However, all of the seeding depths found were within an acceptable range for seed germination and emergence. Optimum barley and wheat seeding depths range between 2.0 and 4.0 cm (Department of Agriculture, Forestry and Fisheries, 2016; Kong et al., 2016; Robertson and Stark, 2003). Optimum seeding depth of canola should be less than 3.0 cm from the soil surface (Brill et al., 2016; Harker et al., 2012; Malhi and Gill, 2004).

Insufficient seeding depth results in poor crop establishment while deep placement of seeds delays crop emergence (Altikat et al., 2013; Nielsen et al., 2018). Seeding depth differed in both production seasons, but the difference were probably not large enough to have a major influence on the emergence of the crops under field conditions ($p < 0.05$; Table 5). An assumption is made that when seed placement is too shallow, it results in poor germination due to inadequate soil moisture in the top soil, while excessively deep seeding reduces crop emergence due to a limitation in the coleoptile length (Altikat et al., 2013; Nielsen et al., 2018). However, in years comparable to first production season (2018), where rainfall was limited at the time of the seeding operation, deeper seeding (> 2.50 cm) could be beneficial to ensure uniform crop emergence.

The placement method and the press wheel of the seed-drill could explain the accuracy and consistency of the seeding depths. The tine seed-drill places the seeds in the sidewalls of the seed-furrows. When the press wheel moves over the seed-furrow to close the furrow, the seeds are less affected after placement in the seed-furrow's sidewalls. The press wheels, mounted on the double disc seed-drill and the combination seed-drill, will both affect the seed placement in the furrows to different extents. Variation in seeding depth should be eliminated as far as possible because different depths of seed placement within a crop row will cause non-uniform crop emergences (Altikat et al., 2013; Celik et al., 2007; Chen, 2004; Liu et al., 2004; Loeppky et al., 1989). To ensure crops that can compete with weeds and crops that are in the same growing stage, producers should invest in seeding equipment that are able to consistently place seeds at the target depth as accurately as possible.

6.3.2 Seedling emergence

In the 2018 production season, seedling emergence commenced approximately 21 days after the seeding operation due to a lack of significant rainfall events at the start of the season (Figure 9 and 10). Where barley was seeded, no significant differences in emergence were found between seed-drills ($p > 0.05$; Figure 9) with the exception of 31 and 42 days after seeding. Thirty-one days after seeding the double disc seed-drill resulted in a higher plant population, while the combination seed-drill resulted in the highest plant population 42 days after seeding.

No differences were found in the number of wheat seedlings up to 35 days after seeding in the 2018 production season ($p > 0.05$; Figure 10). Thereafter, all three of the used seed-drills differed in the plant population established ($p < 0.05$). From 39 days after seeding, plots seeded with the combination seed-drill had on average the highest wheat plant population. The tine seed-drill had the second highest plant population while the seed-drill with double disc openers established the lowest plant population.

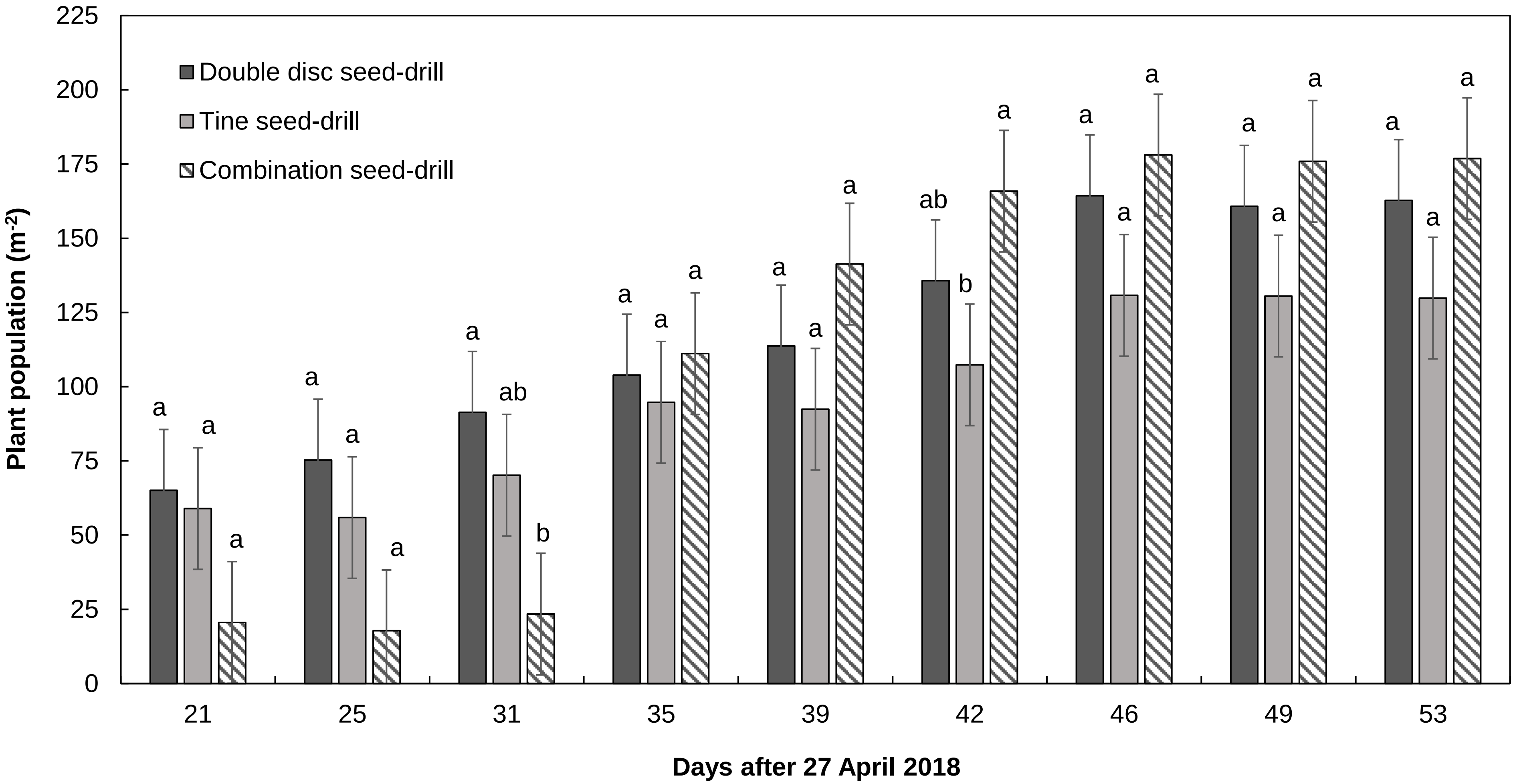

Figure 9. Barley plant population (m^{-2}) where seeding took place with seed-drills with either double disc openers, tine openers or a combination of tine and single disc openers in 2018. Error bars indicate the SE. No common letter indicates a significant difference at p = 0.05 for each sampling date.

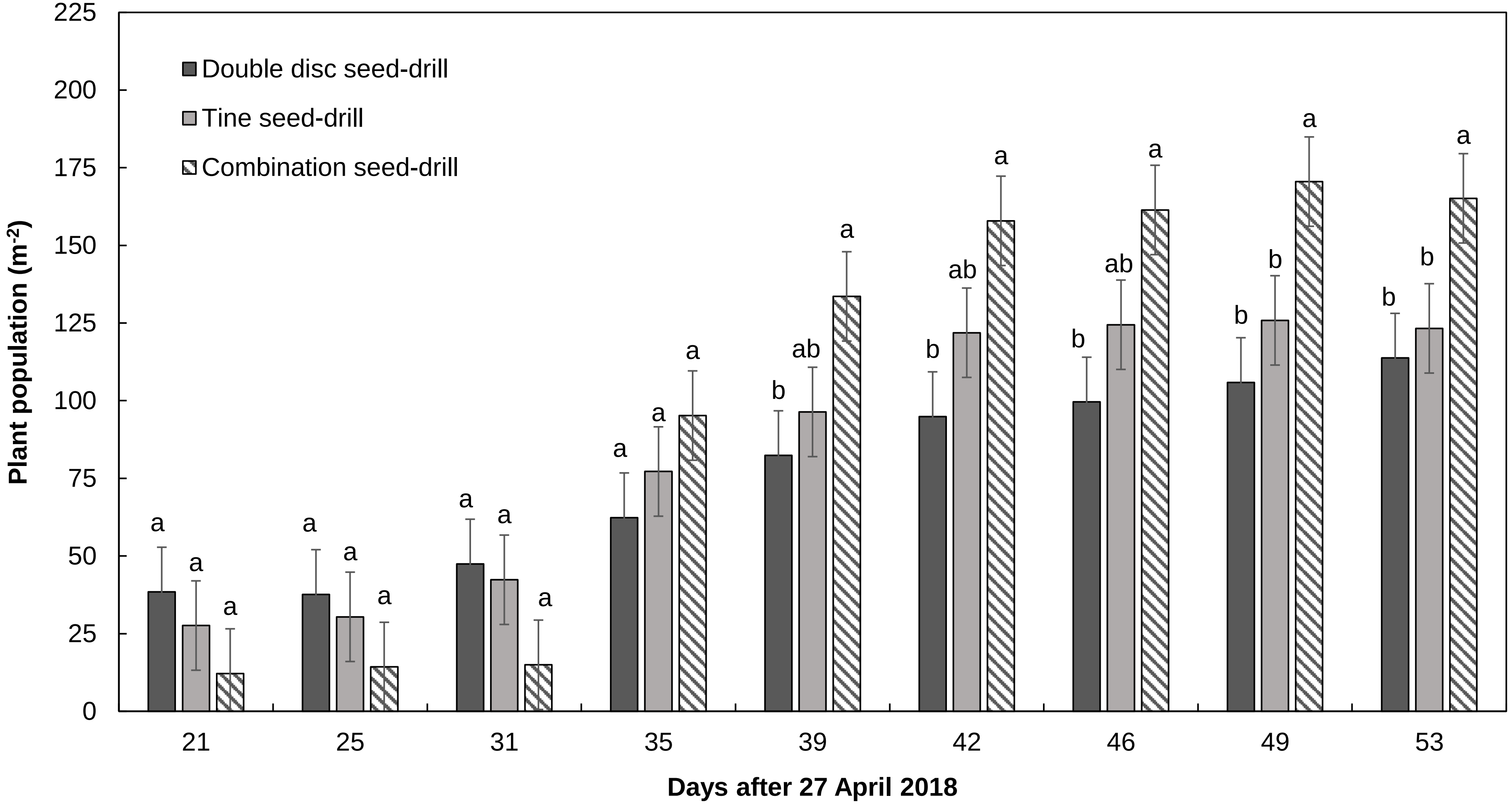

Figure 10. Wheat plant population (m^{-2}) where seeding took place with seed-drills with either double disc openers, tine openers or a combination of tine and single disc openers in 2018. Error bars indicate the SE. No common letter indicates a significant difference at p = 0.05 for each sampling date.

Where seeding took place with the combination seed-drill in the 2018 production season, most barley and wheat seedlings emerged 35 days after the seeding operation. The shallower seeding depth ($p < 0.05$; Table 5) of the combination seed-drill could possibly have resulted in this occurrence. When seeds are placed shallow, soil around the seed as well as the seed are prone to dry out (Barreiro et al., 2016). Small amounts of rainfall, will also allow some of the seeds to germinate and emerge, while other seeds remain in the soil awaiting the next rainfall event. Placement of seeds at slightly deeper depths, within reach for the coleoptile to emergence, comparable to the tine and double disc seed-drills, can ensure more uniform seedling emergence in years with low rainfall. In years with more significant rainfall events at the start of the growing season, comparable to the second production season (2019), or when seeding takes place in moist soil, shallower seed placement will be less disadvantageous to crop emergence.

It seems as if the climatic conditions at the beginning of the growing season together with the seed-drill choice might have influenced the emergence of the cereal crops. Both barley and wheat seedling emergence was delayed at the start of the 2018 season for approximately three weeks. However, towards the end of the first season it seems that the seed-drill choice had a smaller impact on the barley crop compared to the wheat crop in terms plant population.

