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AGRONOMY, SOILS, AND ENVIRONMENTAL QUALITY

Seed-Drill Opener Type and Crop Residue Load Affect Canola Establishment, but Only Residue Load Affects Yield

P.A. Swanepoel,* P. J. G. le Roux, G. A. Agenbag, J. A. Strauss, and C. MacLaren

ABSTRACT

Handling crop residue during planting operations is a challenge to conservation agriculture (CA) farmers worldwide. It remains unclear which tools are most effective in which conditions. Canola (*Brassica napus* L.), an oilseed crop widely used in rotation with cereals, is particularly sensitive to seedbed conditions, and thus may be influenced by residue loads and the choice of seed-drill openers. To identify optimal planting practices, this study compared the performance of disc and tine openers on canola establishment, growth, and yield under differing residue loads in a Mediterranean-type climate region. First, soil disturbance caused by disc and tine openers was evaluated to assess their effect on seedbed conditions; and second, the interacting effects of the openers with different residue loads was investigated. Tine openers and low crop residue loads resulted in the best ($P < 0.05$) canola establishment. However, canola at reduced plant populations compensated in both biomass and grain yield, so that no yield differences resulted from different opener types, and only small yield differences occurred between residue loads ($P > 0.05$).

Core Ideas

- Canola establishment can be affected by the residues of the previous crop.
- Different planting tools may handle crop residue differently.
- Tine and disc furrow openers at different residue loads were tested.
- Canola performed best when established with tine openers and when residue load is low.

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Conservation agriculture is characterized by management practices that include minimum- or no-tillage, maintenance of an organic soil cover and diversity of crops cultivated in rotation or in association. Like in many parts in the world, in the Western Cape of South Africa, multiple advantages have been observed from implementing these practices in dryland farming systems. Conservation agriculture practices have been associated with increased soil quality (Swanepoel and Tshuma, 2017), increased water holding capacity, reduced reliance on mineral fertilizers, reduced risk of soil erosion (Meadows, 2003), reduced weed pressure (MacLaren et al., 2018), interruption of pest and disease cycles (Lamprecht et al., 2011), financial risk mitigation and increased profitability (Knott, 2015; Basson 2017). Subsequently, CA adoption levels have been high, particularly for no-tillage and crop diversity (Smith et al., 2017). Typical crop rotation systems in the Western Cape are based on wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) in rotation with canola and forage crops. Canola is regarded as one of the most important break crops in these systems. Cultivating canola every third or fourth year allows farmers to control grass weeds with selective herbicides (Pieterse 2010). Soil-borne disease pressure for cereals is also reduced on fields where crops are rotated with canola (Lamprecht et al., 2011).

However, crop yields in the Western Cape are not consistently better under CA. This may be due to farmers adopting CA tools and practices that are not suited to local farming systems. To date, minimal research has been done to refine which tools and practices are most suited to Western Cape crops and conditions. In particular, it could be expected that yield may be affected by differences in and interactions between residue management and the seeding equipment ("seed-drills") used to establish crops. Under CA practices, seed-drills either use disc or tine openers to place the seed, and these differ in the amount of superficial soil disturbance they cause. Disc openers cause less superficial soil disturbance than tine openers, and thus may be better able to conserve soil structure and biological activity, resulting in better canola establishment and growth (Tessier et al., 1991). However, the performance of disc and tine openers may vary in different residue loads.

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Abbreviations: CA, conservation agriculture; DAP, days after planting.

In CA systems, crop residue removal is minimized. Advantages of residue retention include mitigation of soil temperature extremes, increased soil fertility (Kumar and Goh, 2002), and water (Smil, 1999) and soil conservation (Bruce et al., 2005). In the Western Cape, approximately 50% of producers leave residue on the field after harvesting. Others will use it as hay or allow grazing of residues during the summer (Smith et al., 2017). Generally, spreaders are used to distribute unchopped straw at harvesting. Residue degradation during the fallow season is slow because of the Mediterranean-type climate, which can result in challenges during the planting process. High crop residue loads can interfere with the planting process and inhibit crop establishment. Canola is known to be particularly sensitive to high residue cover (Bruce et al., 2005). Tine and disc openers use different mechanisms to plant seed through residue, and thus their ability to establish canola effectively in high residue loads is expected to vary. Most producers in the Western Cape rely on seed-drills with tine openers to establish canola. Tine openers create a furrow as they are pulled through the soil, after which the seed and fertilizer are placed in the furrow at separate depths. The furrow closes as the tine moves forward and a press wheel following the seed dispenser compacts the soil for good soil-to-seed contact. The major risk of seed-drills with tine openers is that unanchored, and particularly wet, residue clogs the seed-drill. In contrast, disc openers are designed to handle more residue by cutting through the residue into the soil at an angle. Seed and fertilizer are placed within the opening made by the disc.

A study was conducted to test the effect of opener type on canola established in different residue loads. A seed-drill with interchangeable tine or disc openers was used to eliminate effects of other machine characteristics. The objectives of this study were (i) to compare the effect of tine and disc openers on seedbed soil disturbance and (ii) to investigate the interacting effects of tine and disc openers in different residue loads on canola establishment, growth, and yield.

MATERIALS AND METHODS

Trial Location

The trial was undertaken on Langgewens Research Farm (33°16'42.33" S; 18°42'11.62" E; 191 m above sea level) in the Swartland region of South Africa's Western Cape Province, in 2016 and 2017. In 2016, rainfall during the growing season was 270.8 mm, similar to the long-term average of approximately 320 mm, while in 2017 rainfall during the growing season was only 180.4 mm. However, in both seasons the first substantial rainfall occurred later than usual so canola was planted into dry soils in both seasons. Minimum, maximum, and mean temperatures throughout the trial were similar to long-term averages.

Soils types were variable within the site, but most had a duplex nature. According to the USDA soil taxonomy and the International Classification Systems (IUSS Working Group WRB, 2006; Soil Survey Staff, 2003) these soils are classified as Alfisols or Luvisols, respectively. According to the South African classification system, the most common soil forms were Swartland (pedocutianic-lithic), Klapmuts (eluvic-pedocutanic), Sepane (pedocutanic-cumulic-hydromorphic), and Sterkspruit (prismacutanic) soil forms (Soil Classification Working Group, 1991).

The effectiveness of different seeding equipment may vary with soil quality, particularly soil physical condition (Swanepoel et al., 2017), and so a range of biological, chemical, and physical soil characteristics were measured on each location on the farm used for the study. Representative soil samples were taken from each location prior to planting. Table 1 provides the mean and standard error of each soil characteristic across all locations used in this study. This provides an indication of the type of soil to which the results of this study are applicable: it can be expected that the effects of seeding equipment and residue load observed in this trial would be applicable to soils with similar characteristics, but would not necessarily occur on soils that differ markedly from Table 1, particularly with regard to physical characteristics.

Table 1. Mean ± SE (*n* = 8) values of indicators for all plots included in this study on Langgewens Research Farm, South Africa.

Soil quality indicator	2016	2017
pH (KCl)	5.65 ± 0.13	5.66 ± 0.10
Exchangeable Ca, mg kg^{-1}	1796 ± 197	2131 ± 223
Exchangeable Mg, mg kg^{-1}	107 ± 12.7	160 ± 17.1
Exchangeable Na, mg kg^{-1}	28.6 ± 9.01	86.6 ± 46.4
Exchangeable K, mg kg^{-1}	137.0 ± 11.1	164.5 ± 18.0
Cation exchange capacity, cmol kg^{-1}	6.13 ± 0.56	7.59 ± 0.79
Extractable P, mg kg^{-1}	80.3 ± 6.0	76.6 ± 5.16
Clay, %	10.5 ± 1.0	17.5 ± 1.90
Organic C, %	1.40 ± 0.1	1.16 ± 0.05
Aggregate stability, %	42.2 ± 6.7	40.38 ± 6.36
Bulk density, g cm^{-3}	1.80 ± 0.05	1.41 ± 0.04
β-glucosidase activity, μg^{-1} h^{-1}	787.8 ± 38.15	1454.4 ± 119.9

Trial Layout and Set-up

The trial was located within a replicated crop rotation system on Langgewens Research Farm, and so plot locations for this trial were selected based on whether they were due to be planted with canola in each year of this study. Eight locations were available to the trial each year, four with wheat as the preceding crop, and four with annual *Medicago* spp. Annual *Medicago* pastures were grazed at an appropriate stocking rate of four sheep per hectare. At each location, the trial was laid out in a split plot design. The location (main plot) was divided into two half-plots, with one-half planted with tine openers and one-half with disc openers. Allocation of openers to each half was randomized. Within each half-plot, three subplots with different residue treatments were randomly allocated, following the arrangement outlined in Fig. 1. To summarize, the trial consisted of three residue treatments (low, medium, high) replicated in each opener type (disc, tine) on eight plots.