In the 2019 production season, where barley was seeded with the tine seed-drill, seedlings emerged first ($p > 0.05$; Figure 11). Even though seeding only took place six days after 3 May 2019, with the combination seed-drill, the final plant population were not negatively influenced (take note, days after seeding on the graphs are calculated from the seeding date of the earlier seeding operation). From 20 days after seeding with the tine seed-drill and respectively 14 days after seeding with the combination seed-drill, no differences were seen in the plant populations ($p > 0.05$). Seedling emergence was delayed where the double disc seed-drill was used for seeding purposes ($p < 0.05$; Figure 11*)*, but from 31 days after seeding onwards, the plant population was similar to that of the tine seed-drill ($p < 0.05$).

Where wheat was seeded in the 2019 production season with the tine-type opener, seedlings emerged first ($p > 0.05$; Figure 12). Seedling emergence commenced slightly later, where the combination seed-drill was used (take into consideration that this seed-drill seeded crops six days after the other two seed-drills). Nonetheless, from 16 days after seeding onwards the tine seed-drill and the combination seed-drill did not result in different plant populations ($p < 0.05$). The double disc seed-drill resulted in a slower emergence rate at the start of the growing season, but from 27 days after seeding onwards, the plant population was comparable to both of the other seed-drills ($p < 0.05$).

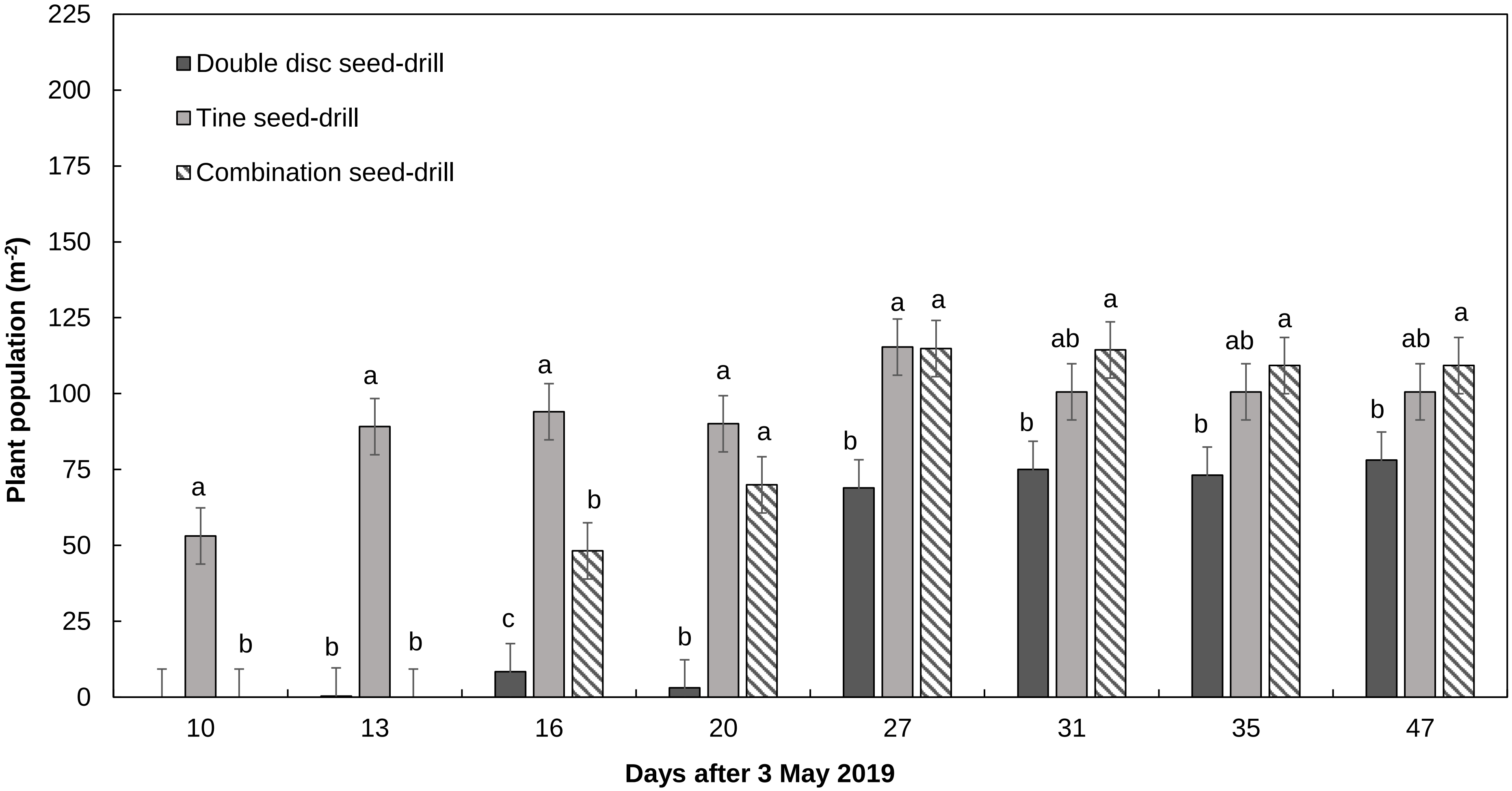

Figure 11. Barley plant population (m^{-2}) where seeding took place with seed-drills with either double disc openers, tine openers or a combination of tine and single disc openers in 2019. Error bars indicate the SE. No common letter indicates a significant difference at $p = 0.05$.

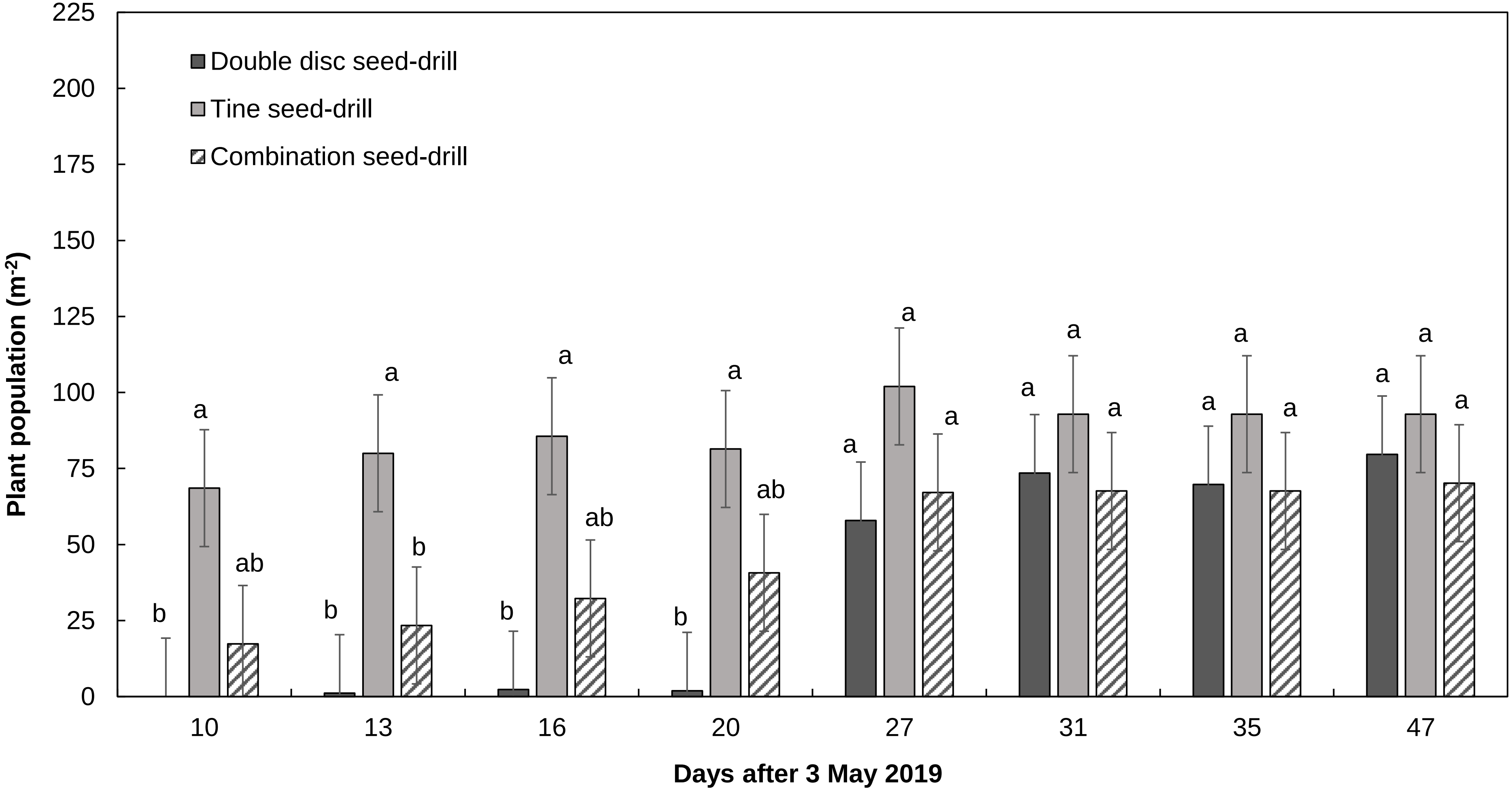

Figure 12. Wheat plant population (m^{-2}) where seeding took place with seed-drills with either double disc openers, tine openers or a combination of tine and single disc openers in 2019. Error bars indicate the SE. No common letter indicates a significant difference at $p = 0.05$.

Similarly to the 2018 production season, where shallower barley seeding took place (1.99 cm with the double disc compared to 2.45 and 3.12 cm with the tine- and combination seed-drills, respectively), seedling emergence was delayed for four weeks. Wheat seedling emergence was also delayed in the 2019 production season where the double disc seed-drill was used for seeding purposes. However, in this year the wheat seeds were placed at comparable depths by all of the seed-drills ($p < 0.05$; Table 5). Therefore, the delay in barley and wheat seedling emergence in 2019 might also be related to the decreased amount of soil disturbance that took place at the time of the seeding operation.

In a year with more rainfall events at the commencement of the season, soil disturbance with a tine might be beneficial for early seedling emergence. In the 2019 production season, barley and wheat plant populations were greater where the tine seed-drill and the combination seed-drill were used for the seeding operation, compared to the double disc seed-drill. Soil disturbance loosens the soil in the close proximity to the seed and allows soil water from deeper soil layers to move upwards towards the seed. Chaudhuri (2001) evaluated the performance of furrow openers in field conditions. Furrow openers that cause deeper soil disturbance allowed moist soil to move up to the seedbed during the seeding operation, which accounted for better germination even though variation in seeding depth and soil disturbance was at a maximum for the analysed furrow openers. Partial upward movement of water can improve germination and increases the uniformity of seedling emergence, if evaporation is not concomitantly increased excessively. Elimination of soil disturbance, at the time of seeding with the double disc seed-drill, delayed seedling emergence, even though seedling numbers per row were comparable later in the growing season. Soil disturbance with the tine seed-drill together with accurate seed placement allowed uniform emergence of barley and wheat seedlings in the 2019 production season.

Håkansson et al. (2011) found an almost linear increase in the time delay for the emergence of 50% of barley with an increase in the seeding depth. Loeppky et al. (1989) investigated the effect of seeding depth on winter wheat development. A seeding depth increase of as little as 17 mm could result in a significant reduction in wheat emergence. In contrast, this study revealed that where seeding took place in dry climatic conditions (2018), the seed-drills that placed the barley and wheat seeds slightly deeper (Table 5), even with a difference exceeding 17 mm, resulted in a higher amount of emerged seedlings 21 days after seeding. It needs to be taken into consideration that all of the crops took longer to emerge compared to emergence that was expected under optimal climatic conditions. The climatic conditions at the start of the growing season had a major influence on the rate and uniformity of crop emergence. Therefore, producers should consider the climatic conditions at the start of the growing season when they decide on a seeding depth. Deeper seed placement (> 2.50 cm) of barley and wheat should be considered in drier years, to ensure uniform crop emergence and to protect the seed from environmental fluctuations at the soil surface. Shallower seed placement (≤ 2.50 cm) can be considered in years with more rainfall at the onset of the season.