Residue loads were manipulated in the residue treatment subplots. In the high residue treatment, residue covered the plot so that no bare soil was visible. Where possible this was achieved using existing crop stubble, but in most cases it was necessary to add additional residue (to best mimic normal field residue conditions, unchopped (long) wheat residue was used). The total amount of residue on the high residue plots was 5.1 t dry matter (DM) ha^{-1} in 2016 and 6.4 t DM ha^{-1} in 2017. The medium residue plots had 50% (visually estimated) soil cover (4.3 t DM ha^{-1} in 2016 and 5.3 t DM ha^{-1} in 2017). No residue was added to low residue plots (1.5 t DM ha^{-1} in 2016 and 1.9 t DM ha^{-1} in 2017). Residue loads vary among farmers in the region and range from very low in systems where residues are heavily grazed, baled, or burned (<1.0 t ha^{-1}), to very high in systems where crop residues

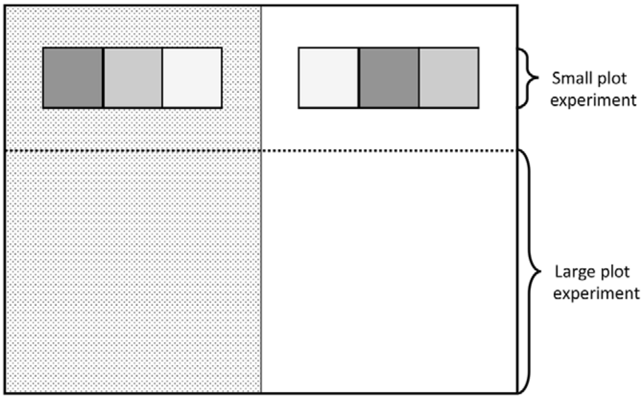

Fig. 1. Schematic of the trial layout of each location. The shaded background indicates that each side was planted using a different opener (tine or disc), and the small squares indicate the "small plot experiment" with shading representing different residue loads randomly assigned to subplots. The large squares below the dashed line indicate the location of the field scale "large plot experiment". This trial layout was replicated eight times.

are not removed (>6.0 t ha^{-1}). Residue loads therefore corresponded to typical residue loads on farms in the region. In 2016, each subplot comprised 55 m^2; and in 2017, subplots were 25 m^2.

Outside of the area used for the residue treatments in each location (the "small plot experiment"), a separate 1500 m^2 plot was demarcated in each of the tine-planted and disc-planted halves (Fig. 1). This additional "large plot experiment" allowed yield to be assessed in response to opener type at a field scale, as high soil variability can prevent plot-scale findings being applicable at the farm scale. However, it was not possible to experimentally manipulate residue loads at this scale.

Planting and Management of Canola

Canola was planted across each location on 25 May in 2016 and 3 May in 2017, using an Equalizer no-till seed-drill with interchangeable weight-dependent tine and single disc openers [Equalizer AG (Pty) Ltd., Cape Town, South Africa]. This avoided any bias resulting from differences in weight and seed delivery efficiency between different planters. Each opener unit was fitted with a hydraulic trip control and downward force control, which were activated when the unit ran over large rocks. This also allowed residue to efficiently flow around the opener units. Each year rainfall arrived at the end of May, which is later than usual, and thus canola was planted into dry soil both years, with a gravimetric water content of between 3.7 and 5.7% at planting. For both years, canola was established at a seeding rate of 3.5 kg ha^{-1} (thousand seed weight > 4 g). The recommended seeding rate for the region is 2 to 5 kg ha^{-1}. Seeding depth of the two openers did not differ significantly and seeds were placed at a depth of approximately 10 mm from the bottom of the furrow (results not shown). Rows were spaced 300 mm apart. The canola cultivars used were Hyola 559TT in 2016 and Atomic in 2017. Both are triazine (atrazine: [6-chloro-*N*-ethyl-N'-(-methylethyl)-1,35-triazine-2,4-diamine]-tolerant cultivars found to perform well in previous cultivar evaluation trials on Langgewens Research Farm. The tractor speed when seeding in 2016 was 5 km h^{-1} for both openers. In 2017 the seeding speed when using a disc opener was increased to 8 km h^{-1}, while the tine opener speed was kept at 5 km h^{-1}, which is considered best practice.

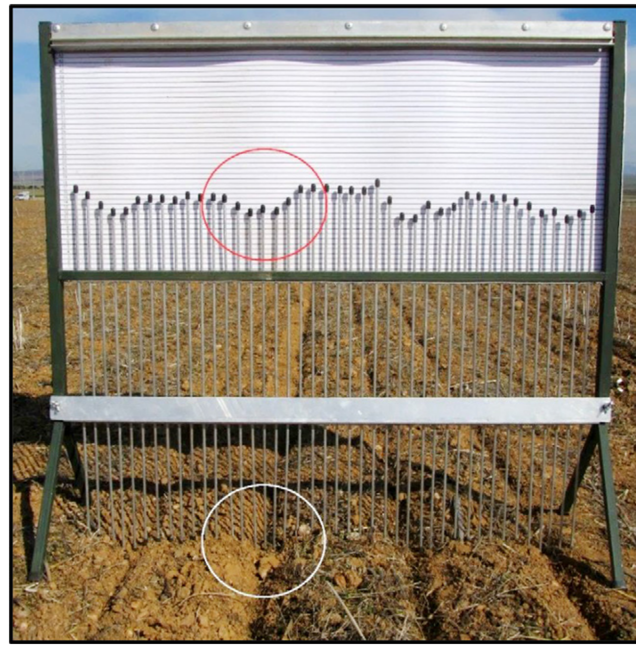

Fig. 2. Pin profiler used to determine the amount of aboveground soil disturbance. The white circle at the bottom indicate the furrow in the soil caused by the opener, while the red circle at the top indicates the roughness profile of the furrow.

In the beginning of each year, representative soil cores were taken in each location at three depths (0 to 150 mm, 150 to 300 mm, and 300 to 450 mm) to assess the soil nutrient status. Accordingly, fertilizer applied at planting comprised 2.5 kg N ha^{-1}, 10 kg P ha^{-1}, 5 kg K ha^{-1}, and 4 kg S ha^{-1}. In 2016 this fertilizer was placed with the seed for both the disc and tine openers. In 2017, this was amended to follow recommended practices for each planter, so the fertilizer was broadcasted prior to planting with the disc opener, but still placed with the seed with the tine opener. Twenty-one days after the canola emerged in 2017, 50 kg N ha^{-1}, 6.2 P ha^{-1}, and 7.8 kg S ha^{-1} was applied as a first top dressing. In 2016, a second top dressing of 40 kg N ha^{-1} and 8 kg S ha^{-1} was applied with bolting stage onset. Boron was applied as a foliar spray prior to flowering in both years. Weed and pest control were managed with pesticides according to recommended best practice for the region.

Data Collection

On the low residue subplots, soil disturbance caused by each opener was assessed. Soil disturbance could not be assessed in the medium and high residue plots as insufficient soil was visible. A pin profiler (Fig. 2) was used to measure the surface roughness and furrow width. This instrument consisted of 42 pins spaced 20 mm apart within a frame where they can slide up and down to conform to surface irregularities (Moreno et al., 2008). The pin profiler was randomly positioned three times per plot perpendicular to the direction of seeding directly after seeding. Three furrows per position resulted in nine measurements per plot. Arithmetical mean surface roughness was calculated as the sum of height values of the pins, where height was measured from the lowest pin. Mean furrow width was visually assessed as the mean value of the width of the rows, determined by the number of pins which touched disturbed soil on either side of the furrow.

Plant population was determined 30 d after emergence by counting the number of seedlings in four 0.25 m^2 quadrats per plot. At 30, 60, and 90 d after emergence, and when the plants reached physiological maturity, 10 plants per plot were sampled by cutting at ground level. These were dried at 60°C for 72 h and weighed to determine aboveground biomass production per plant and multiplying by the plant population to determine biomass production per hectare.

The crop on the small plots was harvested on 20 Nov. 2016 and 1 Nov. 2017 with a HEGE 140 plot combine. Subsequent, yield was determined by weighing the seed of each plot. A commercial combine was used for harvesting the large plots and a weigh wagon grain cart was used to determine yield. Thousand seed mass was determined by counting and weighing 1000 seeds. Harvest index was determined by calculating the ratio of grain yield to plant biomass dry weight for each plot.

Data Analyses

Linear mixed models were used to investigate the effects of opener type and residue loads on canola soil disturbance and canola plant population, biomass, and yield. Residue load was included as an ordered factor. Biomass was log transformed to fit the model assumption of a normal distribution. For the small-plot experiment, the fixed effects were opener (disc or tine), residue load (low, medium, or high), interactions among the previous two, and year. In the large-plot experiment, residue load was not tested so the model contained only opener type as a fixed effect. All models contained "location" as a random effect, given that the treatments were replicated in eight different locations across the farm, and there may have been differences between these locations due to differences in previous management and in localized environmental conditions.

All data analysis was undertaken in R, version 3.4.3 (R Core Team, 2017). Models were calculated in the package lmerTest using restricted maximum likelihood (REML), with *P*-values for the significance of each variable calculated using type III ANOVA based on Satterthwaite's approximation for degrees of freedom. Pairwise comparisons between treatments were calculated using package emmeans*,* which computes contrasts between the estimated marginal means (also known as least-squares means) of each level of each factor. Both linear and polynomial contrasts were investigated, and pairwise comparisons conducted at the appropriate level depending on which were significant. Unless otherwise reported, pairwise comparisons indicated in the results are based on linear contrasts. Contrasts were only conducted between levels of factors that were found to be significant ($P < 0.05$) in the ANOVA.

Results are displayed as boxplots, which indicate the median (thick bar) and interquartile range (box) of the data. Whiskers are the lower value of either 1.5*x* the interquartile range or the minimum/maximum, and open circles are points more than 1.5*x* the interquartile range from the median. Letters at the base of the plots indicate which treatments were different from one another according to the post-hoc pairwise comparisons.