Upon deciding what seed-drill opener type to use, producers should carefully consider and adapt according to the climatic conditions at the start of the season. In seasons with low rainfall at the start of the growing season, uneven seedling emergence was observed with all three of the tested seed-drills. Placement of barley and wheat seeds with the combination seed-drill, which is mounted with tines and single discs, was delayed longer compared to seedling emergence where the other two seed-drills were used. This delayed seedling emergence will only be beneficial if the biomass production and the yield are not compromised. Otherwise, earlier emergence will still be of importance to get the seedlings to grow to ensure a longer growing season as soon as rainfall is received.

In years with more rainfall at the start of the growing season, or when seeding take place in moist soil, seeding with a tine seed-drill will result in the best crop emergence. Crops seeded with the other two seed-drill eventually caught up to the tine seed-drill; nonetheless, safeguarding a uniform and well established crop early in the season was achieved through seeding with the tine seed-drill. Poor crop establishment and low crop stands often limits wheat yields in semi-arid rain-fed production regions. Therefore, rapid germination and emergence is necessary to improve the obtained yields (Nasr and Selles, 1995), because seedlings that emerge early contribute more to crop yield then seedlings that emerge late (Gan et al., 1992). No-tillage systems usually delay crop growth compared to conventionally tilled systems, but crops compensate for slow growth towards the end of the season (Kitonyo et al., 2018; Verhulst et al., 2011). Research has not established if the same principle is applicable for zero-tillage (i.e. double disc seed-drill) and no-tillage (tine seed-drills). More research is necessary to relate early and/or late barley and wheat emergence and compensation of crop growth to grain yields in CA systems.

Canola emergence and survival varied when different seed-drill openers were used for the seeding operation ($p < 0.05$). In the 2018 production season, deeper seed placement (2.27 cm) with the double disc seed-drill, without any prior soil disturbance delayed canola seedling emergences. No differences were noted in the plant population up to 31 days after seeding ($p > 0.05$), thereafter both tine-type seed-drills established higher plant populations compared to the double disc seed-drill ($p < 0.05$, Figure 13).

In the 2019 production season, the depth of seed placement was comparable to the shallower seeding depths measured in the 2018 season, with no differences within the two seasons between the tested seed-drills ($p > 0.05$). In the 2019 production season, the tine seed-drill allowed early and uniform seedling emergence ($p < 0.05$). The combination seed-drill and the double disc seed-drill emerged slightly later in the season, between 31 and 47 days after seeding no difference was found in the plant populations. However, from 47 days after seeding onwards the tine seed-drill established a higher plant population compared to the double disc seed-drill ($p < 0.05$, Figure 14). The combination seed-drill did not differ from either aforementioned seed-drills ($p > 0.05$).

Harker et al. (2012) evaluated the influence of canola seeding depth on the rate of emergence. Two seeding depths, 1 and 4 cm, were compared and the days to emergence and crop density were assessed. Shallower seeding reduced the number of days until emergence from 18 to 16 days. Based on a seeding rate of 150 seeds m^{-2} the crop density was also increased from 37 to 45% as seeding depth decreased from 4 to 1 cm. Even though different seeding depths were not evaluated, it seems as if canola seedlings emerged better when seeding took place at depths shallower than 2 cm. Canola is a smaller seed compared to barley and wheat, which would entail slightly shallower seed placement. Nonetheless, it is not obvious if the amount of soil disturbance, climatic conditions or the seeding depth had a bigger influence on delayed canola emergence.

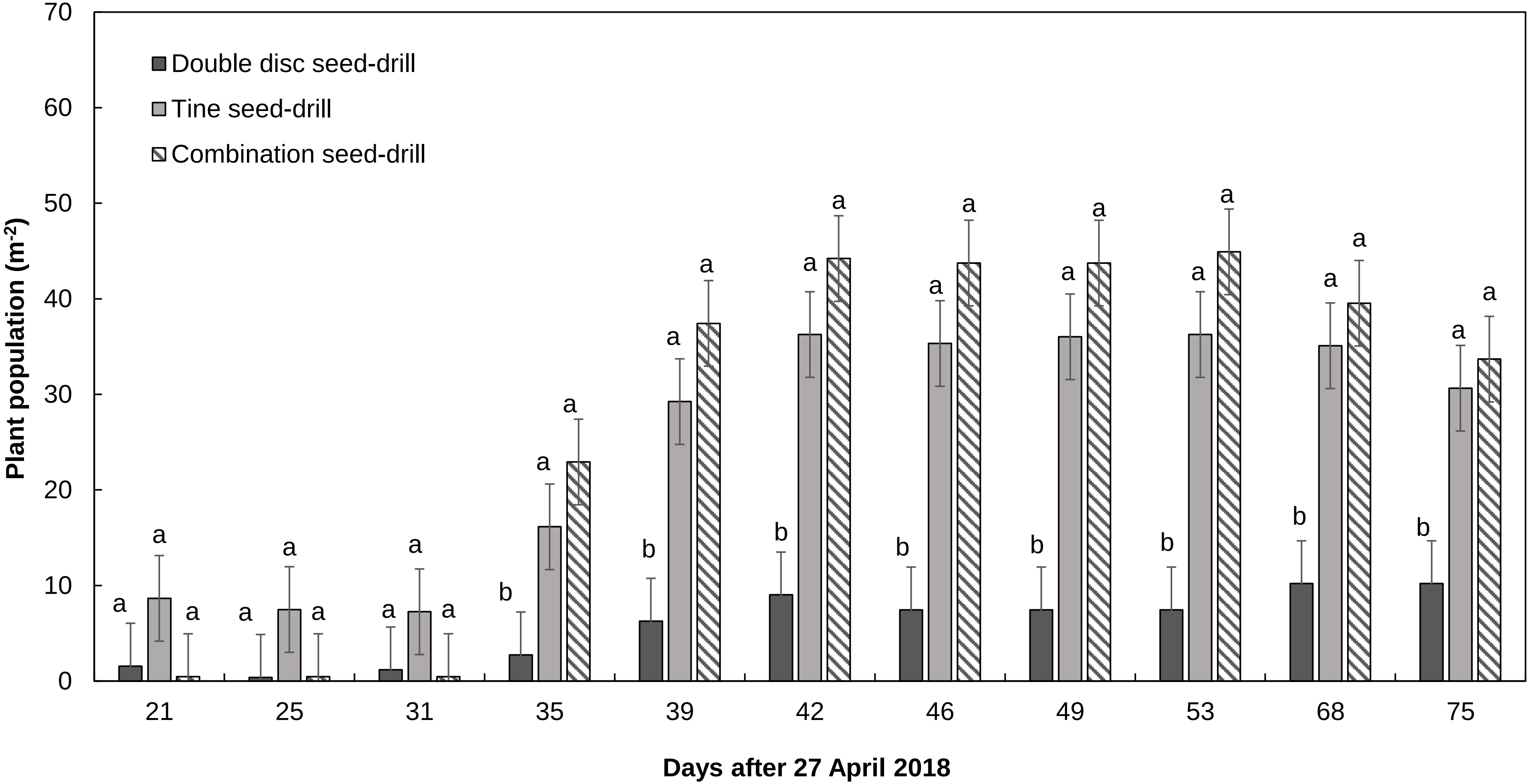

Figure 13. Canola plant populations (m^{-2}) where seeding took place with seed-drills with either double disc openers, tine openers or a combination of tine and single disc openers in 2018. Error bars indicate the SE. No common letter indicates a significant difference at $p = 0.05$.

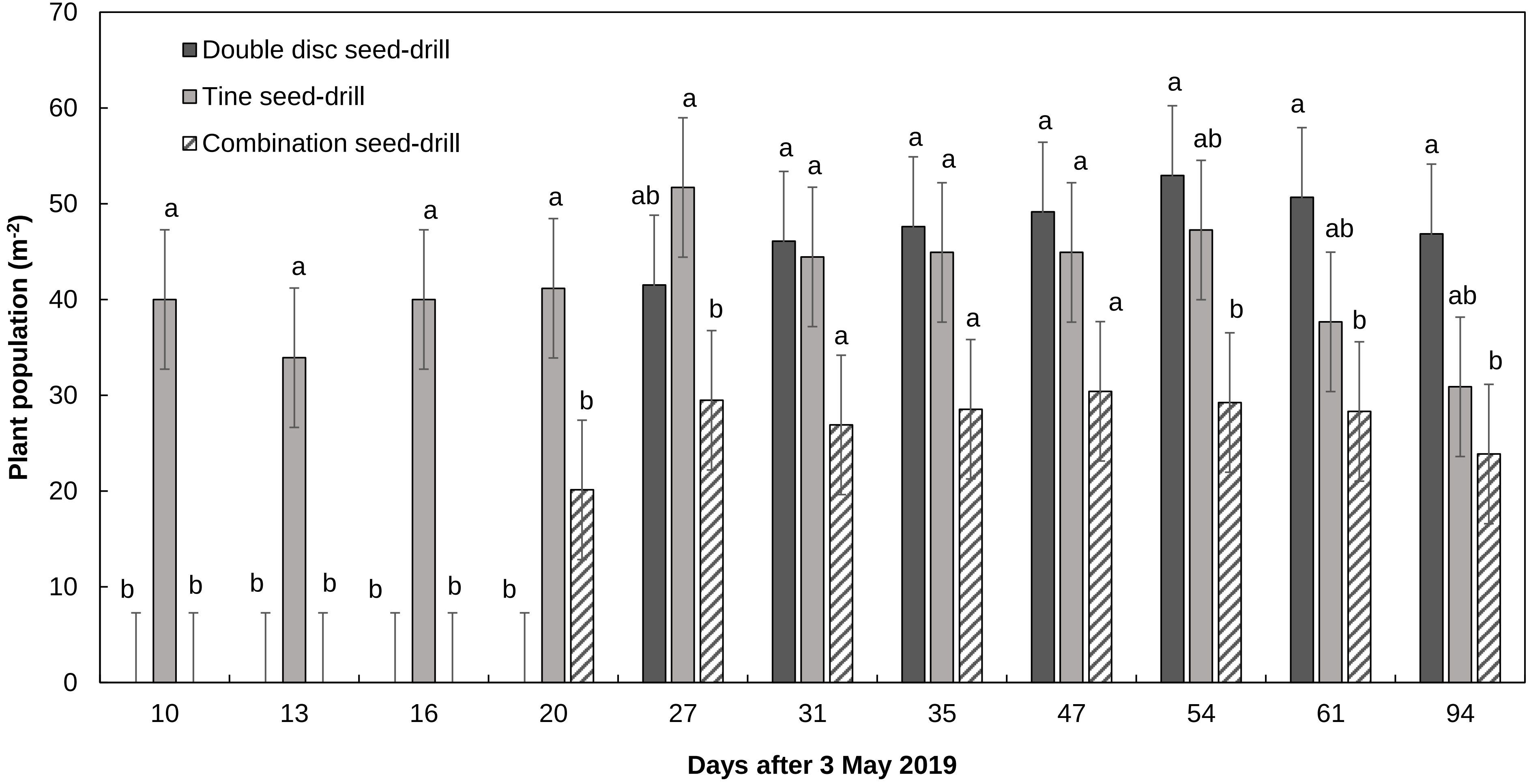

Figure 14. Canola plant population (m^{-2}) where seeding took place with seed-drills with either double disc openers, tine openers or a combination of tine and single disc openers in 2019. Error bars indicate the SE. No common letter indicates a significant difference at p = 0.05.

For successful canola establishment one needs a certain degree of soil disturbance (Piet Lombard, Western Cape Department of Agriculture, personal communication). Swanepoel et al. (2019) evaluated seed-drill openers in terms of canola establishment. Seed-drills with disc openers resulted in lower plant populations compared to tine openers, but overall canola yield was not affected. Similar results were observed in the 2018 data. Soil physical properties, i.e. soil bulk density and gravimetric soil water content, might have influenced canola more than barley and wheat because of the smaller size of the canola seed. Although limited knowledge is available to support this hypothesis, it is known that canola may compensate in crop growth for low plant populations to minimise the influence of low plant populations and seed-drill openers on yield.