Table 2. The ANOVA *F* statistics and *P*-values for the models of surface roughness and groove width in response to opener type and year. Bold is used to illustrate *P*-values < 0.05.

	Surface roughness		Groove width	
Variable	*F* statistic	*P*-value	*F* statistic	*P*-value
Opener type	1.374	0.251	3.828	0.060
Year	1.000	0.326	10.564	**0.003**

RESULTS

Soil Disturbance by Different Openers

Minimal differences were observed in seedbed soil disturbance between tine and disc openers, with no significant difference in surface roughness ($P > 0.05$) and only some evidence that tines produced wider grooves than discs ($P < 0.1$) (Table 2). Groove widths also differed between years and were narrower in 2017, possibly as a result of differences in speed of sowing or high stone content (>30%), although Celik and Altikat (2012) reported that tractor speed had no effect on soil compaction in the furrow and winter wheat establishment. There were no relationships between either surface roughness or groove width and canola plant population, biomass, or yield ($P > 0.1$, results not shown).

Opener Effects on Plant Establishment at Different Residue Loads

Plant population was significantly affected by opener type and by residue load ($P < 0.05$, Table 3). Plant population of the canola planted with tine and disc openers were 43 and 31 plants m^{-2}, respectively. Pairwise comparisons indicate that plant population was significantly higher where a tine was used in low residue (Fig. 3). When a tine was used in a moderate residue load, intermediate plant population was obtained between high and low residue loads. When a disc opener was used, plant populations were always among the lowest ($P < 0.05$), regardless of residue load.

Residue and Opener Effects on Plant Growth

Canola produced more biomass at 30 and 60 d after planting (DAP) when a tine was used in low residue loads ($P < 0.05$). By 90 DAP the effect of residue was no longer significant ($P > 0.05$), but tine-planted canola remained more productive than disc-planted canola until physiological maturity (Table 3, Fig. 4). Biomass production also differed between years, tending to be higher in wetter 2016 than drier 2017 ($P < 0.05$).

Table 3. The ANOVA *F* statistics and *P*-values for the mixed models of plant population and biomass to opener type (OP), residue loads (RL), and year. Location was included as a random variable in each model. Bold is used to illustrate *P*-values < 0.05. DAP = days after planting.

	Plant population		Biomass at 30 DAP		Biomass at 60 DAP		Biomass at 90 DAP		Biomass at physiological maturity	
Variable	*F* statistic	*P*-value	*F* statistic	*P*-value	*F* statistic	*P*-value	*F* statistic	*P*-value	*F* statistic	*P*-value
OP	15.360	**<0.001**	16.539	**<0.001**	10.574	**0.002**	4.508	**0.037**	5.618	**0.020**
RL	4.865	**0.010**	7.842	**<0.001**	5.623	**0.005**	1.305	0.277	0.889	0.416
Year	0.420	0.527	23.289	**<0.001**	0.851	0.372	44.976	**<0.001**	9.286	**0.009**
OP/RL	0.913	0.406	0.745	0.478	0.181	0.835	0.983	0.379	0.227	0.797

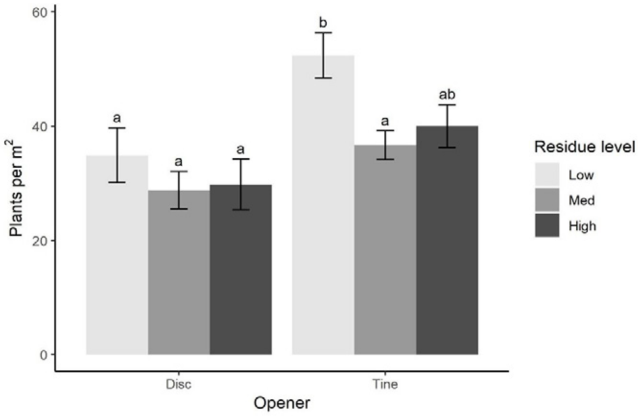

Fig. 3. Plant populations at different residue loads (L = low, M = medium, and H = high) and with different openers. Given that the Residue:opener combinations that do not share a letter were significantly different from one another ($P < 0.05$).

Small-Plot Experiment: Residue and Opener Effects on Harvest Index and Grain Yield

Residue load had a small but significant effect on overall grain yields, with canola planted at higher residue loads tending to produce less than canola planted at low residue loads (Table 4). However, this effect was not sufficiently substantial to detect significant pairwise differences in yield between residue level treatments (Fig. 5a). Yield did not differ between years but harvest index did, with higher harvest indices observed in 2017 ($P < 0.05$, Table 4). However, harvest index was not affected by residue loads or opener type.

Table 4. The ANOVA *F* statistics and *P*-values for the mixed models of yield and harvest index to opener type (OP), residue loads (RL), and year in the small-plot experiment. Location was included as a random variable in each model. Bold is used to illustrate *P*-values < 0.05.