6.3.3 Biomass production

6.3.3.1 Barley and wheat

In the 2018 production season, no differences were found in barley biomass production between the seed-drills 30, 60, 90 and 120 days after seeding ($p > 0.05$; Figure 15 A). One hundred and fifty days after seeding, differences in biomass production were found between the tine seed-drill, the double disc- and the combination seed-drills ($p < 0.05$). The double disc seed-drill and the combination seed-drill resulted in higher barley biomass production compared to the tine seed-drill.

No differences were found in wheat biomass production, 30, 60, 90 and 120 days after seeding ($p > 0.05$; Figure 15 B). The double disc seed-drill resulted in higher biomass produced 150 days after seeding, compared to the combination seed-drill ($p < 0.05$), while the tine seed-drill did not differ significantly from either ($p > 0.05$).

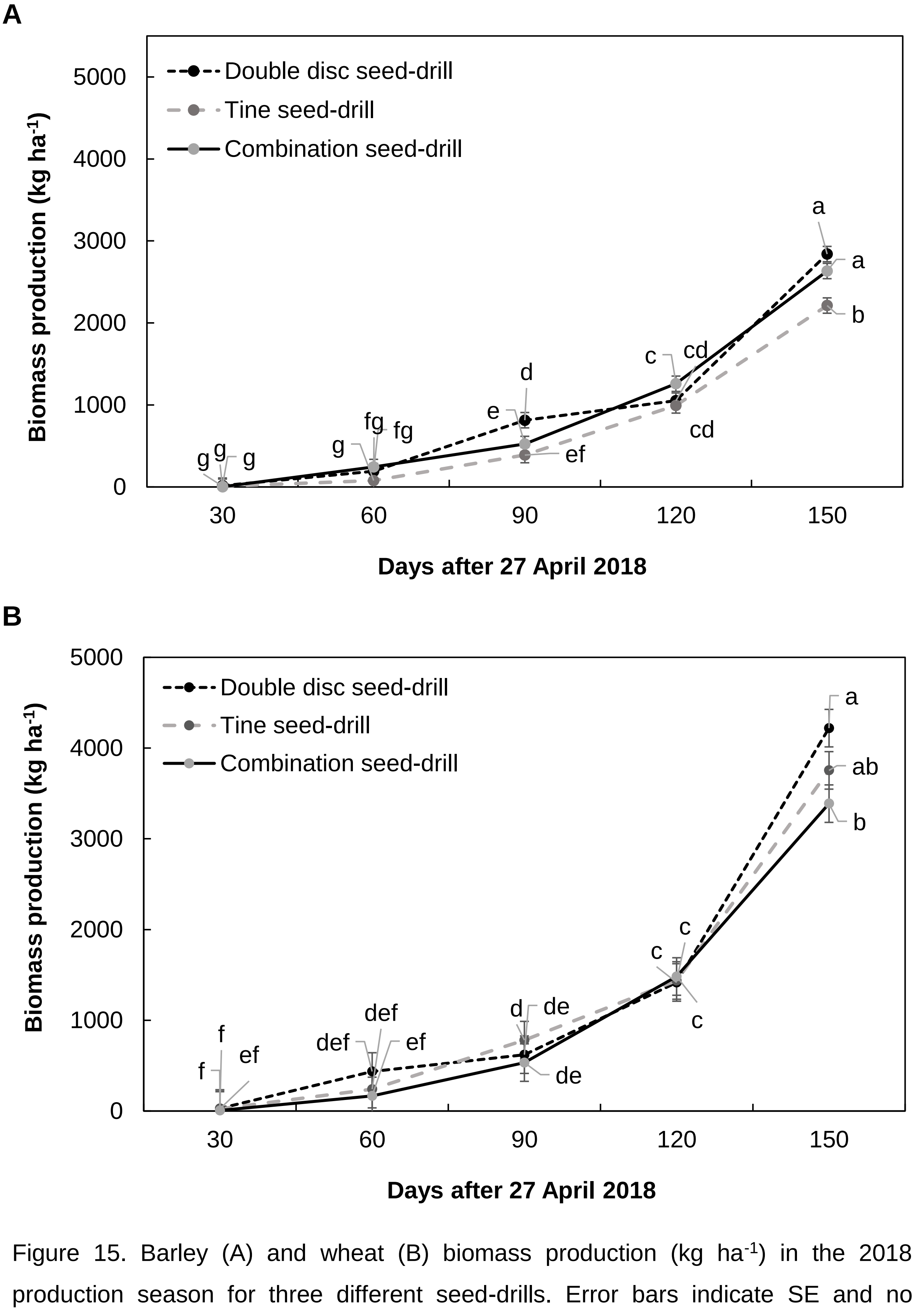

Figure 15. Barley (A) and wheat (B) biomass production (kg ha^{-1}) in the 2018 production season for three different seed-drills. Error bars indicate SE and no common letter indicates significant differences at $p = 0.05$.

Reasons for increased biomass production where the double disc seed-drill were used for seeding purposes are not clear. However, researchers have reported increases in biomass production in various crops in CA systems when compared to conventional production systems. Lalani et al. (2018) reported that CA could improve biomass output as well as yield, even in dry ecological zones. Ali et al. (2016) reported taller wheat plants under zero-tillage compared to conventional tillage. It is unknown if the difference in biomass production by the crops seeded with different seed-drills can be explained through similar occurrences, as noted in different tillage systems, which is exacerbated by contradictory results that have been published. Poor early vegetative growth of wheat is usually observed in no-tillage treatments compared to conventionally cultivated treatments (Chan et al., 1987). However, in most cases the crops under no-tillage reach similar biomass accumulation levels than conventionally tilled treatments (Kitonyo et al., 2018).

In the 2019 production season, no differences in barley biomass were found 30, 60 and 90 days after seeding ($p > 0.05$; Figure 16 A). However, the double disc seed-drill resulted in more barley biomass on the last measuring date at 120 d ($p < 0.05$).

Wheat biomass production increased from the earliest measuring date up to the last measuring date in the 2019 production season, with no differences between the different seed-drills 30, 60 and 90 days after seeding ($p > 0.05$; Figure 16 B). Differences were only found on day 120 after seeding, where the double disc seed-drill resulted in more biomass produced ($p < 0.05$). Both the tine and the combination seed-drills resulted in lower, but comparable, aboveground biomass production.

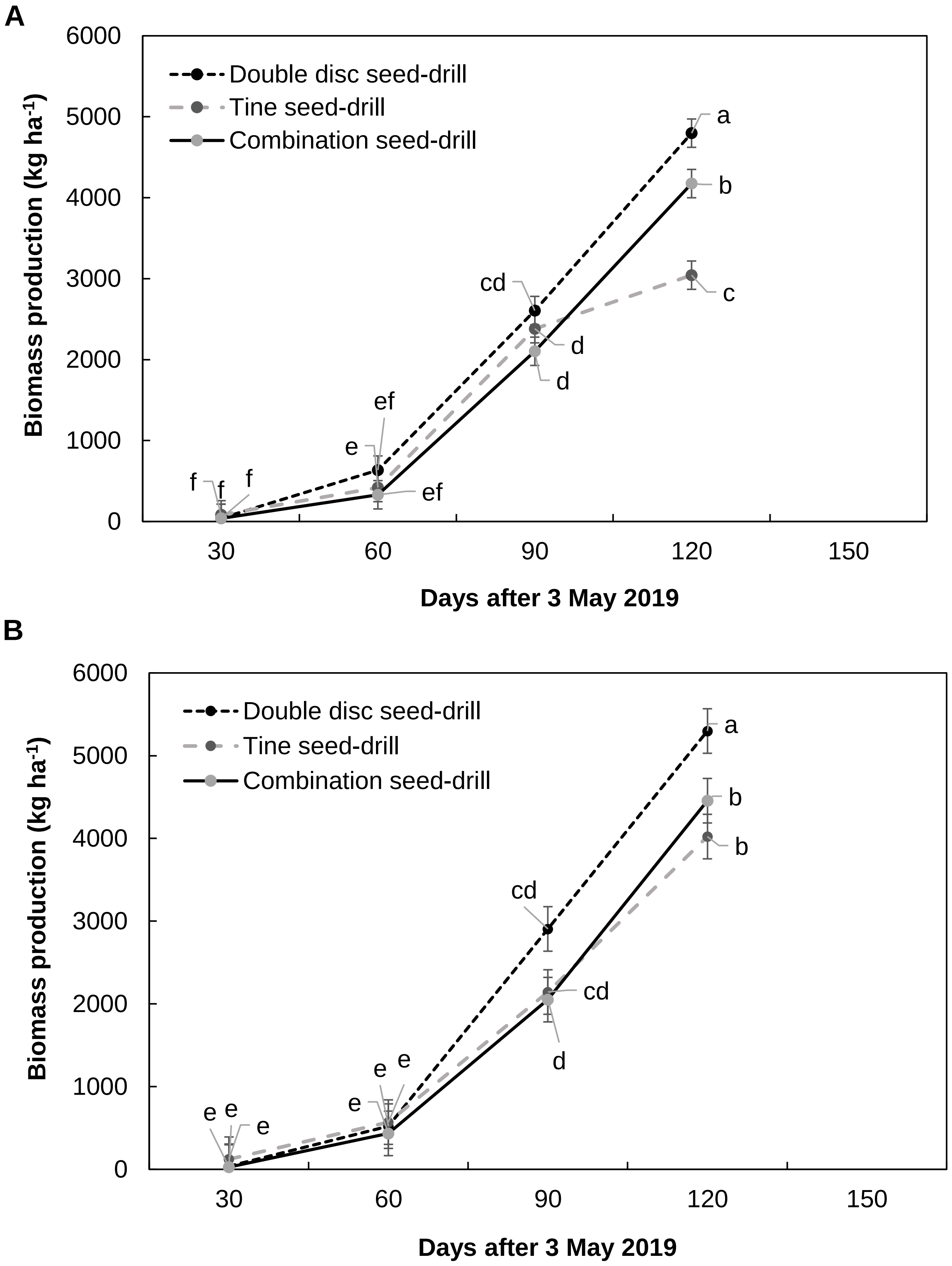

Figure 16. Barley (A) and wheat (B) biomass production (kg ha^{-1}) in the 2019 production season for three different seed-drills. Error bars indicate SE and no common letter indicates significant differences at $p = 0.05$.

6.3.3.2 Canola

In the 2018 production season, canola biomass production was similar up to 120 days after seeding with all three of the utilised seed-drills ($p > 0.05$; Figure 17 A). A treatment effect was found on day 150 after seeding ($p < 0.05$); the double disc seed-drill resulted in a pronounced biomass increase compared to the tine seed-drill and combination seed-drill. In the first production season (2018), canola establishment was not optimal early in the season. Canola seeded with the double disc seed-drill emerged late compared to the tine seed-drill and the combination seed-drill (Figures 13 and 14). Canola plant population was also significantly lower in the 2018 production season where seeding took place with the double disc seed-drill ($p < 0.05$; Figure 14*)*. Canola has the tendency to compensate for open areas in close proximity to the crop (Swanepoel et al., 2019). High canola biomass production might therefore be a result of lower plant populations and compensation in vegetative growth. However, in a recent study canola produced more biomass 30 and 60 days after seeding when a tine seed-drill was used compared to when a disc seed-drill was used (Swanepoel et al. 2019). Nonetheless, due to the ability of canola to compensate in vegetative growth at lower plant populations the disc seed-drill did not disadvantage the overall crop yield.

In the 2019 production season, biomass production increased up to 90 days after seeding, but no differences were found between the different seed-drills on the analysed dates ($p > 0.05$; Figure 17 B). A decrease in biomass production was noticed between day 90 and 120 after seeding ($p < 0.05$). This decrease in canola biomass was probably due to the hot and dry climatic conditions that prevailed during the month of August in 2019.