	Yield		Harvest index		Yield per plant	
Variable	*F* statistic	*P*-value	*F* statistic	*P*-value	*F* statistic	*P*-value
OP	1.867	0.176	0.406	0.526	7.394	**0.008**
RL	3.452	**0.037**	1.931	0.152	0.538	0.586
Year	1.175	0.297	8.065	0.013	4.820	**0.045**
OP/RL	0.417	0.661	0.721	0.489	0.080	0.923

In contrast to overall yield, yield per plant was not sensitive to residue load, and was higher in disc-planted compared with tine-planted canola (Table 4, Fig. 5b). This effect may be due to reduced competition between plants resulting from the lower plant populations established by disc-planters. However, reduced competition was not sufficient to allow the lower plant populations established under high residue to equal the yield produced by the higher populations present at low residues. Given that harvest index, a ratio of yield to biomass, was not significant but yield per plant was, it appears that compensation for a lower plant population occurs during the vegetative production growth stage.

Large-Plot Experiment: Opener Effects on Grain Yield

No differences in grain yield were observed between different opener types at the large-plot scale. This is consistent with the findings from the small-plot experiment that only residue loads influenced grain yield. Large-plot yields did differ between years (Table 5), and tended to be higher in the wetter year of 2016.

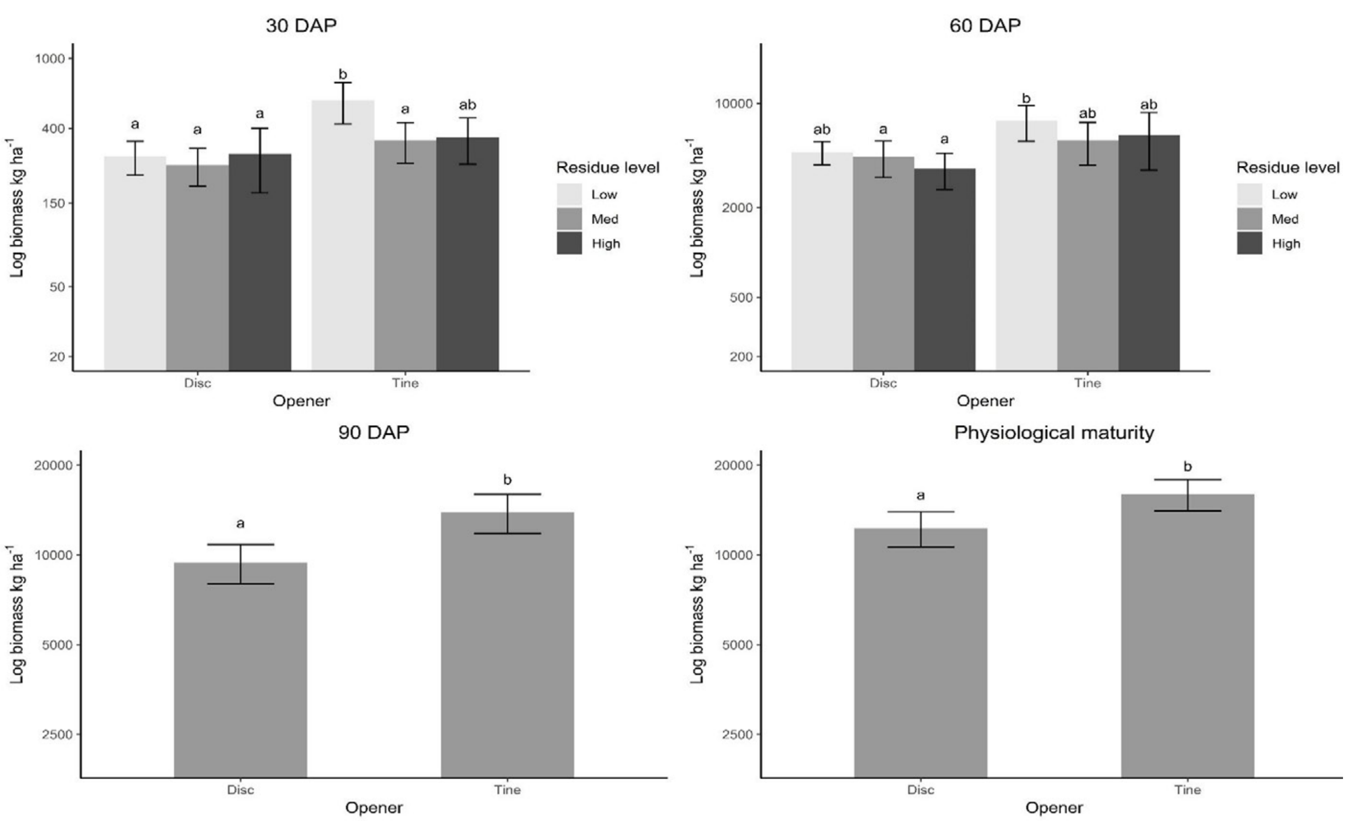

Fig. 4. Biomass production in log kilogram per hectare at 30 d after planting (DAP), 60 DAP, 90 DAP, and 120 DAP, with either discs or tines at different loads of residue. Residue:opener combinations that do not share a letter were significantly different from one another ($P < 0.05$). At 90 DAP and physiological maturity, residue loads were not significant, and thus only means for the different opener types are shown.