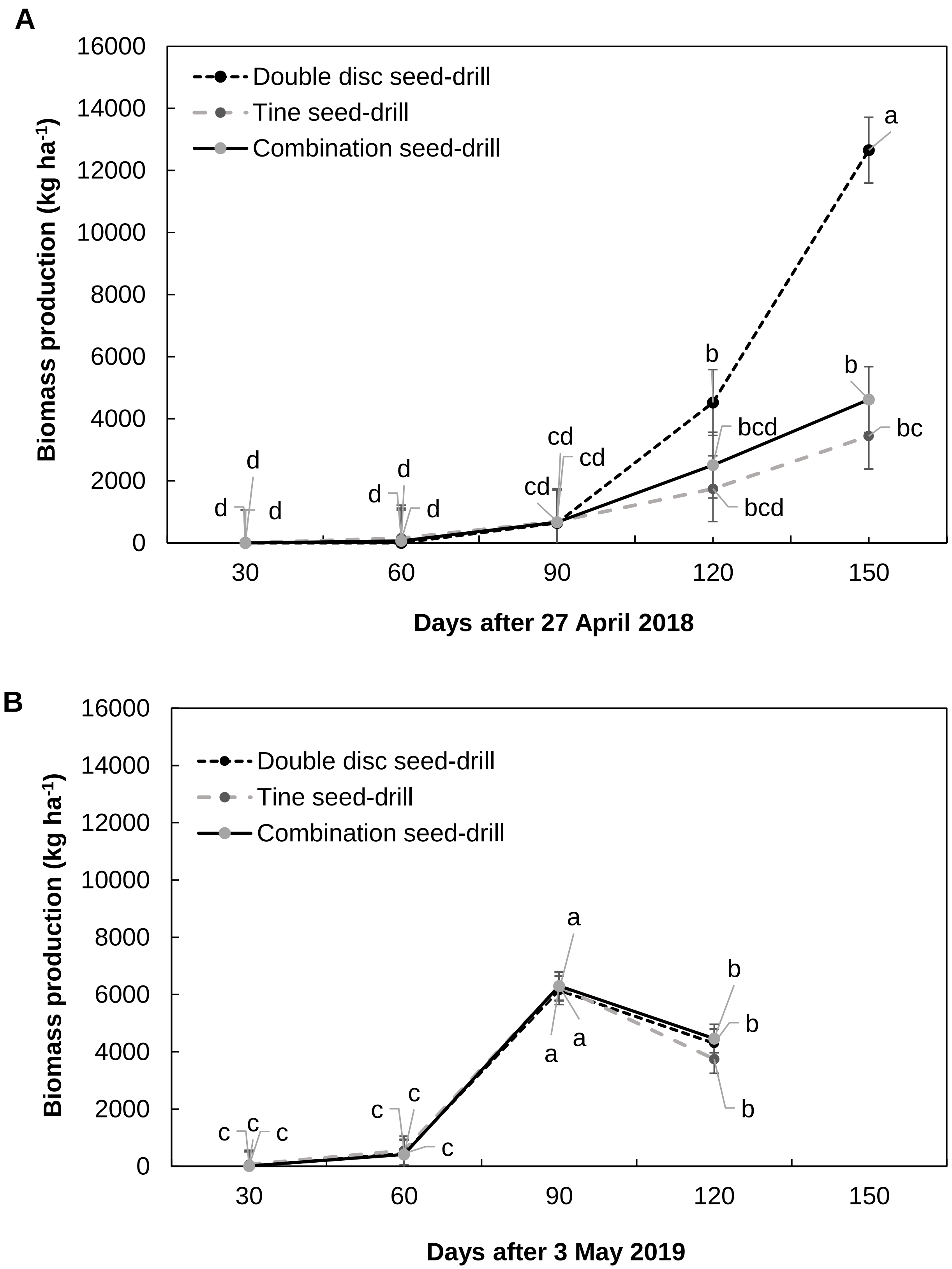

Figure 17. Canola biomass production (kg ha^{-1}) in the 2018 (A) and 2019 (B) production seasons for three different seed-drills. Error bars indicate SE and no common letter indicates significant differences at $p = 0.05$.

6.3.4 Yield

No differences were found in the number of kernels ear^{-1} or the number of ears m^{-2}, in the barley or wheat crops in the 2018 production season when seeding took place with different seed-drills ($p > 0.05$; Table 6). However, the potential barley yield was higher where the double disc seed-drill was used for seeding ($p < 0.05$). The tine seed-drill and the combination seed-drill had similar ($p > 0.05$) potential barley yields. Wheat yield did not differ in the 2018 production season between the different seed-drills ($p > 0.05$).

In the 2019 production season, differences were noted in the barley crop in terms of kernels ear^{-1} and ears m^{-2} depending on the type of seed-drill used during the seeding action ($p < 0.05$; Table 6). The highest amount of kernels ear^{-1} were found where the tine seed-drill was used for seeding, thereafter the double disc seed-drill and combination seed-drill followed. Yield results followed the same trend as it did in the first production season (2018), as barley yielded more in the plots where seeding took place with the double disc seed-drill ($p < 0.05$). Wheat yields did not differ in the second production season (2019) between the tested seed-drills ($p > 0.05$).

Even though seedlings that emerge early contribute more to yield compared to seedlings that emerge later (Gan et al., 1992; Nasr and Selles, 1995), the double disc seed-drill resulted in higher barley yields in both production seasons. It is possible that the increase in yield was due to the increased biomass production (vegetative growth). Production of more biomass per plant may increase the photosynthetic capacity of the plants towards the end of the growing season. However, it is not known if this will be applicable in all years.

Table 6. Kernels ear^{-1}, ears m^{-2} and potential yield (kg ha^{-1}) for barley and wheat at the end of the 2018 and 2019 production seasons. Years were analysed separately. No common letter indicates a significant difference at $p = 0.05$. SE included for each crop.

Year	Crop	Seed-drill	Kernels ear^{-1}	Ears m^{-2}	Potential yield (kg ha^{-1})
2018	**Barley**	Double disc seed-drill	15.03^{a} ± 0.81	302.86^{a} ± 20.52	1643.75^{a} ± 111.19
		Tine seed-drill	13.89^{a} ± 0.81	233.57^{a} ± 20.52	1164.79^{b} ± 111.19
		Combination seed-drill	13.16^{a} ± 0.81	264.44^{a} ± 20.52	1242.53^{b} ± 111.19
	Wheat	Double disc seed-drill	19.26^{a} ± 1.30	188.38^{a} ± 18.51	1316.91^{a} ± 151.32
		Tine seed-drill	18.14^{a} ± 1.30	150.76^{a} ± 18.51	989.55^{a} ± 151.32
		Combination seed-drill	21.87^{a} ± 1.30	181.64^{a} ± 18.51	1407.50^{a} ± 151.32
2019	**Barley**	Double disc seed-drill	18.15^{ab} ± 0.64	379.62^{a} ± 28.84	2467.59^{a} ± 126.55
		Tine seed-drill	19.60^{a} ± 0.64	252.16^{b} ± 28.84	1784.01^{b} ± 126.55
		Combination seed-drill	17.20^{b}± 0.64	235.32^{b} ± 28.84	1443.93^{b} ± 126.55
	Wheat	Double disc seed-drill	16.95^{a} ± 3.35	202.10^{a} ± 17.45	1263.58^{a} ± 226.00
		Tine seed-drill	23.42^{a} ± 3.35	163.39^{a} ± 17.45	1359.34^{a} ± 226.00
		Combination seed-drill	19.89^{a} ± 3.35	179.65^{a} ± 17.45	1264.96^{a} ± 226.00

Even though differences were noted in the barley yield, no difference was seen in the potential wheat yield between the three seed-drills in both production seasons ($p > 0.05$; Table 6*).* In a meta-analysis by Pittelkow et al. (2015) it was concluded that the type of crop was the most important factor influencing the overall yield in response to no-tillage, followed by aridity-index and residue management. Van den Putte et al. (2010) also observed interactions between tillage methods and crop responses. No-tillage affected yield only moderately, but the influence was more pronounced in wheat crops than barley crops (Pittelkow et al., 2015). Therefore, barley- and wheat yields might be due to different crop responses towards varying degrees of soil disturbance at the time of seeding, with seeding methods seemingly influencing barley more than wheat.

Although CA is widely adopted, little consensus exists as to whether yield increases or decreases should be expected (Pittelkow et al., 2015). Yield increases are often noted in dry climatic conditions, while yield decreases are often seen in areas where water is not a limiting factor (Abdullah, 2014; Amato et al., 2013; Michler et al., 2019; Ogle et al., 2012).

6.4 Conclusion

The type of seed-drill opener mounted on the seed-drill performed indifferent on the measured crop performance parameters throughout the growing season. Quantification of specific crop parameters are difficult, since various factors like seeding depth, growth rate, temperature, rainfall and soil physical properties have interacting effects. Positive attributes like constant seeding depth with the tine seed-drill might relate to uniform emergence in certain years. However, more knowledge on seed placement and the correlation with seed germination and seedling emergence is necessary. Furthermore, the influence of seed-drills and its associated soil disturbance were prevalent on the last measuring dates of both production seasons in terms of biomass production. Explanations for the increased biomass production, where seeding took place with less soil disturbance, should be quantified extensively. Yield components did not differ between different seed-drills in the first season, but differences were noted in the second season. The barley crop was affected more pronouncedly than the wheat crop by the type of seed-drill that was used during the seeding operation. Estimated potential yields differed for barley, but not for wheat. The double disc seed-drill resulted in higher barley yields in both years. Whether this outcome is crop specific or if it is related to the amount of soil disturbance that took place during the seeding operation, has to be explored in the long-term. Evidence should be accrued on the influence of seed-drill openers on seedling emergence and biomass production, and the influence thereof on the yield. In this research project, no seed-drill opener can be singled out. The tine seed-drill showed promising results with uniform emergence, while the double disc seed-drill resulted in higher biomass production and yield in some cases. Results may vary over the long-term as seed-drill openers and CA practices mature.

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CHAPTER 7

Conclusions and Recommendations

7.1 Conclusions

To determine the influence of seed-drill choice on soil physical properties and crop performance, three seed-drills were tested on barley, canola and wheat in a semi-arid rain-fed production region of the southern Cape, South Africa. Soil physical properties (i.e. soil bulk density, gravimetric soil water content and unsaturated hydraulic conductivity) and crop performance parameters (i.e. seeding depth, seedling emergence, biomass production and potential yield) were monitored over two growing seasons. Both of the growing seasons received less rainfall during the months April to September compared to the average long-term rainfall of the last thirteen years (approximately 156 mm). The first production season (2018) received 136 mm of rainfall from the date of seeding up to the date of crop termination, compared to 62 mm received during the second production season (2019). Even though the 2018 production season received more rainfall over the course of the season, the amount of rain received at the time of seeding was less than the rainfall received at the beginning of the 2019 production season.

Availability of research information on the influence of different seed-drill openers on crop production is scarce. However, ample research are available on different tillage systems, comparing conventional tillage with different forms of reduced tillage systems (Altikat et al., 2013; Altikat and Celik, 2011; Gozubuyuk et al., 2014; Huang et al., 2015). Research on tillage systems can only motivate producers to convert from conventional tillage systems to CA systems, but it does not supply answers about the seeding operation within these newly adopted CA systems. Earlier research noted differences between different seed-drill openers (Chan et al., 1987; Chaudhry and Baker, 1988; McLeod et al., 1992) and more recently Swanepoel et al. (2017, 2019) also compared seed-drill openers. However, as CA systems improve and seeding equipment are modified, research efforts should be aligned accordingly. This research project managed to demonstrate that within CA systems, different methods of soil disturbance and seed placement could influence soil properties and crop performance significantly over the long-term.

7.1.1 Objective 1: Determine the effect of seed-drills on dynamic soil physical indicators

Soil physical properties were influenced to different extends. Soil bulk density was higher at the start of the first growing season, where seeding took place with the double disc seed-drill that resulted in the least amount of soil disturbance. In the following production season (2019), the tine seed-drill and the double disc seed-drill resulted in similar bulk densities. However, the magnitude of change in the soil bulk density are not expected to limit crop emergence or root growth. A tendency was noted where seeding took place with less soil disturbance that more soil water was conserved. This can be of utmost importance in semi-arid regions where rainfall is a limiting factor for crop production. Especially in regions where rainfall is erratic and unevenly spread over the growing season. Unsaturated hydraulic conductivity was measured only in the first production season and different responses were noted where the three tested seed-drills were used. Moreover, research should be conducted on seed-furrow water movement before any conclusions can be drawn.

7.1.2 Objective 2: Determine the effects of seed-drills on crop performance

The most accurate seeding depth was found where seeding took place with the tine seed-drill. Seed placement in the sidewalls of the seed-furrows and the movement of the press wheel might account for this occurrence. Since seeds are placed in the sidewalls of the seed-furrow instead of the bottom of the seed-furrow, the vertical press action of the press wheel will not influence the placed seeds. In the second production season (2019) with more rainfall at the beginning of the season, the tine seed-drill resulted in early and uniform seedling emergence. It is not known if the earlier and uniform emergence is related to the accuracy of seeding depth, slight increase in soil disturbance with the tine opener or the prevailing weather conditions. In the first production season (2018), where less rainfall was received at the beginning of the season, non-uniform emergence was observed no matter the seeding depth or the type of seed-drill used. Supplementary research is necessary to improve uniform emergence and establishment of crops in CA systems where seeding take place with less soil disturbance. Generally, it is believed that earlier emergence will lead to higher-yielding crops. However, in seasons where climatic conditions are initially not favourable for crop growth, it will be more beneficial to have seedlings that emerge slightly later, yet uniform. More attention should be given towards optimal seeding depths depending on the prevailing climatic conditions and the soil water content at the time of seeding. From the two production seasons it can be concluded that placement of barley and wheat can be deeper (> 2.5 cm) than canola (≤ 2.0 cm), especially in drier seasons from the onset.

Biomass production of barley, canola and wheat was influenced according to the degree of soil disturbance. A tendency was noted that less soil disturbance, led to higher vegetative biomass produced by the end of the growing season. Whether this occurrence is merely related to the degree of soil disturbance at the time of seeding or the crop architecture because of different plant populations, is not known. Nonetheless, increased biomass production can influence the photosynthetic rate of the crop, which might lead to yield increases in favourable seasons. Barley yield was influenced in both years by the type of seed-drill opener that was used during the seeding operation, with the double disc seed-drill yielding more than the tine seed-drill and the combination seed-drill. Unfortunately, no conclusions can be drawn about canola yields since canola was not harvested in any of the seasons.

7.2 General conclusions

Even though no seed-drill can be singled out after two seasons, the double disc seed-drill showed promising results in terms of increased barley yield. If this increase will be noted in all seasons over the long-term, cannot be confirmed. The tine seed-drill had very accurate seed placement, which is beneficial for uniform seedling emergence especially in seasons where the seeding operation take place in moist soils. Soil physical properties that was positively influenced by less soil disturbance included the gravimetric soil water content of the seed-furrows. A tendency was noted that less soil disturbance (i.e. double disc seed-drill) conserved slightly more soil water in the seed-furrows compared to seed-drills that cause more soil disturbance during the seeding operation. With the changes in climatic conditions and rainfall patterns, the importance of soil water conservation in CA systems will increase. Ideally, producers should own both types of seed-drills and adapt according to either the crop seeded or the prevailing conditions at the start of the growing season. Soil type on different camps should also be considered in terms of the amount of soil disturbance that is necessary during the seeding operation.

The type of seed-drill opener that a producer decide to use during the seeding operation will influenced the soil physical properties, emergence rate and growth of the crop in different ways, mainly related to the prevailing climatic conditions. Accurate seed placement, uniform emergence and increased biomass production in direct seeding practices must be aimed for to ultimately contribute to higher-yielding crops over the long-term. Knowledge on direct seeding equipment should be increased to optimise the effectiveness of seeding practices and crop productivity in CA systems in semi-arid rain-fed production regions of South Africa.

7.3 Recommendations

Formal guidelines should be available for research within CA systems. Conservation agriculture is a very broad term and not all systems are managed similarly. Even if research projects comply with all three CA principles, differences in soil disturbance because of equipment do occur. Researchers must be able to classify the degree of soil disturbance that take place with the seeding implement and the residue levels on the soil at the time of seeding, in a universally acceptable method.

In this research project, seed-drills from two different manufactures were compared. However, it will probably be more significant to compare different types of openers with each other instead of the whole seed-drill. If different seed-drill openers can be mounted on a comparable frame, it might eliminate the influence of specific seed-drill properties, like weight and width, for research purposes.

This research project should be conducted in different growing regions, to minimise the effect of climate and soil type. Even though there will be variation within regions, repetition of similar trials will result in more reliable results. Producers in the Swartland-region and the rest of the southern Cape will most likely not benefit from this research since their growing conditions and soils are different from the Napky region.

Even though different seeding depths were not tested, the interaction of the seeding depth and crop emergence was prominent in both seasons. Seeding depth trials should be conducted to determine optimal depth of seed placement for barley, canola and wheat in CA systems. Trials like this should be distributed over the Western Cape to include the influence of climatic conditions and soil type.

7.4 Limitations

Results of this trial is primarily bound to the Napky region since climatic conditions and physical soil properties had an influence on the outcome of the trial. Outcomes should therefore extrapolated to other cereal production regions within the Western Cape and/or South Africa with caution.

Very low rainfall, i.e. lower than usual, influenced the growth of the crops significantly. Even though the project focussed on a semi-arid rain-fed production region, different outcomes could possibly be expected if climatic conditions were more in the optimal range. With the prevailing drought, economic feasibility of crop production should be considered before direct seeding takes place. Possible alternatives could include production of forage for animal feed. Even though potential yields were estimated for barley and wheat, no actual yields were determined during the trial because of the drought. This is a limitation because producers are interested in the yields that they would achieve with the different seed-drills. Different results might be evident between the three seed-drills if yields were determined with a combine harvester.

A major limitation in the soil physical measurements was the high stone content of the soil. Deeper measurements with shallower intervals should give better and more reliable results in terms of the soil bulk density and gravimetric soil water content. In this research project this determinations were only conducted up to a depth of 100 mm, in a single interval, because of the inability to remove an undisturbed soil sample in the field.

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Appendix A

Table 7. Daily rainfall, average temperature and minimum and maximum temperatures for April to September in the 2018 production season, as measured at the experimental site.

Date (2018)	Average temperature ˚C	Minimum temperature ˚C	Maximum temperature ˚C	Rainfall mm
1 April	21.55	28.36	17.89	0.00
2 April	20.89	24.78	17.75	0.00
3 April	20.05	24.64	16.11	0.00
4 April	20.61	23.42	18.67	0.00
5 April	21.25	29.64	17.67	0.00
6 April	18.05	22.73	12.90	0.00
7 April	16.85	23.35	12.15	0.00
8 April	18.17	24.40	13.29	0.00
9 April	20.70	30.91	13.27	0.00
10 April	18.21	21.43	15.62	0.30
11 April	17.37	23.03	12.57	0.00
12 April	20.03	30.84	12.91	0.00
13 April	19.10	23.56	15.74	0.00
14 April	18.74	24.38	14.85	0.00
15 April	18.00	24.74	13.40	0.30
16 April	21.51	30.26	16.47	0.00
17 April	20.13	28.58	14.70	0.00
18 April	17.42	25.36	12.52	0.90
19 April	15.79	21.52	11.32	0.00
20 April	15.20	23.83	8.44	0.00
21 April	16.74	26.73	11.65	0.00
22 April	16.47	27.70	10.22	0.30
23 April	19.92	31.07	11.41	0.80
24 April	17.82	23.75	14.20	0.00
25 April	17.96	26.06	11.85	0.00
26 April	16.69	21.51	11.93	2.60
27 April	18.95	12.70	25.20	0.00
28 April	14.95	11.00	18.90	2.20
29 April	15.55	8.80	22.30	0.00
30 April	16.05	6.80	25.30	0.30
01 May	19.80	7.60	32.00	0.30
02 May	18.50	12.00	25.00	0.30
03 May	17.25	13.20	21.30	0.30
04 May	19.25	11.10	27.40	0.00
05 May	20.20	7.80	32.60	0.00
06 May	18.25	10.70	25.80	0.30
07 May	25.70	15.60	35.80	0.00
08 May	18.50	14.90	22.10	0.00

09 May	15.85	10.30	21.40	0.00
10 May	14.85	6.40	23.30	0.00
11 May	16.40	11.40	21.40	0.00
12 May	16.65	11.20	22.10	0.00
13 May	15.90	11.60	20.20	0.30
14 May	16.65	10.90	22.40	0.00
15 May	17.15	10.00	24.30	0.60
16 May	19.10	8.60	29.60	0.30
17 May	17.70	10.70	24.70	0.00
18 May	21.75	16.80	26.70	0.00
19 May	20.15	10.20	30.10	0.00
20 May	20.05	16.60	23.50	0.00
21 May	20.15	16.60	23.70	0.00
22 May	19.40	16.50	22.30	0.00
23 May	21.25	16.60	25.90	0.00
24 May	16.20	13.70	18.70	2.50
25 May	13.60	10.60	16.60	1.90
26 May	16.00	11.50	20.50	0.30
27 May	15.80	8.90	22.70	0.60
28 May	16.40	10.90	21.90	0.00
29 May	14.85	10.80	18.90	1.90
30 May	13.50	7.70	19.30	0.30
31 May	16.40	11.60	21.20	0.00
01 June	13.15	8.60	17.70	4.20
02 June	14.25	7.30	21.20	1.80
03 June	11.65	7.90	15.40	3.70
04 June	11.25	4.30	18.20	0.30
05 June	13.60	5.60	21.60	0.30
06 June	18.05	6.90	29.20	0.30
07 June	15.90	9.80	22.00	0.00
08 June	17.40	12.90	21.90	0.00
09 June	15.90	11.40	20.40	0.30
10 June	13.10	8.90	17.30	0.00
11 June	13.50	5.90	21.10	0.30
12 June	17.35	5.80	28.90	0.60
13 June	21.25	12.00	30.50	0.00
14 June	16.60	13.40	19.80	2.10
15 June	14.70	11.60	17.80	0.30
16 June	13.70	9.20	18.20	0.00
17 June	16.35	8.60	24.10	0.50
18 June	15.10	11.30	18.90	0.00
19 June	15.40	10.70	20.10	0.00
20 June	15.20	9.80	20.60	0.00
21 June	13.75	4.80	22.70	0.00
22 June	14.35	7.60	21.10	0.00
23 June	14.60	8.20	21.00	0.00

24 June	13.40	7.70	19.10	0.00
25 June	13.90	9.50	18.30	0.00
26 June	15.20	7.60	22.80	0.30
27 June	12.25	8.50	16.00	4.20
28 June	10.75	4.80	16.70	0.00
29 June	11.90	7.00	16.80	1.40
30 June	15.40	10.30	20.50	2.10
01 July	15.40	9.00	21.80	7.10
02 July	8.30	6.50	10.10	14.00
03 July	10.30	5.20	15.40	0.00
04 July	11.60	5.00	18.20	0.00
05 July	11.95	4.80	19.10	0.30
06 July	15.00	6.00	24.00	0.60
07 July	14.55	4.60	24.50	0.30
08 July	14.10	5.20	23.00	0.00
09 July	16.40	6.60	26.20	0.00
10 July	15.45	9.40	21.50	0.00
11 July	16.75	7.50	26.00	0.90
12 July	17.75	14.80	20.70	0.00
13 July	12.20	7.60	16.80	0.00
14 July	10.45	6.60	14.30	1.30
15 July	10.70	3.90	17.50	0.30
16 July	11.60	7.70	15.50	0.00
17 July	16.20	7.90	24.50	0.00
18 July	19.20	10.80	27.60	0.00
19 July	19.20	11.50	26.90	0.30
20 July	18.80	11.70	25.90	0.00
21 July	13.95	9.50	18.40	0.30
22 July	19.05	8.50	29.60	0.60
23 July	21.20	11.70	30.70	0.00
24 July	15.95	10.40	21.50	0.00
25 July	14.95	11.70	18.20	0.00
26 July	18.80	13.70	23.90	0.00
27 July	13.35	10.30	16.40	1.70
28 July	14.40	9.50	19.30	0.00
29 July	12.60	7.40	17.80	0.30
30 July	11.85	3.60	20.10	0.00
31 July	13.60	6.80	20.40	0.00
01 August	14.70	9.50	19.90	0.00
02 August	12.80	5.40	20.20	0.00
03 August	14.15	9.80	18.50	0.60
04 August	12.75	8.70	16.80	0.00
05 August	13.25	6.40	20.10	0.60
06 August	14.45	9.00	19.90	3.00
07 August	9.85	6.80	12.90	3.40
08 August	8.75	3.00	14.50	0.30