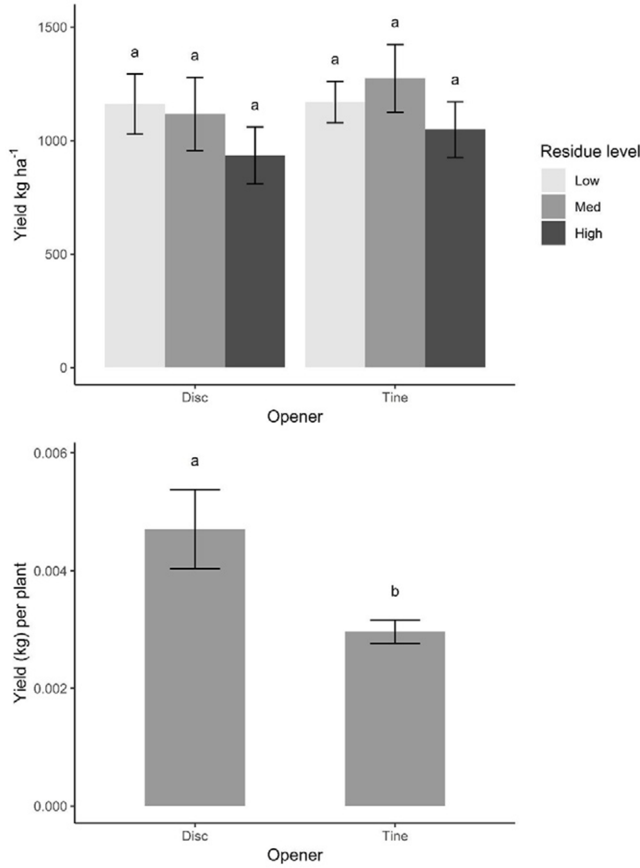

Fig. 5. Canola yield in (A) kilogram per hectare and (B) per plant. Although residue load was significant for overall yield (Table 4), there were no significant pairwise differences. For yield per plant, residue level was not significant and so only the difference between the opener types is shown.

DISCUSSION

The ability for canola to compensate in grain yield at reduced plant populations suggests that there is no major disadvantage to using either a tine or disc opener. However, a higher plant population would increase the potential to realize higher yields, if environmental and management factors are optimal. It would also be expected to help canola plants compete with late emerging weeds. Local guidelines recommend a canola plant population of 40 to 50 plants m^{-2} (G.A. Agenbag, personal communication, 2018). Canola plants have the capacity to compensate when plant populations are low and competition for space is not limiting, by forming more flowering branches. There are reports that there is no grain yield penalty for canola at low plant populations of 30 to 40 plants m^{-2} (Angadi et al., 2003; French et al., 2016). French et al. (2016) found that the overall economic optimum plant density for canola in Western Australia (similar climate to the Western Cape) was 30 to 40 plants m^{-2}. In the current study, suboptimal plant populations (about 31 plants m^{-2}) often resulted when a disc was used to establish canola, particularly in high residue loads. Although no significant difference was observed in yield between disc and tine openers in this study, it may not be optimal for farmers to consistently rely on such low plant populations. The risk of reduced yields is higher with low plant populations in unfavorable years, and with a high input crop such as canola, a financial risk is incurred if the plant population dips below 40 plants m^{-2} to maintain yield.

Table 5. The ANOVA *F* statistics and *P*-values for the mixed model of yield to opener type (OP), and year in the large-plot experiment. Location was included as a random variable in the model. Bold is used to illustrate *P*-values < 0.05.

Variable	*F* statistic	*P*-value
OP	0.108	0.745
Year	3.491	**0.071**

Our results suggest that canola can tolerate some degree of residue, but that canola would perform best when located in a rotation sequence following a low-residue producing crop (most leguminous cover crops, for example), or a crop that has been grazed or harvested for biomass (hay, silage, or biofuel) with relatively little residue thus left on the field. This is supported by Bruce et al. (2005), who also found that high residue loads reduced both canola establishment and yield. The residues themselves could also be grazed shortly before planting (Hunt et al., 2016). Integrating livestock in the crop rotation systems, would not only support better canola production, but also confers various other benefits such as increased yields and reduced reliance on herbicides and fertilizers (MacLaren et al., 2018). Choppers and spreaders at harvest can also be used to manage crop residue, but chopping residue limits the usefulness of residue for grazing and/or baling after exit from the combine. Another option is to use residue managers mounted to the seed-drill to clear the row during planting, to reduce the residue load encountered by the openers.