09 August	9.40	2.70	16.10	0.30
10 August	11.25	7.00	15.50	0.80
11 August	11.70	2.90	20.50	0.60
12 August	13.05	6.40	19.70	0.00
13 August	13.20	10.60	15.80	0.90
14 August	11.70	6.20	17.20	0.00
15 August	11.50	4.90	18.10	0.00
16 August	11.45	2.80	20.10	1.70
17 August	9.90	5.10	14.70	2.10
18 August	10.75	1.00	20.50	0.00
19 August	11.65	3.30	20.00	0.80
20 August	11.30	9.70	12.90	4.70
21 August	11.25	5.40	17.10	0.30
22 August	12.85	6.90	18.80	0.00
23 August	13.30	7.80	18.80	0.00
24 August	13.85	4.30	23.40	0.30
25 August	13.20	5.60	20.80	2.40
26 August	8.90	6.60	11.20	5.00
27 August	11.35	7.00	15.70	0.00
28 August	14.45	9.60	19.30	0.00
29 August	14.50	9.90	19.10	0.00
30 August	17.30	13.10	21.50	0.00
31 August	17.70	13.00	22.40	0.30
01 September	16.10	10.50	21.70	0.00
02 September	12.50	10.40	14.60	7.40
03 September	16.40	11.20	21.60	0.00
04 September	15.75	9.20	22.30	0.30
05 September	11.10	13.17	7.05	5.80
6 September	8.79	13.26	4.53	2.10
7 September	9.53	11.90	8.03	10.10
8 September	10.89	14.66	8.05	1.90
9 September	11.11	18.13	4.82	0.00
10 September	12.71	22.87	4.61	0.30
11 September	13.85	23.09	7.61	0.30
12 September	14.57	20.93	8.47	0.30
13 September	15.02	21.37	10.20	0.00
14 September	15.02	21.07	10.34	0.00
15 September	13.51	17.94	10.72	0.00
16 September	14.90	24.03	8.72	0.00
17 September	16.00	22.55	10.98	0.00
18 September	13.87	16.55	11.65	2.60
19 September	9.43	12.11	5.78	9.40
20 September	9.66	17.83	2.13	0.30
21 September	12.70	19.80	6.87	0.00
22 September	12.56	20.74	5.81	0.00
23 September	12.88	20.89	6.03	0.30

24 September	15.76	28.18	8.40	0.00
25 September	16.84	23.45	11.73	0.30
26 September	17.69	24.33	10.68	0.00
27 September	19.41	26.60	14.44	0.00
28 September	15.89	20.56	10.71	3.40
29 September	15.39	20.97	10.39	0.00
30 September	19.90	36.05	9.40	0.00

Table 8. Daily rainfall, average daily temperature and minimum and maximum temperatures for April to September in the 2019 production season as measured at the experimental site.

Date (2019)	Average temperature °C	Maximum temperature °C	Minimum temperature °C	Rain mm
1 April	15.88	20.05	12.02	0.30
2 April	16.86	22.38	11.24	0.00
3 April	1892	28.68	14.24	0.00
4 April	16.67	19.76	13.67	2.90
5 April	15.34	20.16	11.74	0.00
6 April	17.37	24.64	11.90	0.00
7 April	19.76	26.70	15.53	0.00
8 April	20.07	26.32	16.12	0.00
9 April	20.13	26.71	16.68	0.00
10 April	22.59	32.62	16.93	0.00
11 April	18.87	26.05	15.64	0.30
12 April	20.19	25.30	17.39	0.00
13 April	18.43	23.63	14.94	2.40
14 April	14.03	18.87	11.25	2.40
15 April	14.42	17.27	12.01	2.10
16 April	14.20	17.21	10.69	1.10
17 April	15.63	19.62	12.44	0.00
18 April	15.75	23.72	8.91	0.30
19 April	18.67	29.00	11.71	0.30
20 April	17.25	21.98	12.77	0.00
21 April	16.48	21.03	12.57	0.60
22 April	17.40	20.43	14.72	0.50
23 April	17.09	17.96	16.24	3.00
24 April	18.11	22.15	15.69	1.90
25 April	18.35	26.15	15.22	0.60
26 April	16.62	20.98	12.27	0.30
27 April	16.38	22.81	12.13	0.30
28 April	18.90	31.08	13.95	0.60
29 April	16.09	25.70	11.68	0.60

30 April	18.69	23.67	14.69	0.00
1 May	18.45	23.81	14.24	0.00
2 May	19.36	29.96	10.60	0.30
3 May	17.95	22.02	13.82	0.00
4 May	14.90	18.92	11.59	0.00
5 May	16.10	22.51	11.50	0.00
6 May	18.90	29.34	14.16	0.00
7 May	15.74	22.44	10.49	0.30
8 May	17.22	22.43	12.11	0.00
9 May	16.92	23.46	13.02	0.00
10 May	16.75	28.70	8.92	0.30
11 May	16.09	24.38	8.66	0.00
12 May	15.63	23.60	8.71	0.00
13 May	16.41	22.00	12.05	0.60
14 May	20.06	27.33	15.79	0.00
15 May	17.17	21.75	12.57	0.00
16 May	15.05	20.82	10.21	0.00
17 May	17.41	24.56	14.35	0.00
18 May	15.94	23.34	10.89	0.00
19 May	15.92	24.80	8.79	0.30
20 May	14.58	18.93	9.42	7.90
21 May	13.99	20.30	8.80	0.00
22 May	13.67	21.23	6.54	0.00
23 May	14.15	20.70	9.81	0.30
24 May	12.64	20.06	7.74	0.60
25 May	16.14	24.00	12.12	0.00
26 May	20.58	29.35	12.53	0.00
27 May	15.66	18.36	12.98	3.90
28 May	14.13	17.13	12.28	0.00
29 May	15.93	23.79	11.05	0.00
30 May	16.18	23.46	11.53	0.00
31 May	13.05	18.49	8.42	0.30
1 June	13.18	20.44	7.94	0.60
2 June	14.97	20.29	11.92	0.00
3 June	15.44	23.32	10.54	0.00
4 June	14.50	18.21	11.84	9.30
5 June	13.89	16.97	11.51	1.80
6 June	10.68	14.62	5.61	1.40
7 June	12.16	21.34	2.81	0.30
8 June	14.43	18.75	11.86	1.70
9 June	18.19	29.97	8.05	0.00
10 June	15.75	20.34	10.65	0.00
11 June	14.70	25.78	6.47	0.30
12 June	13.51	15.98	8.21	0.00
13 June	9.69	16.12	4.53	0.00

14 June	9.52	20.09	1.91	0.00
15 June	9.99	20.72	2.24	0.30
16 June	11.40	25.67	3.28	0.60
17 June	10.90	19.75	4.34	0.00
18 June	11.87	23.31	4.78	0.60
19 June	15.05	27.85	7.93	0.00
20 June	14.30	26.15	6.84	0.00
21 June	17.75	24.86	10.96	0.00
22 June	14.90	17.84	13.17	1.80
23 June	13.79	19.18	10.07	0.30
24 June	12.15	16.93	8.58	1.60
25 June	13.40	14.57	12.21	6.90
26 June	13.90	18.13	9.99	0.00
27 June	13.66	22.28	6.12	0.90
28 June	13.38	17.03	10.61	1.90
29 June	14.15	19.59	9.39	0.00
30 June	13.17	20.24	6.91	0.00
1 July	12.70	15.96	9.14	2.70
2 July	15.32	19.35	10.31	0.00
3 July	15.86	21.39	10.94	0.00
4 July	13.82	20.99	8.03	1.40
5 July	12.73	17.69	8.78	0.30
6 July	14.09	20.10	7.74	0.30
7 July	14.08	17.46	9.90	1.10
8 July	15.30	21.47	9.94	0.00
9 July	13.74	21.26	8.74	0.00
10 July	13.66	19.77	8.96	0.30
11 July	12.01	18.47	5.59	0.60
12 July	14.06	16.60	12.32	0.30
13 July	14.36	19.75	10.74	0.00
14 July	12.56	19.63	6.64	0.90
15 July	11.49	19.78	6.78	0.60
16 July	11.33	22.20	4.31	0.60
17 July	14.11	23.16	5.46	0.60
18 July	18.57	23.23	15.67	0.00
19 July	12.36	16.75	8.02	0.90
20 July	8.66	12.58	5.81	0.00
21 July	10.26	21.60	3.77	0.00
22 July	14.02	21.94	4.51	0.00
23 July	13.03	15.91	9.33	11.80
24 July	12.72	17.51	9.26	2.10
25 July	14.57	20.68	11.07	0.00
26 July	14.16	19.95	10.39	0.00
27 July	11.70	20.32	6.12	0.90

28 July	11.61	14.95	9.20	0.60
29 July	13.46	17.27	11.68	0.00
30 July	15.70	19.12	10.70	0.00
31 July	12.66	17.80	9.68	1.80
1 August	12.04	18.56	7.13	0.60
2 August	13.30	18.72	9.18	0.00
3 August	11.83	20.05	4.89	0.60
4 August	13.23	22.53	7.18	0.90
5 August	15.64	20.62	9.80	0.00
6 August	16.83	23.10	10.87	0.00
7 August	11.60	21.25	4.35	0.60
8 August	11.21	16.58	7.15	0.00
9 August	13.05	20.39	7.54	0.00
10 August	11.29	21.58	3.30	0.00
11 August	14.50	19.94	9.02	0.00
12 August	13.15	18.51	8.71	0.00
13 August	12.51	21.27	3.70	0.00
14 August	14.70	20.15	10.29	0.00
15 August	12.55	25.49	5.37	0.60
16 August	14.12	19.55	8.28	0.30
17 August	15.51	19.31	13.28	0.90
18 August	16.40	27.36	9.77	0.30
19 August	14.00	18.92	9.04	0.00
20 August	11.55	20.97	4.24	0.00
21 August	14.57	29.27	6.40	0.30
22 August	14.53	25.64	6.72	0.30
23 August	14.89	23.31	9.72	0.00
24 August	16.15	29.74	6.52	0.60
25 August	14.74	23.65	8.18	0.30
26 August	13.90	18.39	8.85	0.00
27 August	11.31	15.73	7.58	0.80
28 August	10.78	17.25	5.64	0.00
29 August	10.12	18.04	2.38	0.00
30 August	12.58	19.10	6.21	1.00
31 August	12.86	18.30	8.82	1.30
1 September	14.81	24.18	7.93	0.00
2 September	13.95	21.82	8.74	0.00
3 September	13.22	23.31	6.75	0.60
4 September	14.05	18.59	10.39	0.00
5 September	14.29	18.36	11.60	0.00
6 September	15.99	26.00	9.92	0.00
7 September	21.31	36.30	7.31	0.30
8 September	23.17	38.16	13.38	0.00
9 September	17.68	23.96	13.30	0.00

10 September	17.23	23.99	13.84	0.00
11 September	17.77	23.33	14.06	0.00
12 September	14.88	17.76	11.22	3.30
13 September	13.27	18.06	9.61	2.20
14 September	13.89	22.45	6.32	0.00
15 September	16.51	25.66	10.73	0.00
16 September	16.59	26.20	9.04	0.00
17 September	16.84	26.57	9.69	0.30
18 September	17.79	24.64	12.37	0.30
19 September	21.15	25.64	18.20	0.00
20 September	20.10	26.92	14.53	0.00
21 September	15.33	23.44	8.59	0.60
22 September	13.74	16.83	11.43	1.60
23 September	13.96	21.48	7.36	0.00
24 September	13.60	19.37	7.30	0.00
25 September	17.56	27.02	10.48	0.00
26 September	21.65	37.54	7.78	0.30
27 September	20.73	35.40	12.56	0.00
28 September	19.15	22.42	17.84	0.00
29 September	15.76	17.99	11.89	13.00
30 September	14.95	19.28	11.48	0.00

Appendix B

Figure 18. Illustration of the amount of stones on the soil surface at the time of the seeding operation on 3 May 2019.