In contrast to previous findings, no difference between the performance of either tine or disc openers at different residue loads was observed. Both openers are thought to be affected by high residue loads, with tine openers prone to dragging residue into clumps that can smother emerging seedlings (Dillon, 2013; Celik and Altikat 2012) and disc openers having a tendency to "hairpin" the residue into the furrow (Yao et al., 2009). Hairpinning is where the disc folds the residue into the soil instead of slicing through it, and this can reduce seed to soil contact and inhibit establishment. That this effect was not observed in this study may be due to the late rainfall and dry conditions in which canola was planted in both years. The desiccated condition of the residue may have made it easier to avoid both hairpinning with discs and excessive clumping with tines.

It is important to consider the entire cropping system when choosing a suitable opener to establish canola. Other factors to take into consideration include crop rotation composition, fertilizer placement in soil, compatibility of the seeding equipment with agrochemicals, maintenance, and fuel costs. Most farmers do not have specialized seeding equipment for different crops, and it is typical on Western Cape farms for farmers to use the same seeding equipment to establish both wheat and canola. Previous research in Western Cape conditions indicates that disc openers may promote better establishment of wheat, particularly where soil quality is low (Swanepoel et al., 2017). Given that no yield differences were observed between disc and tine openers for canola in this study, a disc opener seems preferable for farmers whose main crops are wheat and canola, as the disc may benefit the wheat and would not disadvantage canola.

Fertilizer placement is also important to the choice of opener due to the possibility of toxicity to the seed and emerging seedlings, and whether the fertilizer is placed at a suitable rate and in the correct area for root uptake may also affect nutrient uptake efficiency and yield (Darmora and Pandey, 1995). Most seed-drills with tine openers place fertilizer a few centimeters below the seed while single disc openers place the seed and the fertilizer in the same furrow, and thus a tine opener can reduce the risk of fertilizer damage to seedlings. Canola has a small seed and a single radicle, and is therefore particularly sensitive to chemical injury from fertilizers. This may be a reason that the disc opener resulted in low canola plant populations in the current study (although in the second year of the trial fertilizer at planting with the disc opener was broadcast instead of placed with the seed to avoid this risk). More research is needed to determine whether fertilizer placement explains the effect of the disc opener on canola establishment. So far, additional ongoing trials in the Western Cape suggest that disc-planted canola in fertilizer-free treatments also does not establish well, but this has not yet been confirmed (P. Swanepoel, unpublished data, 2018).

It may also be important to consider interactions between herbicides and openers. For example, trifluralin [2,6-Dinitro-*N*,*N*-dipropyl-4-(trifluoromethyl)aniline], a pre-emergent herbicide commonly used in Western Cape crop rotation systems, can only be applied with tine openers in no-till systems as it is light sensitive and needs to be covered by soil during planting for effective action. However, trifluralin can prove toxic to canola in stressful conditions (Majid et al., 2003) and thus may be best avoided if alternatives are available.

Maintenance costs and fuel consumption are expected to differ significantly between tine and disc openers (Sijtsma et al., 1998). Tractors pulling tine openers usually require more power (kW), and would therefore have a higher fuel consumption than disc openers. This is, however, dependent on soil strength and weight load required to achieve the same penetration with different openers (Ashworth et al., 2010). It is suggested that further research focuses on an economic evaluation of disc and tine openers, taking into account soils with different strengths and their interactions with fertilizers and herbicides, to give farmers further insight when choosing between the two openers.

It would be valuable to conduct opener trials over the longer term and in a greater variety of soil conditions. At this stage, no other work comparing the performance of tine and disc openers has been published, so it is not clear whether similar trends would be observed in different climates and on soil types not included in this study. For example, differences in opener-residue interactions may occur in wetter conditions, and increased soil moisture could also influence levels of soil disturbance caused by each opener. Over the long term, even small differences in such measures may have consistent effects on yield or soil health that lead to a specific opener type outperforming the other.

CONCLUSION

Canola establishment was higher with tine openers than with disc openers, and was also the highest when crop residue load was low. However, the ability for canola to compensate in both biomass and grain yield at reduced plant populations suggests that there is no major disadvantage to using either tine or disc openers, and that canola can tolerate some degree of residue. Canola would, however, perform best when located in a rotation sequence following a low-residue producing crop, or a crop that has been grazed or harvested for biomass with relatively little residue left on the field. Further research is required to see if these results are consistent in different climates and soil types, and over the long term.

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