Appendix C

2018 production season:

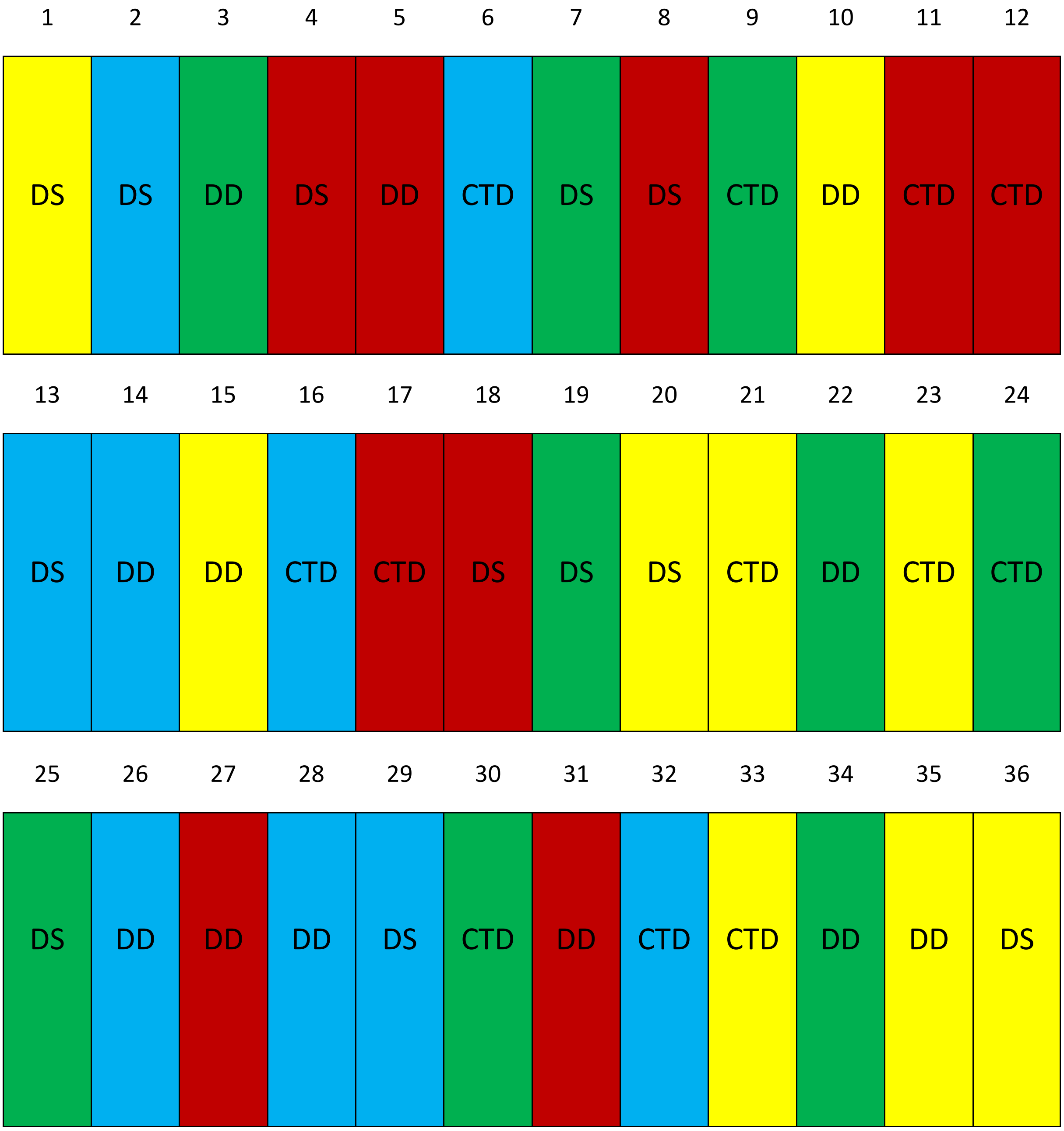
Key

DS: Tine seed-drill

DD: Double disc seed-drill

CTD: Combination seed-drill

🟨	🟩	🟦	🟥
Canola	Wheat	Barley	Cover crop



1	2	3	4	5	6	7	8	9	10	11	12
🟨 DS	🟦 DS	🟩 DD	🟥 DS	🟥 DD	🟦 CTD	🟩 DS	🟥 DS	🟩 CTD	🟨 DD	🟥 CTD	🟥 CTD
13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
🟦 DS	🟦 DD	🟨 DD	🟦 CTD	🟥 CTD	🟥 DS	🟩 DS	🟨 DS	🟨 CTD	🟩 DD	🟨 CTD	🟩 CTD
25	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
🟩 DS	🟦 DD	🟥 DD	🟦 DD	🟦 DS	🟩 CTD	🟥 DD	🟦 CTD	🟨 CTD	🟩 DD	🟨 DD	🟨 DS

2019 production season:

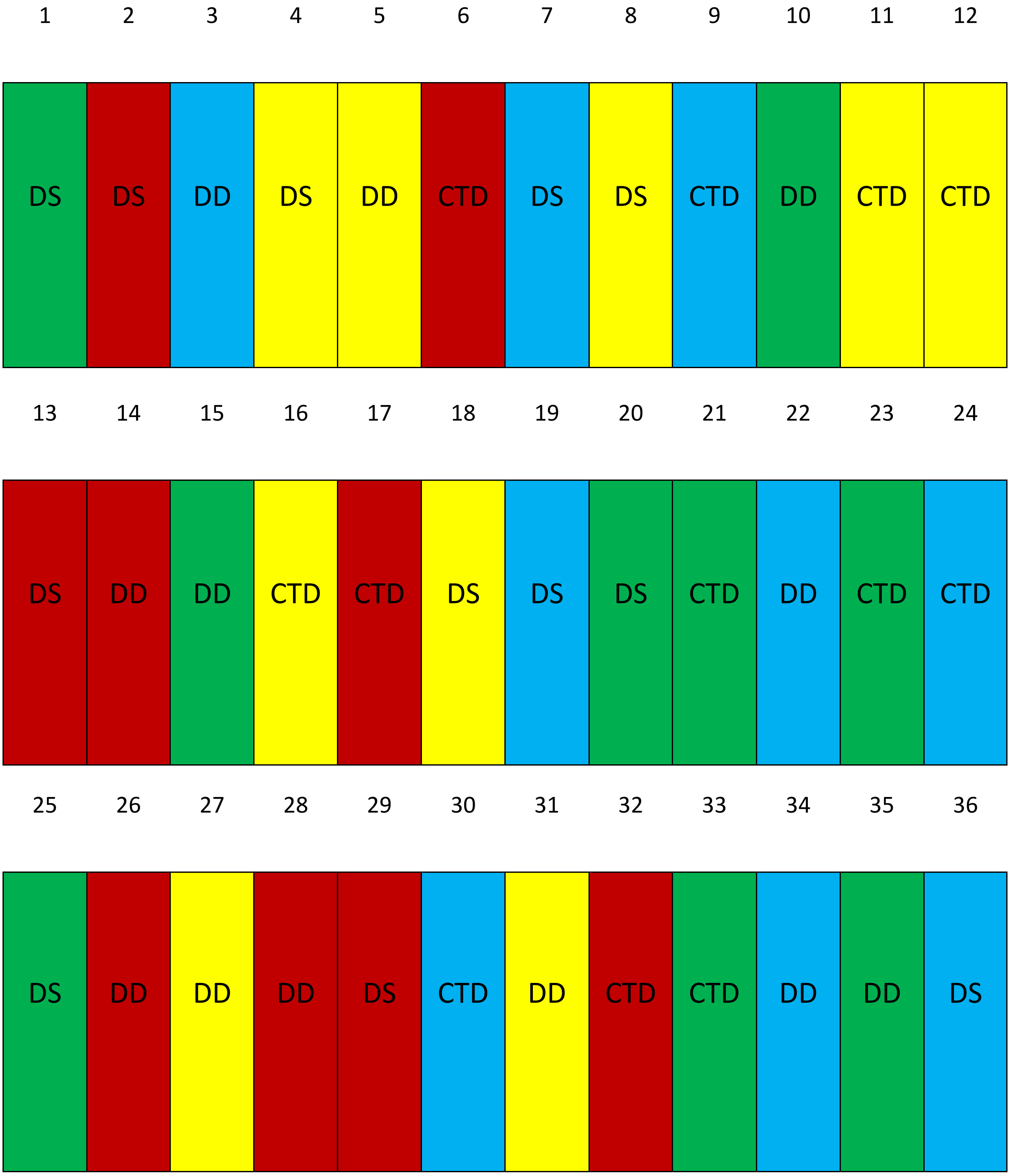
Key

DS: Tine seed-drill

DD: Double disc seed-drill

CTD: Combination seed-drill

🟨	🟩	🟦	🟥
Canola	**Wheat**	**Barley**	**Cover crop**



1	2	3	4	5	6	7	8	9	10	11	12
🟩 DS	🟥 DS	🟦 DD	🟨 DS	🟨 DD	🟥 CTD	🟦 DS	🟨 DS	🟦 CTD	🟩 DD	🟨 CTD	🟨 CTD

13	14	15	16	17	18	19	20	21	22	23	24
🟥 DS	🟥 DD	🟩 DD	🟨 CTD	🟥 CTD	🟨 DS	🟦 DS	🟩 DS	🟩 CTD	🟦 DD	🟩 CTD	🟦 CTD

25	26	27	28	29	30	31	32	33	34	35	36
🟩 DS	🟥 DD	🟨 DD	🟥 DD	🟥 DS	🟦 CTD	🟨 DD	🟥 CTD	🟩 CTD	🟦 DD	🟩 DD	🟦 DS

Appendix D

Table 9. Crop rotations that were followed on the plots in the 2018 and 2019 production seasons. with the accompanying seed-drill that remained set on the plot.

Plot	Crop (2018)	Crop (2019)	Seed-drill
1	Canola	Wheat	Tine seed-drill
2	Barley	Cover crop	Tine seed-drill
3	Wheat	Barley	Double disc seed-drill
4	Cover crop	Canola	Tine seed-drill
5	Cover crop	Canola	Double disc seed-drill
6	Barley	Cover crop	Combination seed-drill
7	Wheat	Barley	Tine seed-drill
8	Cover crop	Canola	Tine seed-drill
9	Wheat	Barley	Combination seed-drill
10	Canola	Wheat	Double disc seed-drill
11	Cover crop	Canola	Combination seed-drill
12	Cover crop	Canola	Combination seed-drill
13	Barley	Cover crop	Tine seed-drill
14	Barley	Cover crop	Double disc seed-drill
15	Canola	Wheat	Double disc seed-drill
16	Barley	Canola	Combination seed-drill
17	Cover crop	Cover crop	Combination seed-drill
18	Cover crop	Canola	Tine seed-drill
19	Wheat	Barley	Tine seed-drill
20	Canola	Wheat	Tine seed-drill
21	Canola	Wheat	Combination seed-drill
22	Wheat	Barley	Double disc seed-drill
23	Canola	Wheat	Combination seed-drill
24	Wheat	Barley	Combination seed-drill
25	Wheat	Wheat	Tine seed-drill
26	Barley	Cover crop	Double disc seed-drill
27	Cover crop	Canola	Double disc seed-drill
28	Barley	Cover crop	Double disc seed-drill
29	Barley	Cover crop	Tine seed-drill
30	Wheat	Barley	Combination seed-drill
31	Cover crop	Canola	Double disc seed-drill
32	Barley	Cover crop	Combination seed-drill
33	Canola	Wheat	Combination seed-drill
34	Wheat	Barley	Double disc seed-drill
35	Canola	Wheat	Double disc seed-drill
36	Canola	Barley	Tine seed-drill